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Integrated radon monitoring in Tatun Volcanic Areas of Northern Taiwan

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ABSTRACT

Taiwan is highly active tectonically and intensively faulted resulting in occurrence of number of big earthquakes in the region. In the northern part of Taiwan Island, a group of volcanoes are distributed. These volcanoes are known as the Tatun volcano group (TVG). During the past decade, volcanological, seismological, and geochemical observations have shown that Tatun Volcano Group has potential for future eruptive activity. In the present study solid state nuclear track detectors (SSNTDs) technique has been used for the measurement of radon-thoron concentrations in soil gas for volcanic and seismic study in Taiwan. The semiautomatic track count using a Nikon digital camera coupled to a PC and employing software "SCION" has been checked and tested by comparing the results with manual counting. In order to study radon-thoron in volcanic areas, pre-calibrated radon-thoron discriminators with LR films has been installed in Hsiaoyoukeng (SYK), Dayoukeng (DYK), Bayen (BY), and Gungtzeping (GTP) of Tatun Volcanic area in a hole (about 50 cm depths) having different temperatures for a defined period (bi-weekly to monthly). Radon behaviour observed is different at above said sites. We have also monitor radon using SSNTDs along with active detectors (RAD 7) in Bayen (BY) area of Tatun for comparative study. The observations have shown potential precursory signals for some earthquakes that occurred during the observation period having an epicenter in and around the TVG. Our monitoring stations in TVG area are sensitive to the events within a distance of 60 km.

1. INTRODUCTION

Since last few decades, scientific community has recognised that the variations of soil gas radon concentration as a useful tool for geodynamical monitoring in active fault zones (Singh et al. 1999; Walia et al. 2003, 2013; Planinić et al. 2004; Kumar et al. 2009) for surveillance in volcanic areas (Connor et al. 1996; Monnin and Seidel 1997; Segovia et al. 2003) and for tracing neotectonic faults (Burton et al. 2004). Rn-222 (radon hereafter) is a naturally occurring radioactive (3.8 d half-life) noble gas, produced in uranium bearing rocks as part of the U-238 decay series. Radon is generated within mineral grains by alpha decay from Ra-226. Due to its recoil energy, radon can move in the solid material and migrate from the solid grain into the air or water filled interstices of porous media (emanation).Within the air filled or water-filled pores, radon can migrate via diffusion towards lower concentration regions and/or via advection in response to a pressure gradient. Diffusive and advective transport processes in the pore space of porous materials enable radon to escape into the Earth's atmosphere and indoor environments (exhalation).

The Tatun Volcano Group (TVG) on the northern tip of the island of Taiwan covers an area of approximately 300 km^2 (Fig. 1). It is only about 10 km north of the capital city of Taipei, which is characterized by andesitic flows that took place during and after the Early Pleistocene orogeny. From a tectonic point of view, it is located at the western end of the subduction system in the northern Taiwan area, where the Philippine Sea plate (PSP) is subducting northward beneath the Eurasian plate. Simultaneous subduction

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of the Philippine Sea plate is occurring under the Ryukyu arc located offshore (northeast of Taiwan).The group is composed of over 20 andesitic volcanic composites, cones, and domes (Chen and Wu 1971; Wang and Chen 1990), enclosed by NE-SW trending faults (Komori et al. 2013). A look at historical volcanic eruptions has suggested that volcanism has been extinct since the last major activity that occurred from 0.8 - 0.2 Ma BP (e.g., Juang 1993; Tsao 1994). However, recent studies offer suggestions that the potential for volcanic activity exists in the area: extensive hydrothermal activity is discharging a large amount of heat (e.g., Chen 1970); there are strongly acidic hot springs (pH approximately 1 to 3) (e.g., Liu et al. 2011; Ohsawa et al. 2013); magmatic contributions are found in fumarolic gases (e.g., Yang et al. 1999, 2003; Lee et al. 2005; Ohba et al. 2010); relatively young ejecta can be observed (<< 20 ka, Chen and Lin 2002; 6 ka, Belousov et al. 2010), and the presence of clustered seismicity and shallow pressure sources suggest fluid flows (Lin et al. 2005a; Konstantinou et al. 2007, 2009; Murase et al. 2014). Seismic (Lin et al. 2005b; Konstantinou et al. 2007) and geochemical data (Yang et al. 1999, 2005a; Lee et al. 2005; Witt et al. 2008; Ohba et al. 2010) infer that a magma chamber may exist under northern Taiwan. In the recent study of both S-wave shadow and P-wave delay by Lin (2016) has shown substantial evidence for the presence of a deep magma reservoir. Data generated from GPS stations in TVG area have not demonstrated any clear deformation caused by volcanic activity (Lin et al. 2011; Murase et al. 2014). However, ground displacements at TVG reportedly (Yu et al. 1997; Shyu et al. 2005) controlled to first order by tectonics, which may be responsible for the long-term linear trends on the north and east components. In addition, seasonal displacements are attributed to atmospheric and hydrologic loading (Dong et al. 2002).

Rn-222 (radon) is the major radioactive gas in the volcanic area. The study of radon concentration variations in volcanic areas has been considered as a useful tool to investigate the volcanic and seismic activity in one area (Cigolini et al. 2009; Moreno et al. 2009; Viveiros et al. 2009). Instruments for the measurements of radon and its decay products are based mostly on the detection of alpha particles. The radon sampling devices can be divided into active devices that require electric power to collect a sample and passive devices that do not require electric power (dry battery operated). SSNTDs are passive detectors, cheap and can be installed near the volcanic areas. They have some advantage over the active detectors, although the active detectors are more accurate and precise than passive detectors. In views of this in our earlier study (Kumar et al. 2013) cellulose nitrate alpha detector films (LR-115) were installed in discriminative cups at the selected site in Hsiaoyoukeng (SYK), Dayoukeng (DYK), Gungtzeping (GTP), and Byen (BY) of Tatun volcanic areas of northern Taiwan. Before installation of these films in the field, the LR-115 films in rodon-thoron discriminator has been calibrated and suitable site for integrated radon monitoring has been selected (Kumar et al. 2013). The low value for the thoron in TVG area has been observed which seems to be not useful for this study. The objective of this paper is monitor integrated radon concentration in TVG areas using SSNTDs to observe possible radon flux changes with and seismic and volcanic activities in the area. In addition to that radon behaviour

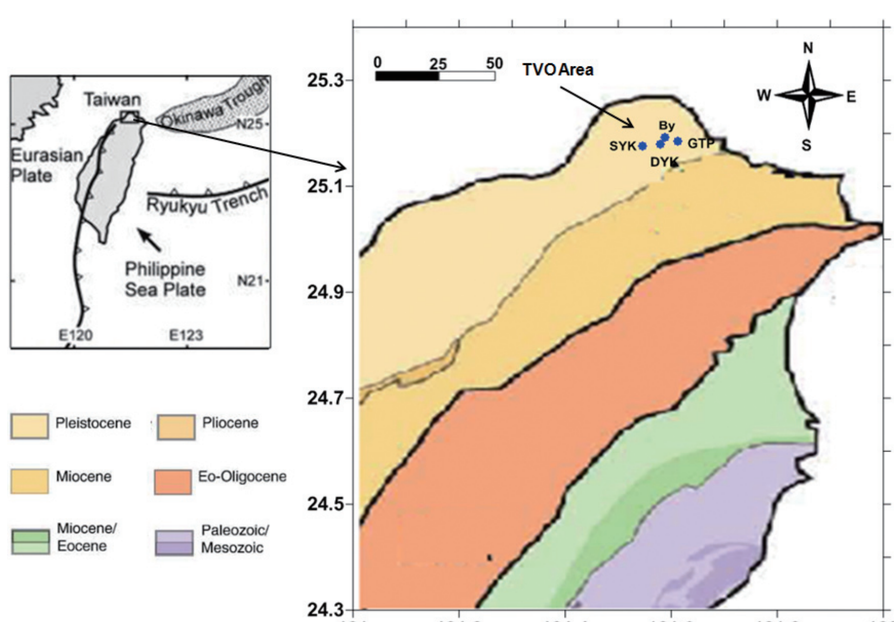


Fig. 1. Simplified geological map of Taiwan and geodynamic setting of the arc-continent collision, which shows the locations of monitoring stations in TVG area (modified from Mouthereau et al. 2009).

observed at each station as well the result of radon concentration recorded with LR115 (passive detectors) and RAD7 (active detector) at By station for comparison study will also be presented.

2. METHODOLOGY

After the calibration of LR-115 films in radon-thoron discriminator and selecting the suitable site for radon monitoring in SYK, DYK, GTP, and BY of Tatun Volcanic areas (Fig. 1) as reported in the earlier study (Kumar et al. 2013). The integrated radon monitoring has been carried out by using LR-115 plastic detectors for volcanic and seismic study in sites mentioned above. For the present study, radon-thoron discriminators with LR films were installed in these sites having different temperatures in a hole (about 50 cm depths) for a defined period (bi-weekly to monthly). After retrieval and etching the films from the above sites the tracks were counted using semiautomatic methodology (Arias et al. 2005). It is a simple and reliable methodology with a semiautomatic track count using a Nikon digital camera coupled to a PC and employing software "SCION" freely available on the Internet (https://en.wikiversity.org/wiki/Scion_Image). The computed tracks per cm^2 in the films were converted to kBq m^{-3} using the calibration factor calculated in the earlier study (Kumar et al. 2013). In order to study the radon variations with the metrological parameters and seismic activity in the study area, the respective data has been taken from Central Weather Bureau (http://www.cwb.gov.tw/eng/) and Tatun Volcanic Observatory, Taiwan. Taiwan is one of the most active seismic regions of the world with an average of about 20000 earthquakes occurring every year in or around Taiwan as reported by Central Weather Bureau of Taiwan (http://www.cwb.gov.tw). Therefore, it is essential to define selection criteria to identify threshold earthquakes for this study. From the literature, it has been found that the various criteria for selection of the earthquakes had been adopted by different studies (Fleischer 1981; Virk 1996; Martinelli and Dadomo 2017). However, from previous studies in Taiwan (Yang et al. 2005b; Fu et al. 2009; Walia et al. 2009, 2013; Kumar et al. 2015) the earthquake selection criteria has been defined as: earthquakes having local intensity $\geq$ 1 at the monitoring stations with epicentral distance (R) $<$ 100 km having D/R ratio $\geq$ 1 with focal depth $<$ 40 km. It is fitted well in different fault zones in Taiwan and used in the present study. In D/R ratio, D is effective/strain radius (D in km) for earthquake preparation zone has been calculated by using Dobrovolsky et al. (1979) formula: $D = 10^{0.43M}$ and R is epicentral distance. Similarly, in order to identify possible threshold values of anomalous radon concentration, various statistical methods have been used by different authors in the past (Walia et al. 2005; Fu et al. 2009; Kumar et al. 2009). In the present context, statistical threshold values of gas anomalies are fixed at average ($\bar{x}$) plus one standard deviation (σ). For defining the mean and standard deviation, the anomalously high and anomalously low value was neglected, which may cause unnecessary large variations and perturb the real anomalies.

3. RESULTS

Before using the semiautomatic track count using a Nikon digital camera coupled to a PC and employing software "SCION" it has been checked and tested by comparing the results with manual counting. To carry out this, radon-thoron discriminators along with LR films were installed in different sites having different temperatures in a hole of about 50 cm depths. After a defined period (bi-weekly to monthly) of exposure, films were retrieved, etched and tracks were counted manually as well as semiautomatically by using the technique mentioned above. Tracks recorded for thoron was very low, so we were unable to find thoron concentration in these sites using this method. Table 1 shows the radon concentrations obtained by manual counting and semiautomatic counting. It is evident from the table that radon concentrations obtained by manual counting and semiautomatic counting are comparable and acceptable.

The distribution of background seismicity and all of the selected earthquake events, which satisfy our criteria in the TVG area during the observation period have shown in Fig. 2, along with a different symbolic representation of focal depth range. Data recorded in integrated soil gas radon monitoring using SSNTDs along with atmospheric temperature, pressure, rainfall and earthquake events at BY monitoring station for 2014 - 2016 times period has been shown in Fig. 3. No correlation of radon with metrological parameters has been observed in this monitoring station. Table 2 shows the correlations of radon anomalies observed in this station with the earthquake events occurred during this time period in the study area. Total seven radon anomalies have been recorded during this time period. Except for two anomalous radon value out of seven anomalous radon value have not correlated with the earthquake event during this time period. The first anomalous value in radon has been recorded from 2014/2/17 to 2014/4/02, which was followed by earthquake event of magnitude 4.0 on 2014/2/12. Whereas, one event of magnitude 4.2 was recorded prior to this anomalous value on 2014/1/21. The second anomalous value in radon has been recorded from 2014/08/22 to 2014/10/15, which was followed by earthquake events of magnitude 4.8 on 2014/11/20. The third anomalous value in radon has been recorded from 2014/12/18 to 2015/1/15, which was followed by earthquake event of magnitude 4.7 on 2015/1/17. The fourth anomalous value recorded from 2015/02/12 to 2015/2/26 has not been followed by any events. The fifth anomalous value in radon has been recorded from 2015/02/26 to 2015/3/13, which was followed by earthquake event of magnitude 4.1 on 2015/4/9. The sixth anomalous value recorded from 2015/12/02 to

2015/12/21 has not been followed by any events. The seventh anomalous value in radon has been recorded from 2016/01/07 to 2016/1/21, which was followed by earthquake event of magnitude 4.0 on 2016/2/16. In this station, we have also used same soil gas source for radon monitoring using SSNTDs (passive detector) and RAD7 (active detector) for comparison. In the case of a passive method the interval is biweekly or more, but for active technique, the interval is shorter, i.e., 15 minutes. So for the comparison, 15 minutes data for active technique is reduced to biweekly or more. Figure 4 shows the comparison between the radon values observed in two different methods. It is evident from the figure that radon value trend observed by two different methods is almost same.

Figure 5 shows the data recorded in integrated soil gas radon monitoring using SSNTDs along with atmospheric temperature, pressure, rainfall and earthquake events at DYK monitoring station for 2014 - 2016 times period. No correlation of radon with metrological parameters has been observed from this monitoring station data. Table 3 shows the correlations of radon anomalies observed in this station with the earthquake events occurred during this time period in the study area. Total three radon anomalies have been recorded during this time period and have correlated with the earthquake event occurred in the study region. The first anomalous value in radon has been recorded from 2014/10/29 to 2014/11/12, which was followed by a seismic event of magnitude 4.8 on 2014/11/20. The second anomalous value in radon has been recorded from 2014/12/03 to 2015/1/15, which was followed by two seismic events of magnitude 4.0 and 4.7 on 2014/12/21 and 2015/1/17, respectively. The third anomalous value in radon has been recorded from 2015/12/21 to 2016/2/19, which was followed by a seismic event of magnitude 4 on 2016/2/16.

Recorded integrated soil gas radon data at GTP monitoring station using SSNTDs along with atmospheric temperature, pressure, rainfall and seismic events for 2014 - 2016 times period has been shown in Fig. 6. This station has also not shown any correlation of radon with metrological parameters during this time period. Table 4 shows the correlations of radon anomalies observed in this station with the earthquake events occurred during this time period in the study area. Total five radon anomalies have been recorded during this time period. Except for one anomalous radon value out of five anomalous radon value have not correlated with the earthquake event during this time period.

The first anomalous value in radon has been recorded from 2014/03/21 to 2014/4/2. One event of magnitude 3.3 is recorded prior to this anomalous value on 2014/3/10. The second anomalous value in radon has been recorded from 2014/07/11 to 2014/08/08. Before and after of this anomaly no events were recorded. The third anomalous value in radon has been recorded from 2014/09/18 to 2014/12/18, which was followed by two earthquake events of magnitude 4.8 and

Table 1. Radon concentrations calculated after weekly or biweekly exposure of SSNTDS films at TVG area by manual counting as well as semiautomatic counting.

Temperature (°C)		Exposure Time	Radon Concentration (kBq m^{-3})	
During Installation	During Retrieval		Manual counting	Semiautomatic counting
GTP				
56	60	14	40.2	36.0
57	60	20	8.8	7.0
55	59	22	2.9	3.2
SYK				
22.7	23	22	13.18	12.95
25	26	26	10.28	9.28
22	24	20	6.04	4.72
DYK				
63	65	25	2.54	2.13
60	63	23	1.58	0.97
46.8	39.1	14	1.21	0.69

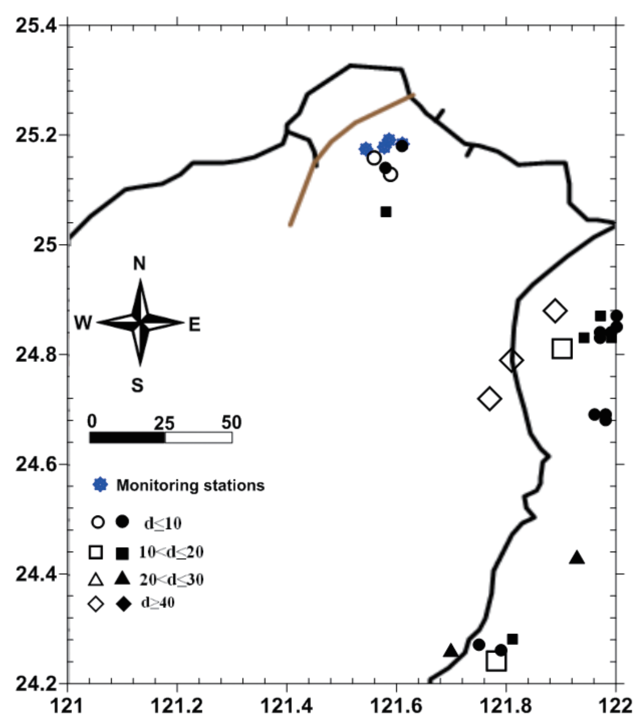


Fig. 2. Map showing the distribution of background seismicity and all of the selected earthquake events which satisfied our selection criteria recorded in TVG area during the study period. Seismic events are given by different symbolic representation of focal depth range.

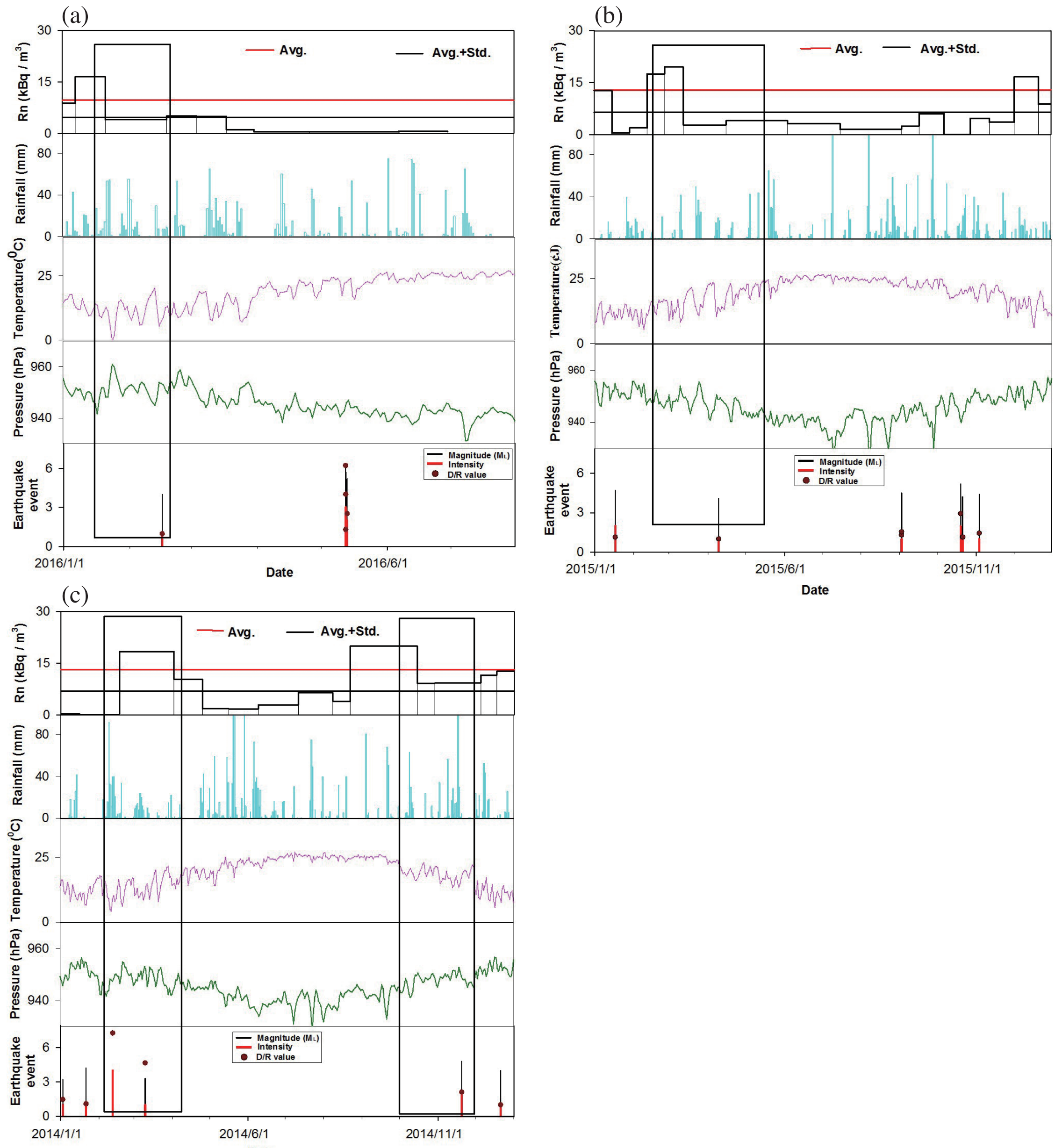
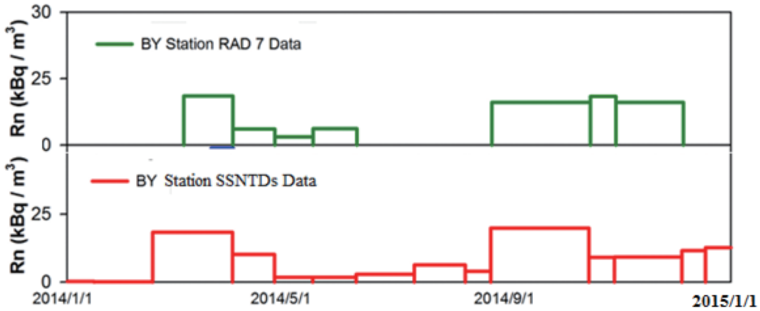


Fig. 3. Plots of recorded integrated soil gas radon using SSNTDs along with atmospheric temperature, pressure, rainfall, and earthquake events recorded by central weather bureau at BY from the period of 2014 - 2016. Black rectangle shows the earthquake events recorded after and before the anomalous radon values.

Table 2. Shows the time of radon anomalies observed, earthquake events recorded after and before the anomalous radon value and earthquake events parameter, i.e., magnitude, depth, intensity, surface distance, direct distance, and D/R in BY station with the earthquake events occurred in the study area.

Anomaly time	EQ time	M_L	Depth (km)	Intensity	Surface distance (km)	Direct distance (km)	D/R
2014/2/17 - 2014/4/02	2014/1/21 13:53:00	4.2	3.9	1	59	59	1.08
	2014/2/12 0:31:00	4	6.3	4	4	7	7.26
2014/08/22 - 2014/10/15	2014/11/20 1:46:00	4.8	9	2	54	55	2.11
2014/12/18 - 2015/1/15	2015/1/17 3:12:00	4.7	22.4	2	89	92	1.14
2015/02/12 - 2015/2/26							
2015/02/26 - 2015/3/13	2015/4/9 13:48:00	4.1	13.4	1	56	58	1.00
2015/12/02 - 2015/12/21							
2016/01/07 - 2016/1/21	2016/2/16 7:35:00	4	11	1	52	54	0.98

Fig. 4. Comparison plot between the radon value observed by RAD7 (active detector) and SSNTDs (passive detector) from the period of 2014/01/01 to 2015/01/01.



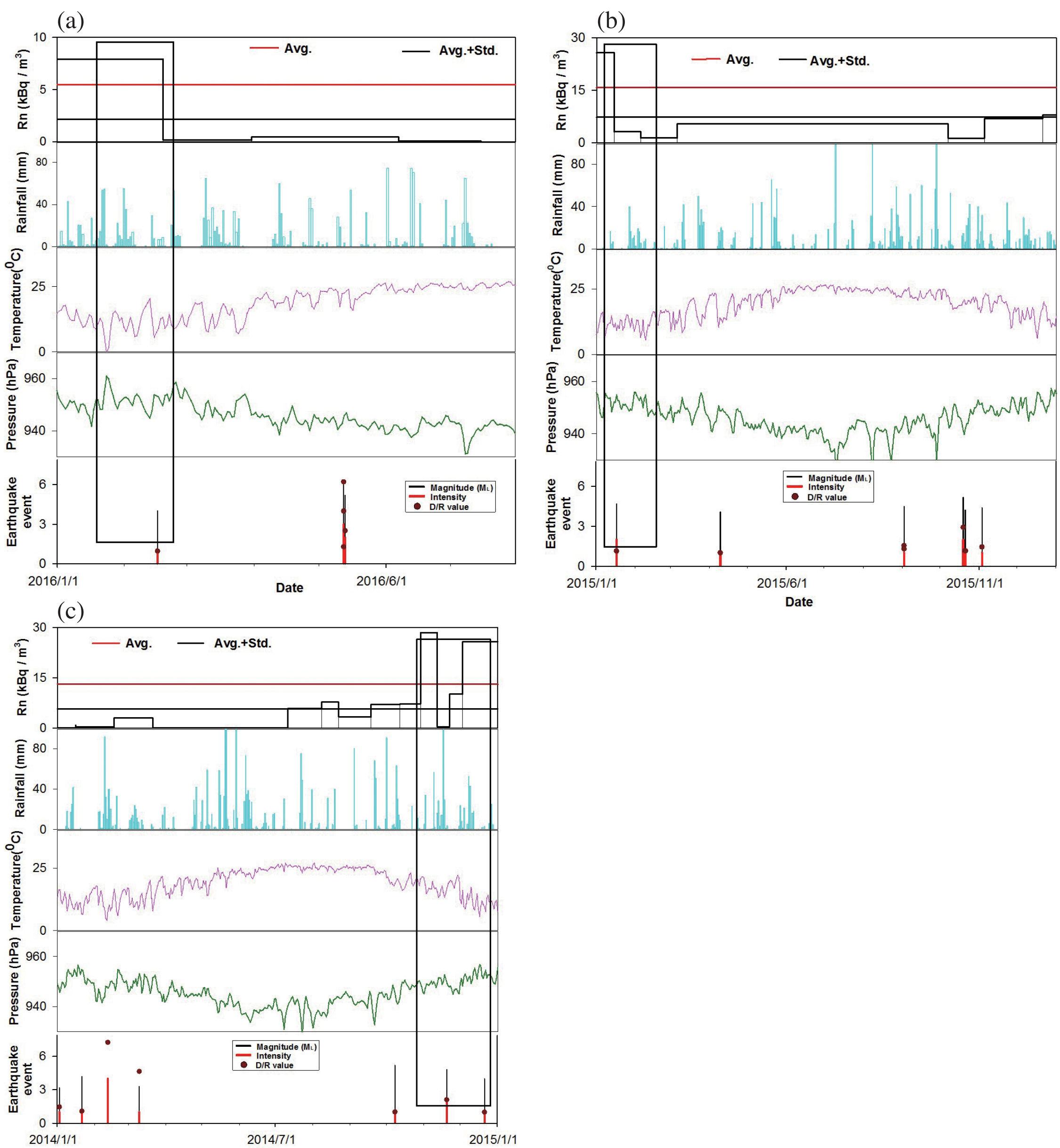


Fig. 5. Plots of recorded integrated soil gas radon using SSNTDs along with atmospheric temperature, pressure, rainfall, and earthquake events recorded by central weather bureau at DYK from the period of 2014 - 2016. Black rectangle shows the earthquake events recorded after and before the anomalous radon values.

Table 3. Shows the time of radon anomalies observed, earthquake events recorded after and before the anomalous radon value and earthquake events parameter, i.e., magnitude, depth, intensity, surface distance, direct distance, and D/R in DYK station with the earthquake events occurred in the study area.

Anomaly time	EQ time	M_L	Depth (km)	Intensity	Surface distance (km)	Direct distance (km)	D/R
2014/10/29 - 2014/11/12	2014/11/20 1:46:00	4.8	9	2	54	55	2.11
	2014/12/21 9:12:00	4	10.3	1	52	53	1.00
2014/12/03 - 2015/1/15	2015/1/17 3:12:00	4.7	22.4	2	89	92	1.14
2015/12/21 - 2016/2/19	2016/2/16 7:35:00	4	11	1	52	54	0.98

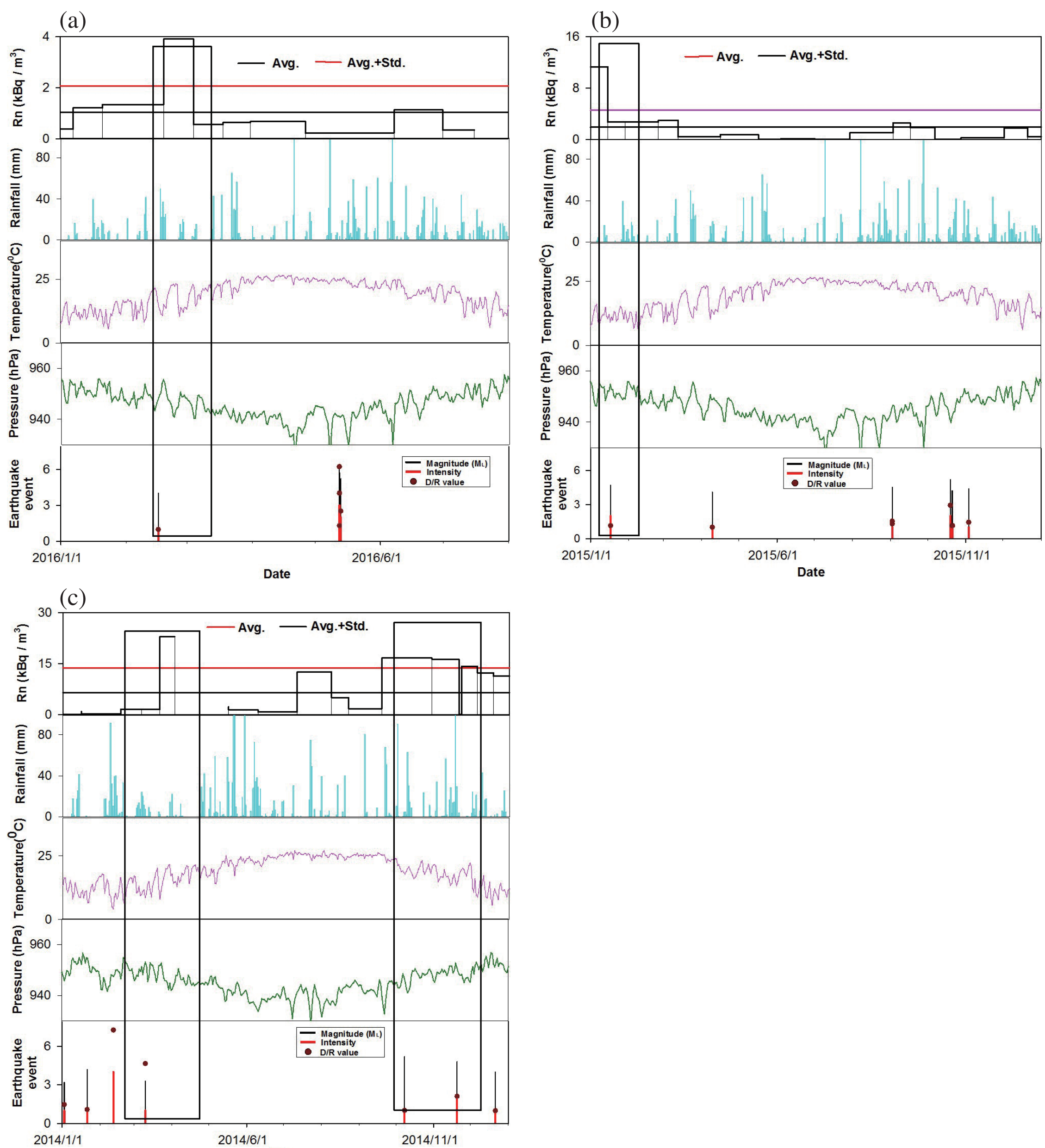


Fig. 6. Plots of recorded integrated soil gas radon using SSNTDs along with atmospheric temperature, pressure, rainfall, and earthquake events recorded by central weather bureau at GTP from the period of 2014 - 2016. Black rectangle shows the earthquake events recorded after and before the anomalous radon values.

Table 4. Shows the time of radon anomalies observed, earthquake events recorded after and before the anomalous radon value and earthquake events parameter, i.e., magnitude, depth, intensity, surface distance, direct distance, and D/R in GTP station with the earthquake events occurred in the study area.

Anomaly time	EQ time	M_L	Depth (km)	Intensity	Surface distance (km)	Direct distance (km)	D/R
2014/03/21 - 2014/4/2	2014/3/10 3:47:00	3.3	4.7	1	3	6	4.65
2014/07/11 - 2014/08/08							
2014/09/18 - 2014/12/18	2014/11/20 1:46:00	4.8	9	2	54	55	2.11
	2014/12/21 9:12:00	4	10.3	1	52	53	1.00
	2014/12/21 9:12:00	4	10.3	1	52	53	1.00
2014/12/18 - 2015/1/15	2015/1/17 3:12:00	4.7	22.4	2	89	92	1.14
2016/02/19 - 2016/3/4	2016/2/16 7:35:00	4	11	1	52	54	0.98

4.0 on 2014/11/20 and 2014/12/21, respectively. The fourth anomalous value recorded from 2014/12/18 to 2015/1/15, which was followed by earthquake event of magnitude 4.7 on 2015/1/17. The fifth anomalous value in radon has been recorded from 2016/02/19 to 2016/3/4, which was followed by earthquake event of magnitude 4.0 on 2016/2/16.

Integrated soil gas radon monitoring data recorded using SSNTDs along with atmospheric temperature, pressure, rainfall, and earthquake events at SYK monitoring station for 2014 - 2016 times period has been shown in Fig. 7. This station has also shown no correlation of radon with metrological parameters. Table 5 shows the correlations of radon anomalies observed in this station with the earthquake events occurred during this time period in the study area. Total three radon anomalies have been recorded during this time period and have correlated with the earthquake event occurred in the study region. The first anomalous value in radon has been recorded from 2014/11/22 to 2014/12/5, which was followed by earthquake event of magnitude 4.0 on 2014/12/21. Where as one event of magnitude 4 prior to this anomalous value has been recorded on 2014/12/21. The second anomalous value in radon has been recorded from 2015/03/13 to 2015/4/2, which was followed by two earthquake event of magnitude 4.1 on 2015/4/9. The third anomalous value in radon has been recorded from 2016/02/19 to 2016/3/4, which was followed by earthquake event of magnitude 4.0 on 2016/2/16.

4. DISCUSSIONS

Semiautomatic track count using a Nikon digital camera coupled to a PC and employing software "SCION" semiautomatic method for track counting is helpful to save time and get rid of counting the etched tracks under an optic microscope manually which is a tedious and time-consuming procedure.

The observations have shown potential precursory signals for some earthquakes that occurred during the observation period. Anomalous radon value has been observed for the events of magnitude 4 and 4.7, which were occurred on 2016/2/16 and 2015/1/17 respectively in all the monitoring stations. For the event of magnitude 4.8 which were recorded on 2014/11/20 have shown anomalous value in three stations, i.e., at BY, DYK, and GTP. In the present study, most of the seismic events related with radon anomalies are of magnitude ≥ 4. Only one earthquake of magnitude 3.3 with a shallow focal depth of 4.7 km and epicentral distance less than 5 km (see Tables 2 - 5) has been recorded. In TVG area, clustered micro-earthquakes with some typical volcanic characteristics have been reported (Lin et al. 2005a, b; Konstantinou et al. 2007). In total more than five thousand micro-earthquakes with a local magnitude < 3 have occurred in the area from 2003 - 2015. Most of these micro-earthquakes are classified as volcano-tectonic earthquakes, or often called A-type volcanic earthquakes, which have a double-couple source and thus both P- and S-waves can be identified (Lin et al. 2005a). Moreover, a few of the earthquakes detected at the TVG are recognized as typical volcanic earthquakes such as short-duration monochromatic events, long-duration spasmodic bursts and a phreatic eruption (Lin et al. 2005a, b; Konstantinou et al. 2007; Lin 2016).

In all the precursory studies, authors aimed to find anomalies prior to seismic events. However, in some cases, post-seismic anomalies have also been found by various studies (Hartmann and Levy 2005). So in our case, we did find some correlated anomalies to post-seismic events. Four monitoring sites in the present study are geographical close to each other but they have different characteristics in anomalous signals detecting. This may be due to the different reasons, e.g., temperature, radon flux, etc.

Most of the earthquakes correlated with anomalous radon value are within 60 km from the monitoring stations (Fig. 8). So from this study, we can also conclude that our monitoring stations in TVG area are sensitive to the events within the distance of 60 km. Continue longterm monitoring in these stations is required to test and verify this hypothesis in future.

Table 6 shows the yearly average value and standard

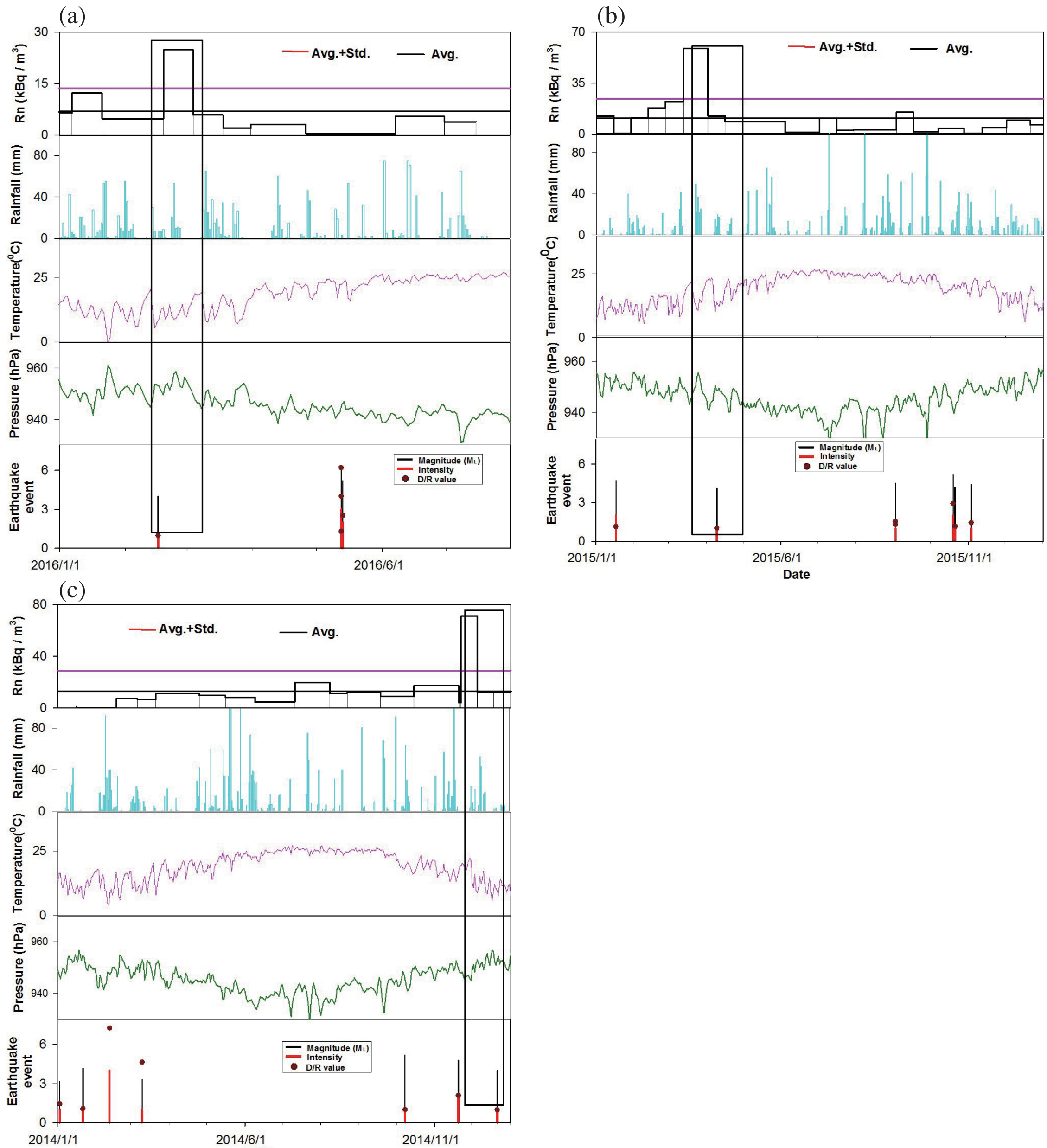


Fig. 7. Plots of recorded integrated soil gas radon using SSNTDs along with atmospheric temperature, pressure, rainfall, and earthquake events recorded by central weather bureau at SYK from the period of 2014 - 2016. Black rectangle shows the earthquake events recorded after and before the anomalous radon values.

Table 5. Shows the time of radon anomalies observed, earthquake events recorded after and before the anomalous radon value and earthquake events parameter, i.e., magnitude, depth, intensity, surface distance, direct distance, and D/R in SYK station with the earthquake events occurred in the study area.

Anomaly time	EQ time	M_L	Depth (km)	Intensity	Surface distance (km)	Direct distance (km)	D/R
2014/11/22 - 2014/12/5	2014/12/21 9:12:00	4	10.3	1	52	53	1.00
	2015/1/17 3:12:00	4.7	22.4	2	89	92	1.14
2015/03/13 - 2015/4/2	2015/4/9 13:48:00	4.1	13.4	1	56	58	1.00
2016/02/19 - 2016/3/4	2016/2/16 7:35:00	4	11	1	52	54	0.98

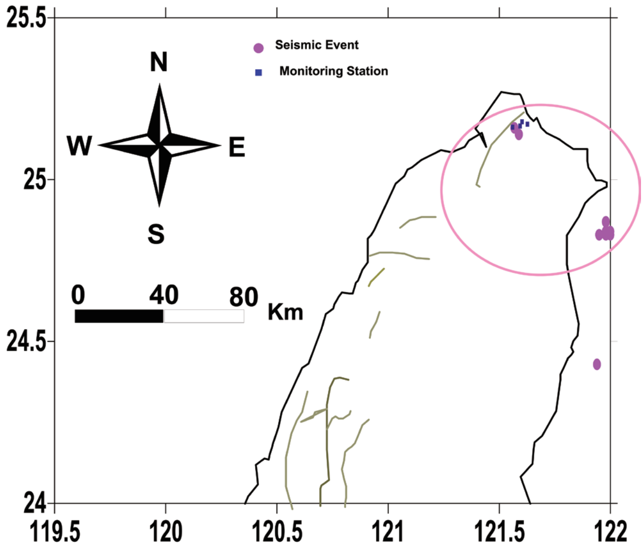


Fig. 8. Map showing the locations of monitoring stations and events correlated with the anomalous value of radon in TVG area, whereas, the circle represents the sensitive zone for the monitoring stations.

Table 6. Average radon and standard deviation value observed in TVG area monitoring stations, i.e., GTP, SYK, DYK, and BY from the period of 2014 - 2016.

Monitoring Station	2014	2015	2016
Average Radon (kBq m^{-3})			
GTP	6.48	1.89	1.05
SYK	12.88	10.92	6.85
DYK	5.73	7.34	2.15
BY	6.88	6.49	4.71
Standard Deviation			
GTP	7.3	2.7	1.0
SYK	16.0	13.2	6.7
DYK	7.4	8.5	3.3
BY	6.3	6.4	5.0

deviation recorded in each station in TVG areas from 2014 - 2016. Annual average radon value is decreasing in all the stations from 2014 - 2016. The maximum annual average value is recorded at SYK (12.88 kBq m^{-3}) in 2014 whereas minimum annual average value is recorded at GTP (1.05 kBq m^{-3}) in 2016. Various authors have noticed that radon value changes with time (i.e., seasonal variations, annual variation, etc.) due to many factors. Also, it can be seen from the recorded data that radon behaviour is different at different sites. This may be attributable to the difference in radon flux and temperature range (may be due to the presence of fumaroles and vents) in the respective sites (Kumar et al. 2013). In other words, radon emanation is effected by temperature. In general radon shows a positive correlation with temperature, i.e., the value of radon concentration increases as temperature increases and decreases with decrease in temperature. It is considered that in TVG area hydrothermal fluid may be supplied from the magma chamber to the deep hydrothermal reservoir at a depth of 2 km (Murase et al. 2014). However, some crustal deformation associated with this kind of fluid input event can not be detected by using the present radon study.

5. CONCLUSIONS

The efficiency of semiautomatic track count method (Nikon digital camera coupled to a PC and employing software "SCION") has been checked and tested in the present study. Also, the integrated soil gas radon data using SSNTDs (in boreholes of about 50 cm) at four different places in TVG has been generated for seismic and volcanic study. The recorded data have shown that radon behaviour is different at different sites. No correlation of radon with meteorological parameters has been observed in the monitoring stations of TVG area. The observed data have also shown potential precursory signals for some earthquakes that occurred during the observation period. Our monitoring stations in TVG area are sensitive to the events within a distance of 60 km. Continuous long-term monitoring in these stations is required to test and verify this hypothesis in future.

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