CrossMark

Influence of meteorological parameters on the soil radon (Rn^{222}) emanation in Kutch, Gujarat, India

Sushanta Ku Sahoo · Madhusudhanarao Katlamudi ·
Jerin P. Shaji · K. S. Murali Krishna ·
G. Udaya Lakshmi

Abstract The soil radon (Rn^{222}) and thoron (Rn^{220}) concentrations recorded at Badargadh and Desalpar observatories in the Kutch region of Gujarat, India, have been analyzed to study the sources of the radon emissions, earthquake precursors, and the influence of meteorological parameters on radon emission. Radon and meteorological parameters were recorded using Radon Monitor RMT 1688-2 at these two stations. We used the radon data during February 21, 2011 to June 8, 2011, for Badargadh and March 2, 2011 to May 19, 2011, for the Desalpar station with a sampling interval of 10 min. It is observed that the radon concentrations at Desalpar varies between 781 and 4320 Bq m^{-3} with an average value of 2499 Bq m^{-3}, whereas thoron varies between 191 and 2017 Bq m^{-3} with an average value of 1433.69 Bq m^{-3}. The radon concentration at Badargadh varies between 264 and 2221 Bq m^{-3} with an average value of 1135.4 Bq m^{-3}, whereas thoron varies between 97 and 556 Bq m^{-3}. To understand how the meteorological parameters influence radon emanation, the radon and other meteorological parameters were correlated with linear regression analysis. Here, it was observed that radon and temperature are negatively correlated whereas radon and other two parameters, i.e., humidity and pressure are positively correlated. The cross correlogram also ascertains similar relationships between radon and other parameters. Further, the ratio between radon and thoron has been analyzed to determine the deep or shallow source of the radon emanation in the study area. These results revealed that the ratio radon/thoron enhanced during this period which indicates the deeper source contribution is prominent. Incidentally, all the local earthquakes occurred with a focal depth of 18–25 km at the lower crust in this region. We observed the rise in the concentrations of radon and the ratio radon/thoron at Badargadh station before the occurrence of the local earthquakes on 29th March 2011 (M 3.7) and 17th May 2011 (M 4.2). We clearly observed the radon level crossing the mean + 2*sigma level before the occurrence of these events. We conclude that these enhanced radon emissions are linked with alteration of the crustal stress/strain in this region as this observing station is near the epicenters of the earthquakes. We did not observe considerable variations in radon at the Desalpar station which is far from the earthquake location.

Keywords Soil radon · Thoron · Linear regression · Correlation and earthquakes

S. K. Sahoo · M. Katlamudi (✉)
Institute of Seismological Research, Gandhinagar, Gujarat, India
e-mail: madhuspl@yahoo.com

J. P. Shaji · K. S. Murali Krishna
Manonmaniam Sundaranar University, Tirunelveli, Tamil Nadu, India

G. Udaya Lakshmi
Osmania University, Hyderabad, Telangana, India

Introduction

Radon a natural radioactive inert gas, which is produced by the radioactive elements present in the rocks and soil in the Earth's crust containing radioactive elements akin

to uranium and thorium. It has comparatively high half-life period which envisages the transport of radon to larger distances in the subsurface of the Earth through different processes such as the molecular diffusion, convection, or advection (Nazaroff and Nero 1988). Diffusion is the process by which radon moves through the soil pores (gases/liquids) in response to a concentration gradient, whereas, in convective transport, the movement of pore fluids through the soil pores occurs due to influence of external force (Schumann and Owen 1988). In seismotectonic environs, among different geochemical parameters, the radon is generally chosen for the study of short-term earthquake precursors because of its long half-life period. Variation of radon concentration in soil is mainly attributed to various processes within the Earth such as the tectonic disturbance, fluid flow, changes in pore pressure, deformation, micro crack development, and generation of charged particles (Chaudhuri et al. 2013).The Tashkent (Russia) earthquake in 1966 is the first example where the radon level enhanced just before the earthquake (Ulomov and Mahashev 1968). Maldonado et al. 1996 observed the anomalous variation of radon concentration as a precursor to earthquakes along pacific coast of Mexico. Walia et al. 2005 studied the variation of radon concentration in both soil and groundwater along the main boundary thrust at N-W Himalayas and revealed that a 62% correlation was found between the precursory nature of radon and the occurrence of micro earthquakes. Das et al. 2005 found the anomalous fluctuation of radon at the Bakreswar thermal spring prior to the high-magnitude earthquakes in the Sumatra Island, Indonesia. Yang et al. 2005 found the variation of soil radon and thoron along the fault lines at SW Taiwan which they projected as a useful tool for the earthquake surveillance. Kumar et al. 2009 also found the radon anomaly before earthquakes at the Kangra valley of Northwest Himalayas. Chaudhuri et al. 2010 observed a long range correlation between the fluctuation of the geochemical gases (He, radon) and the occurrence of the seismic activities at a large distance (> 1000 km) and proposed some empirical relation between the epicentral distance, the precursor time, and the magnitude of the earthquake. Baykut et al. 2010 reported the anomalous soil radon emanation before earthquakes in the seismically active region of Marmra, Turkey. Laskar et al. 2011 found the signatures of the radon anomaly before the earthquakes along the prominent lineaments near Guwahati, Assam, India. Sac et al. 2011 monitored the

radon variation along the fault line in western turkey and revealed that the increase of radon emanation is well correlated with the seismic activities. Imme and Morelli 2012 reviewed studies related to radon emissions associated with earthquakes and concluded that in some cases, radon levels increased before the occurrence of earthquakes. Jaishi et al. 2014a studied the variation of the soil radon and thoron along the Mat Fault, Mizoram, India, and concluded that there is a positive correlation between the variation of the geochemical gases (radon and thoron) and the occurrence of the earthquakes. Deb et al. 2016 observed anomalous fluctuations in the radon datasets prior to recent earthquakes including the Nepal earthquake (7.8 M) on 25th April 2015. Neri et al. 2016 studied the variation of soil radon concentration during the tectonic and volcanic activities in the Mt. Etna volcano for a period between 2009 and 2011. They found that the source of the radon is a shallow depth and the soil radon concentration reached the peak just before a seismic swarm.

Several models and empirical algorithms have been developed globally to establish a relation between the emanation of radon and the occurrence of earthquakes. In each model, there are different parameters chosen where sometimes they fit into the observed datasets and in the next moment it has resulted a complete failure (Scholz et al. 1973; Fleischer 1981). Similarly, several investigators have deduced an empirical relation between the earthquake parameters such as magnitude, precursory time, epicentral distance, and time series characteristics of radon such as range, duration, and number of radon anomalies (Walia et al. 2003, 2005; Rikitake 1976; Friedmann 1991). There is a drawback in the empirical relationship where we assume that the emanation of radon concentration is only controlled by the seismic activity; however, it is also influenced by the meteorological parameters like soil moisture, rain fall, temperature, pressure, and relative humidity (Chaudhuri et al. 2010; Walia et al. 2005; Weinlinch et al. 2006). Several studies reported the influence of meteorological parameters on soil-gas radon emission (Singh et al. 1988; Sundal et al. 2008; Chambers et al. 2015). Singh et al. 1988 studied the influence of meteorological parameters on soil radon emission at a non-mineralized site for a period of 1 year. In this study, they attempted to compute the correlation between soil radon and the meteorological parameters for different time-scale durations like 1, 7, 15, and 30 days. From these correlations, they observed that the soil radon shows weak inverse correlation with

barometric pressure, rainfall, and humidity, whereas it shows positive correlation with the temperature and wind velocity. They also observed the diurnal variation in the soil radon emission, pressure, and temperature. Another study by Walia et al. 2005 along the main boundary thrust (MBT) in NW Himalaya revealed that the radon exhalation is positively correlated with the temperature, relative humidity, and rainfall, whereas it is negatively correlated with the wind velocity for both the soil-gas and groundwater radon. Jaishi et al. 2014a have tried to differentiate the radon anomalies belonging to seismic activities and the anomalies belonging to meteorological parameters. They tried to explain the processes involved in this like, firstly, when the rainwater interacts with radon, some of the radon flows along the rainwater and subsequently radon decreases; secondly, if the air temperature is lower as compared to soil temperature, the radon flow increases due to the convection process; thirdly, the radon flow decreases when the air temperature is higher than the soil temperature.

All these studies highlight the influence of meteorological parameters on radon emanation and its correlation with earthquakes. The present study is also an attempt to study the influence of meteorological parameters on radon emanation and its correlation with earthquakes in the Kutch region, Gujarat, India.

Seismotectonics of Kutch region

The Kutch region is the second active seismic region after the Himalayan belt in the Indian sub-continent and this region falls in zone V of the seismic zonation of India (BIS 2002). Two damaging earthquakes occurred in 1819 (Mw 7.8) and 2001 (Mw 7.7) in Kutch. Another event of magnitude 6.3 also occurred on July 21, 1956, at north of Anjar. All the four directions surrounded by Kutch are (i) Nagar Parkar Uplift in North, (ii) Radhanpur-Barmer arch in East; (iii) North-Kathiawar Fault (NKF) in South; and (iv) eastern Arabian Sea in West. The Kutch region is tectonically active since the Mesozoic times. This activity has resulted to the alteration of the geomorphic settings like the creation of faults and changes in drainage patterns. In terms of geology, the Kutch region is basically characterized by sediments of quaternary/tertiary age, Jurassic sandstones and Deccan volcanic rocks which rest on the Archean basement (Gupta et al. 2001). Most of the area in this region comprise thick layer of Mesozoic-

Cenozoic sediments (1–4 km), the rigid basement thick layer and several igneous bodies which are unevenly distributed all over the area.

The Kutch region comprises of major faults, such as (a) Nagar Parkar Fault, (b) Allahbund Fault, (c) Kutch Mainland Fault, (d) Katrol Hill Fault, (e) Vigodi Fault, (f) Gedi Fault (GF), (g) North Wagad Fault (NWF), and (h) South Wagad Fault (SWF). All the faults are subvertical dipping 90°–75° towards the adjacent half graben or graben (Biswas 1987). Here, the tectonic trend is oriented in E-W direction, the rifting also resulted along the E-W trend which subsequently formed as the Kutch Rift Basin (KRB).The Kutch rifting took place in the late Triassic-Early Jurassic (Biswas 1987). This rift basin is now under the influence of compressional stress regime resulted due to the collision of the Indian and Eurasian plates. We can see various uplifts (KMU and WU) and low-lying residual depressions in the Kutch region. Uplifts are found mainly along the major subparallel E-W striking longitudinal faults.

Materials and method

The monitoring of soil radon and thoron have been carried out at Badargadh (23°.47 N, 70°.62 E) and Desalpar (23°.74 N, 70°.69E) in the Kutch region of Gujarat, India, as shown in Fig. 1. The monitoring sites are situated along the most active seismic faults. The Desalpar observatory is situated along the Gedi Fault, whereas the Badargadh observatory is above the South Wagad Fault. Both the faults are E-W trending. Radon measurements in the soil were carried out by RTM 1688-2 which is manufactured by SARAD, Germany. This instrument is also capable of measuring thoron, temperature (− 20 to 40 °C), pressure (800–1200 mbar), and humidity (0–100%), where all the sensors are placed inside the probe itself. Due to radon decay inside the measuring chamber, the short-living daughter products will be generated and through these short-living daughter products, the radon (Rn-222) will be measured. The measured data are logged in a data logger kept in an adjacent laboratory. There is a software named Radon vision provided by the manufacturing company which has been used to visualize the raw data. The instrument records the radon data at every 10-min interval.

Figure 2 depicts the whole diagram of the instrument, installation, and data acquisition. The radon monitor is
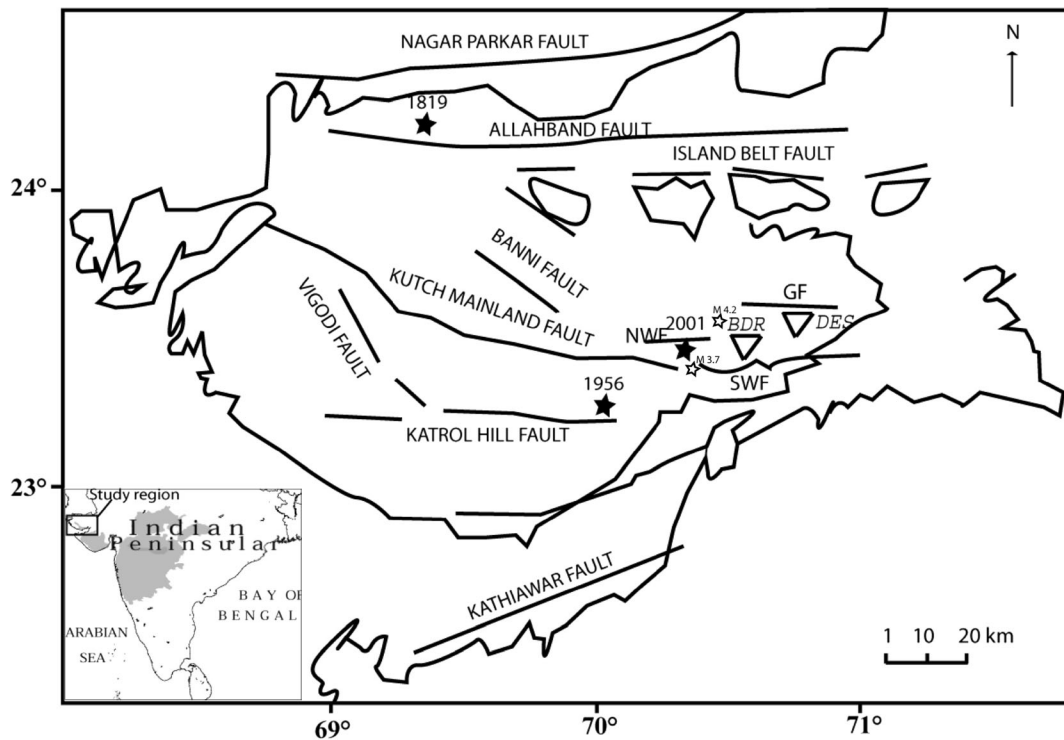
Fig. 1 Seismotectonic map of Kutch along with locations of magnetic stations

installed at a sub-surface depth of 1 m surrounded by a PVC pipe. The upper end of the PVC pipe is completely sealed to reduce the rainwater penetration onto the probe. The gravels down the pipe protect the probe from ground water.

Descriptive statistics like minimum, maximum, average, and standard deviation (SD) are determined to understand the background values of radon, thoron, temperature, relative humidity, and pressure in the study area. To understand how meteorological parameters are influencing radon emanation, the radon and other meteorological parameters were correlated with linear regression analysis and cross correlograms. We adopted the mean plus 2 standard deviation of the radon level to define the radon anomaly (Guerra and Lombardi 2001).
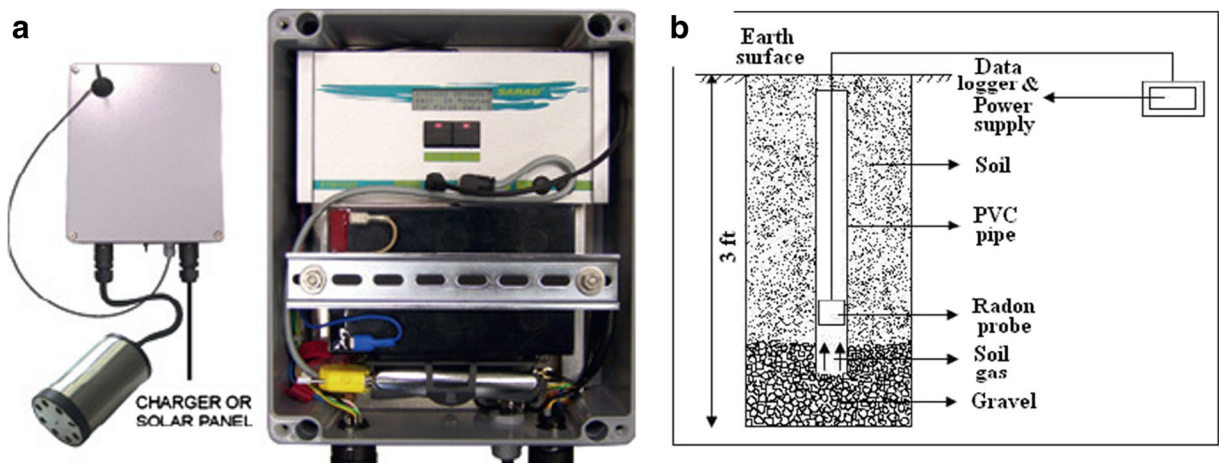
Fig. 2 The diagram of **a** radon detector and data acquisition system and **b** installation setup

Results and discussion

Kutch is an active region in terms of seismic activity. There are several active faults in this region. The entire crust in this region is critically stressed and brittle as evidenced by focal depths of earthquakes from near surface to 36 km. Most of the epicenters of earthquakes are closely associated with well-known faults. The detailed description of the seismotectonics of the region is given in the previous section. In order to pursue the science of medium- and short-term precursors for earthquakes, the Institute of Seismological Research established three multiparametric geophysical observatories near active faults in the Kutch region, Gujarat. Soil-gas radon is also one of the parameters being monitored continuously in these observatories. In this study, the radon data of Badargadh and Desalpar stations have been analyzed to find the correlation between radon emission and meteorological parameters (pressure, temperature, and humidity) and to correlate with local earthquakes. The weather in Kutch is mostly arid and dry climate with occasional rains during monsoons which mostly cover during August–October. The summers mostly cover during March–June and are extremely hot and dry with maximum temperatures reach up to 49 °C in the daytime and the temperature is around 30 °C during night hours. The soil radon and other parameters used in this study are confined to the summer period of the year at both the stations.

In order to apply statistical and numerical tools on radon time series to understand the influence of meteorological parameters, the time series should be continuous and regular without any gaps and spikes. We carefully examined the radon data of Badargadh and Desalpar and selected the data for this study. Meteorological parameters were also recorded simultaneously at these respective locations. The time series of radon, atmospheric pressure, temperature, and humidity used in this study are shown in Fig. 3 for the Badargadh station during the period of Feb 21, 2011, to June 8, 2011, and Fig. 4 for the Desalpar station during the period of Mar 2, 2011, to May 19, 2011. There was no rainfall during this period. The descriptive statistics of radon data of the Badargadh station are shown in the Table 1. The radon varies with a minimum value of 264 Bq m^{-3} to maximum value of 2221 Bq m^{-3}, the average of radon is obtained as 1135.41 Bq m^{-3}. The standard deviation (SD) is 247.794 Bq m^{-3} and it shows a variance of 0.2182. The thoron varies with a minimum

value of 97 Bq m^{-3} to maximum value 556 Bq m^{-3}, the average of thoron is obtained as 189.4 Bq m^{-3}. The standard deviation (SD) is 36.04 Bq m^{-3}. Whereas, the temperature shows an average value 34.05 °C, with a minimum of 23°C and maximum of 42.5 °C. The SD for the temperature is 3.69 °C and the variance is 0.11.

Humidity shows a variation from 36% as the minimum to 93% as the maximum, the average is calculated as 75.82%. The SD for the humidity shows 9.22 and the variance is 0.1277. The pressure has a minimum value of 974 mb and the maximum value of 996 mb; the average of the data is 984.93 mb and the SD and percentage of variance calculated as 4.48 and 0.0045, respectively.

Similarly, the descriptive statistics of the Desalpar station are shown in the Table 2. The radon varies with a minimum value of 781 Bq m^{-3} to maximum value 4320 Bq m^{-3}, the average of radon data is obtained as 2450.09 Bq m^{-3}. The thoron varies with a minimum value of 191 Bq m^{-3} to maximum value 2017 Bq m^{-3}, the average of thoron is obtained as 433.69 Bq m^{-3}. The standard deviation (SD) is 203.78 Bq m^{-3}. Whereas, temperature shows an average value 30.54 °C, with a minimum of 25.5 °C and a maximum 40 °C. The SD for the temperature is 2.5 °C and the variance is 0.081. Humidity shows a variation from 87% as the minimum to 98% as the maximum, the average is calculated as 93.87%. The SD for the humidity shows 2.51 and the variance is 0.02. The pressure has a minimum value of 996 mb and a maximum value of 1015 mb, the average of the data is 1005 mb and the SD and percentage of variance calculated as 2.94 and 0.003, respectively.

From the above tables, it can be observed that the average value of soil radon at Desalpar is slightly higher than that of Badargarh due to its geological and tectonic settings that favor the transport of radon. In the next step, we checked whether the radon data shows normal distribution or not. In general, the soil data is following the fundamental laws of geochemistry which are usually normally distributed (Ahrens 1954). In order to check this, we performed the probability plot (Q-Q plot) and probability distribution of samples of radon time series at both the stations which are shown as Fig. 5 for Desalpar and Fig. 6 for Badargadh. From the quantile and probability distribution plots at both the observatories, it can be observed that the soil radon is normally distributed.
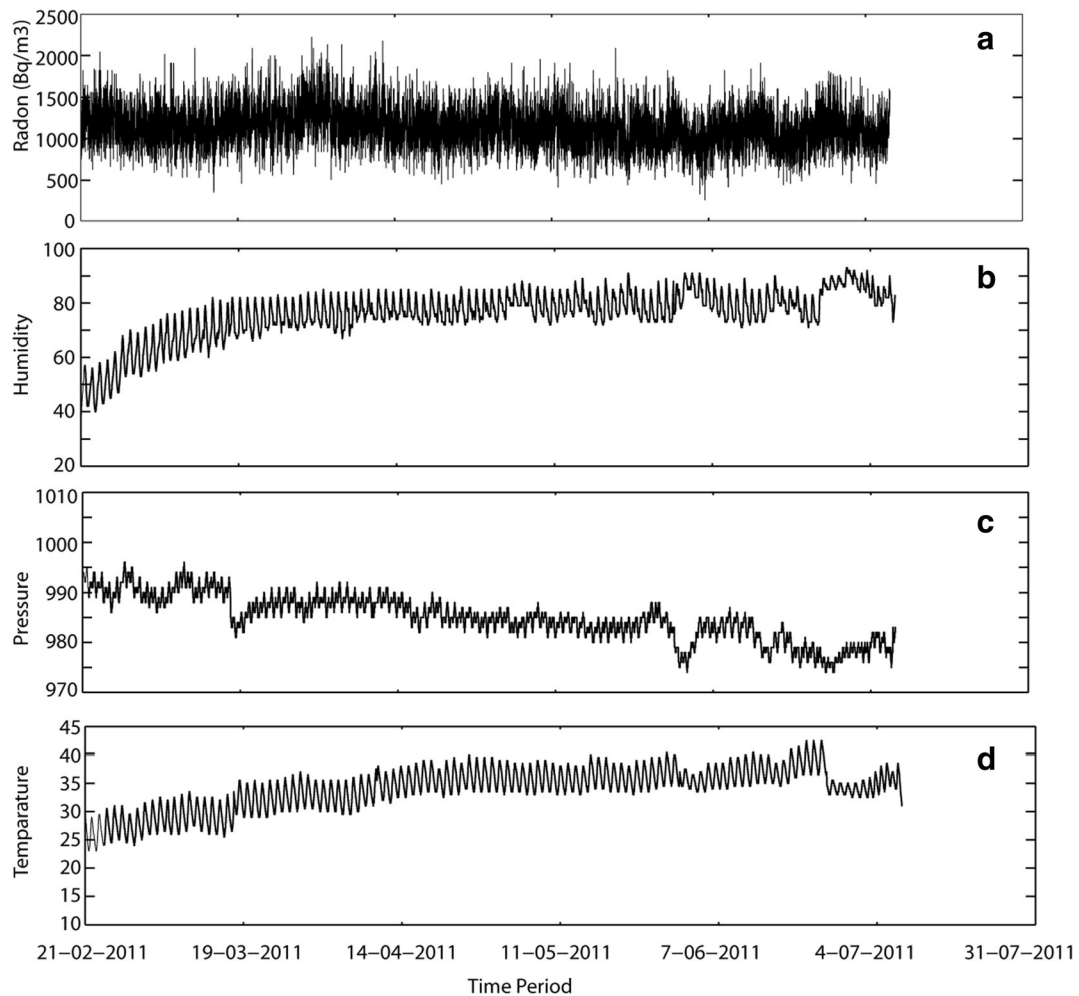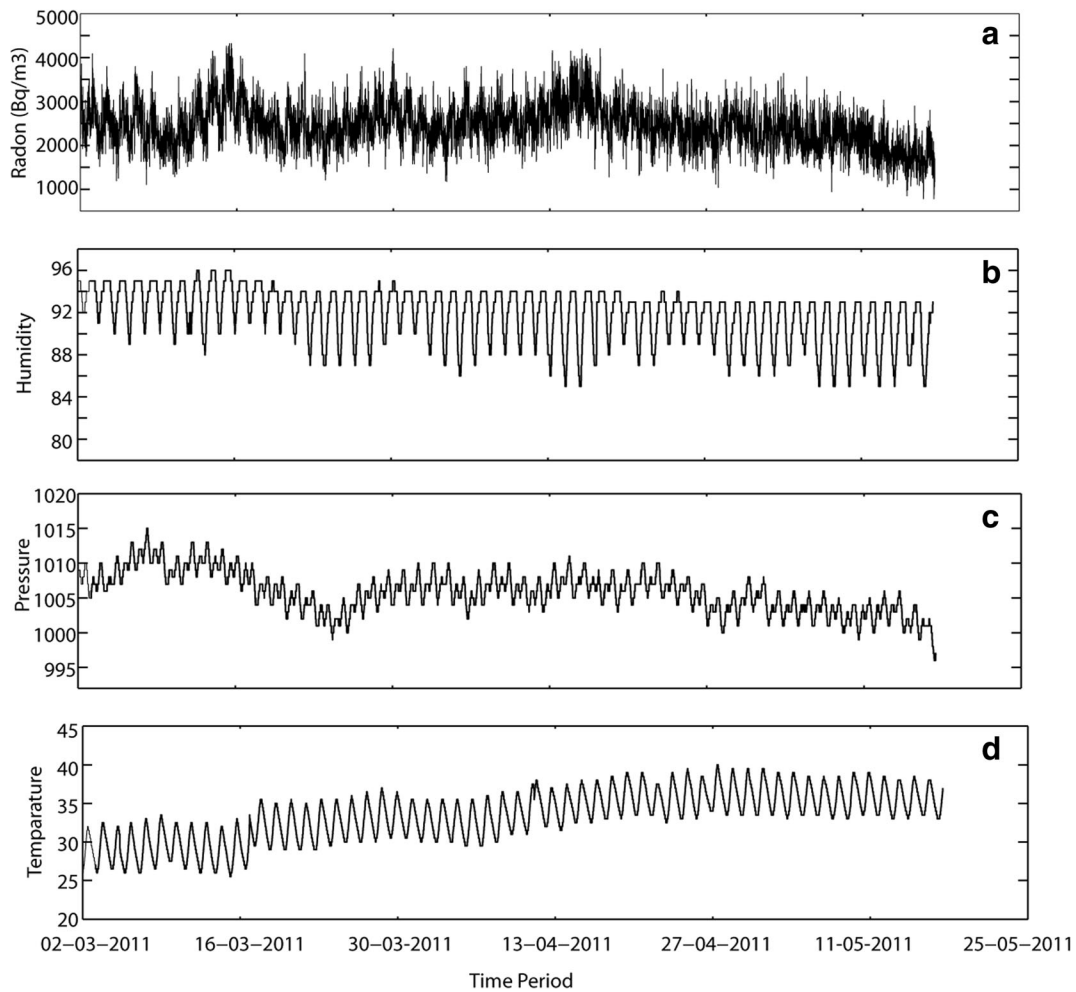
Fig. 3 **a** Radon concentration variation, **b** humidity, **c** pressure, and **d** temperature at the Badargadh station

Correlation with the meteorological parameters

The radioactive elements such as uranium and thorium in rocks and soils inside the Earth decay and are primarily responsible for radon concentration in any area. However, the radon concentration also fluctuates under the influence of meteorological factors (Schumann and Owen 1988). The increase or decrease of radon concentration due to the influence of meteorological parameters may cause misinterpretation of radon data. Correlation of radon concentration with meteorological parameters such as temperature, relative humidity, and pressure provides how the radon emanation is influenced by these parameters and avoid misinterpretation of radon data. First, we randomly selected a week duration and plotted the radon time series as shown in Fig. 7 to see the fluctuations in the measurements of radon concentration.

The trend of radon concentration is showing the peak during early hours in the morning from 00 to 06 h and during midnight hours. As the sunlight increases, the radon concentration decreases and shows a lower peak during 12–16 h. Whenever the soil temperature increases, the release of radionuclides increases from the soil by drying it; the radon concentration slowly increases after solar peak hours (Crawford et al. 2015). Moreover, the convective motion of the atmosphere also influence the radon emanation as the atmosphere is relatively calm with little convective motion during night hours which gradually increases the radon concentration (Chambers et al. 2014). To further look at the variations in any single day, we plotted the time series of radon, temperature, relative humidity and pressure recorded on Feb 22, 2011 (Fig. 8).

Fig. 4 **a** Radon concentration variation, **b** humidity, **c** pressure, and **d** temperature at Desalpar station

It is very clear that during the night hours and early morning hours, the temperature is low and relative humidity is high. The radon concentration is also found to be higher during this time and we did not find much variations in pressure data. In order to quantify the correlations between these parameters for whole time series, the correlation coefficients have been computed for both the observatories and listed in Table 3.

Although, we get different correlation coefficient values from each of these stations for different set of parameters but we found similar relationships at both these stations. In the case of the Badargadh station, the

Table 1 Descriptive statistics of radon and the meteorological parameters in the Badargadh station

Parameters	Max	Min	Average	Standard deviation (σ)	Correlation coefficient	Variance
Radon (Bq/m3)	2221	264	1135.40	247.79	–	0.218
Thoron(Bq m^{-3})	556	97	189.4	36.02		
Temperature (°C)	42.5	23	34.05	3.69	-0.2136	0.108
Humidity (%)	93	36	75.82	9.22	0.1277	0.121
Pressure (mb)	996	974	984.93	4.48	0.1723	0.004

**Table 2** Descriptive statistics of radon and the meteorological parameters in the Desalpar station

Parameters	Max	Min	Average	Standard Deviation (σ)	Correlation coefficient	Variance
Radon (Bq m^{-3})	4320	781	2450.09	522.37	–	0.213
Thoron(Bq m^{-3})	2017	191	433.69	203.78		
Temperature (°C)	40	25.5	30.54	2.50	− 0.1594	0.081
Humidity (%)	98	87	93.87	2.51	0.2525	0.026
Pressure (mb)	1015	996	1005.85	2.94	0.2424	0.0029

correlation coefficient between radon and humidity was found to be 0.1277, while between radon and temperature, it is found to be − 0.2136 (Fig. 9). The temperature shows a negative correlation with radon data, so whenever the temperature increases the radon emission decreases. A similar relationship has been reported by many researchers (Kovach 1945; Klusman and Jaacks 1987; Jaishi et al. 2014b). Klusman and Jaacks (1987) reported a negative correlation of radon with soil temperature. They attributed that if the air temperature is lower than soil temperature, radon's upward movement will be increased due to the convection process. But, in the case of lower soil temperature as compared to air temperature, radon's upward movement will be decreased. Jaishi et al., 2014b also reported the negative correlation between radon and temperature along Mat Fault in the Serchhip district, Mizoram (India). In our study, the correlation coefficients between radon and pressure are found to be a positive value of 0.1723. This

indicates the radon emission increases with the increase in pressure. The process of convection will increase fluid movement through the soil pores which will subsequently enable more possibility for the transport mechanism of soil radon (Schumann and Owen 1988). Similarly, we found a positive correlation between radon and humidity with a correlation coefficient value of 0.1277. Jaishi et al. 2014b observed that the measured radon data shows a moderate positive correlation with relative humidity along Mat Fault in the Serchhip district, Mizoram (India). Sanjay Singh et al. 2016 have also inferred a moderate positive correlation between radon and relative humidity in Aizawl, Mizoram, in North Eastern part of India near the Indo-Burma subduction zone. This positive correlation between radon levels and humidity has been explained with the increase of radon levels with increase in soil moisture (Damkjaer and Korsbech 1985). We may attribute that the soil moisture may play a role in the increase of
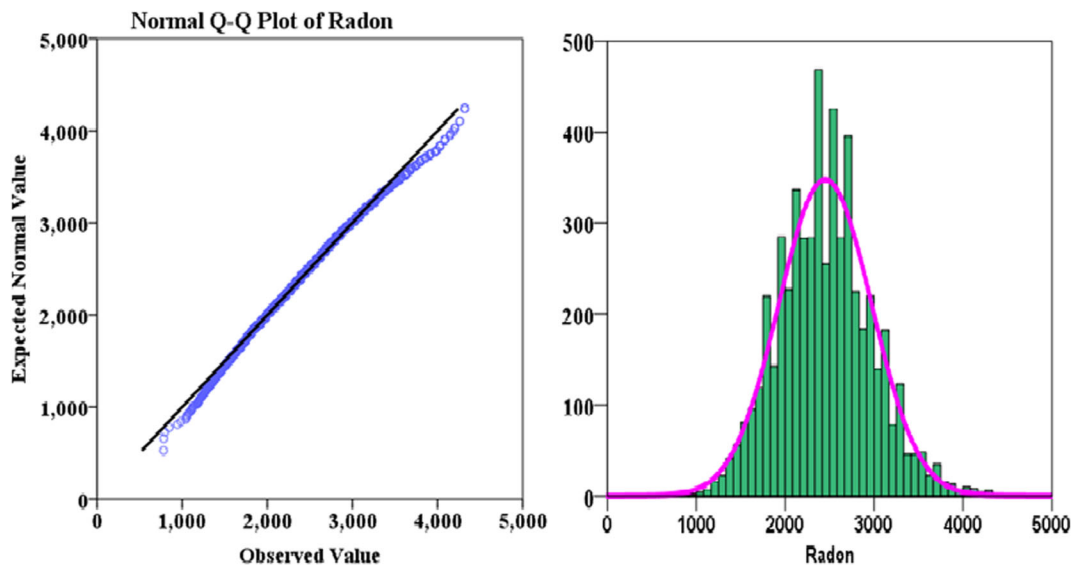
Fig. 5 Quantile plot (left) and histogram with probability distribution (right) of radon at Desalpar
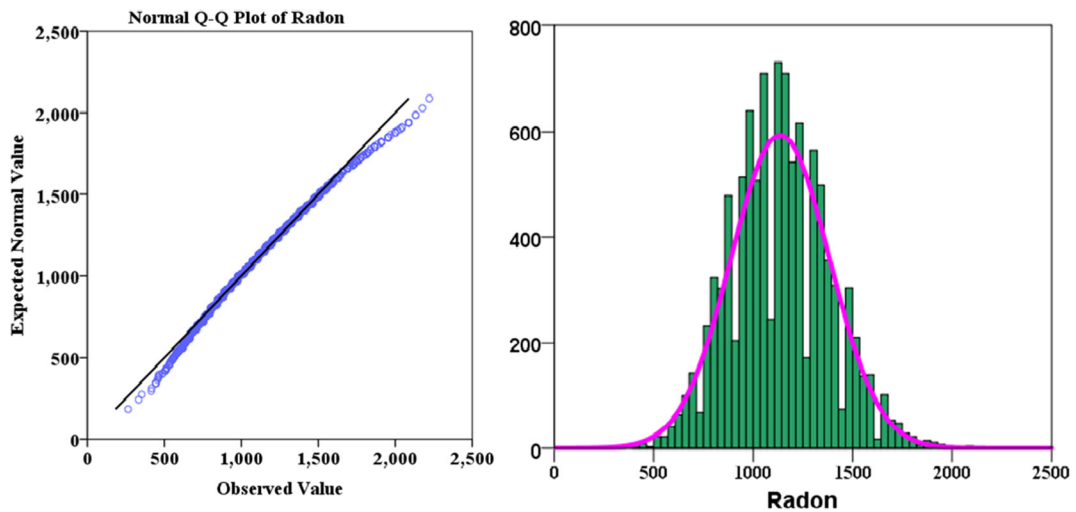
Fig. 6 Quantile plot (left) and histogram with probability distribution (right) of radon at Badargadh

humidity which might be a causative factor for the increase in radon produced in rocks to migrate into pore fluids which subsequently increase in radon content in soil (Tanner 1964; Fleischer 1983).

In the case of Desalpar, the correlation coefficient between radon and humidity was found to be 0.2525 whereas the correlation between radon and temperature gives a negative coefficient of − 0.1594, and radon and pressure also show a positive correlation coefficient of 0.2431 (Fig. 10). From the above correlation, we found that the temperature has a negative influence on radon emission, while the positive correlation of radon with humidity and pressure has an effect on radon emission. So, we found proportionality existing between humidity and pressure with radon emission. The positive correlation between the radon and the soil pressure again confirmed the convective transport of radon through the soil pores similar to the Badargadh site. The low moisture content of the soil has enhanced the radon emission without any trapping.

In order to further ascertain the above relationships among radon and other meteorological parameters, we also performed the cross correlation between these parameters and the cross correllograms are shown in Fig. 11 (Badargadh) and Fig. 12 (Desalpar). For the nonstationary time series like the soil radon which has periodic oscillations due to influence of meteorological parameters, the cross correlogram plays a significant role in determining the relationships among these parameters. For periodic signals, the pattern of one time series is followed by another time series with an interval of certain time duration (Lag) and this situation can be analyzed by performing Lag correlation.

Figure 11 depicts the cross correlation between radon and other meteorological parameters (pressure, temperature, and humidity) at Badargarh. For this station, it is clearly evident of showing the similar relationships among these parameters similar to as obtained by linear regression. The radon is showing negative correlation with temperature and the radon is showing the positive
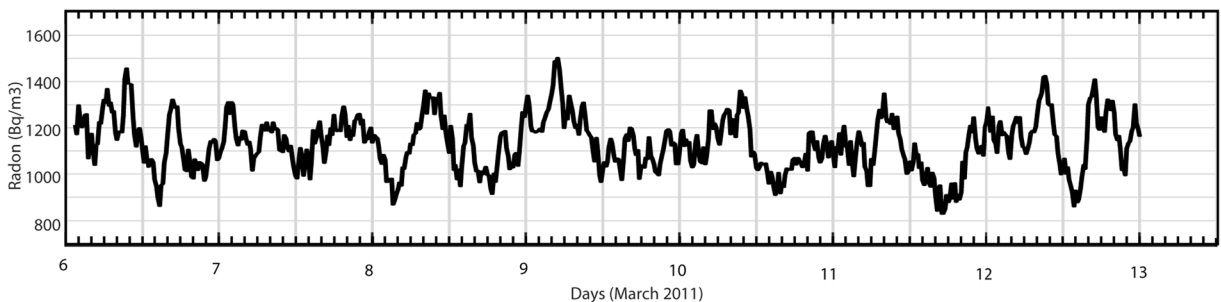
Fig. 7 Diurnal variations of radon concentrations from 6th to 13th March 2011 at Badargadh
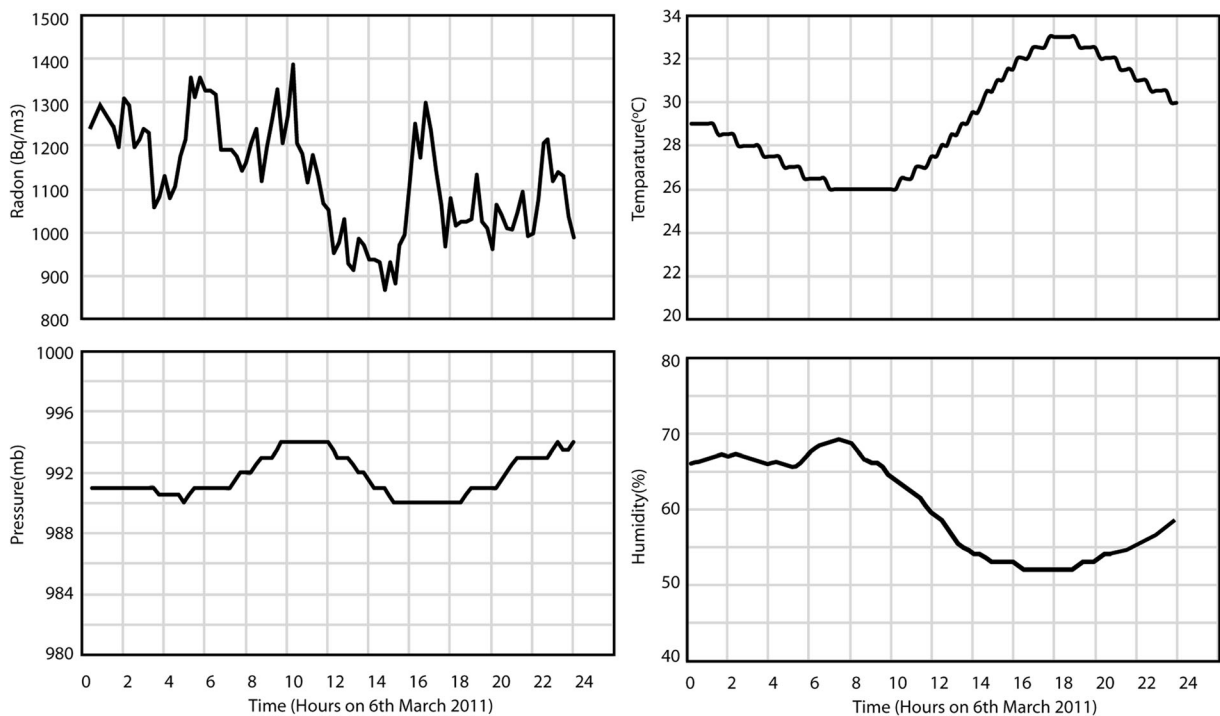
Fig. 8 Diurnal variations of radon, temperature, pressure, and relative humidity on 6th March 2011 at Badargadh

correlation with pressure and humidity. We can interpret the results by understanding the peaks and troughs by how one parameter is influencing other parameters at what interval, etc. Similarly, Fig. 12 depicts the cross correlation between radon and other meteorological parameters (pressure, temperature, and humidity) at Desalpar. In this case also, the relationships are similar to as we got in linear regression. The radon is found to be negatively correlated with temperature and the radon is found to be positively correlated with pressure and humidity.

From the above analysis, it can be inferred that the correlation coefficient between the soil radon and other meteorological parameters in both the monitoring stations are moderate to weak. The main reason for such correlations is that our dataset of soil radon is covering

Table 3 Correlation coefficient values between radon and other meteorological parameters

Correlated parameter	Badargadh	Desalpar
Radon-humidity	0.1277	0.2525
Radon-pressure	0.1723	0.2424
Radon-temperature	−0.2136	−0.1594

dry months during 7th Feb 2011 to 22nd June 2011 for Badargadh and Mar 2, 2011 to May 19, 2011, for Desalpar. During this period, the soil permeability and moisture levels are uniform and the air is arid. However, the sign of correlation either positive or negative is very significant as both the stations are showing the similar sign of correlations. Similar moderate and low values of the correlation coefficients between these parameters have been reported in many papers at different environs (King 1978; Ramola et al. 1989; Yogesh Prasad et al. 2009; Pispak et al. 2010; Jaishi et al. 2014a; Singh et al. 2016). King 1978 found the inverse relationship (−0.35) between radon emanation and air temperature in the San Andreas Fault region. Ramola et al. 1989 have shown that the soil radon shows a weak correlation (< ± 0.2) with the temperature, barometric pressure, relative humidity and rainfall. Yogesh Prasad et al. 2009 found weak correlation of soil-gas radon with temperature (−0.2) and with humidity (0.1) at Badshahi Thaul Campus, Tehri Garhwal, in the Himalayan region. Pispak et al. 2010 have found that the soil-gas radon have shown weak correlation with air pressure (0.134) and air temperature (0.068) and stated that the meteorological parameters have non-significant influence on the radon emission. Jaishi et al. 2014a have found that the soil

Fig. 9 Linear fitting of radon data of Badargadh with meteorological parameters. **a** Air temperature. **b** Pressure. **c** Relative humidity
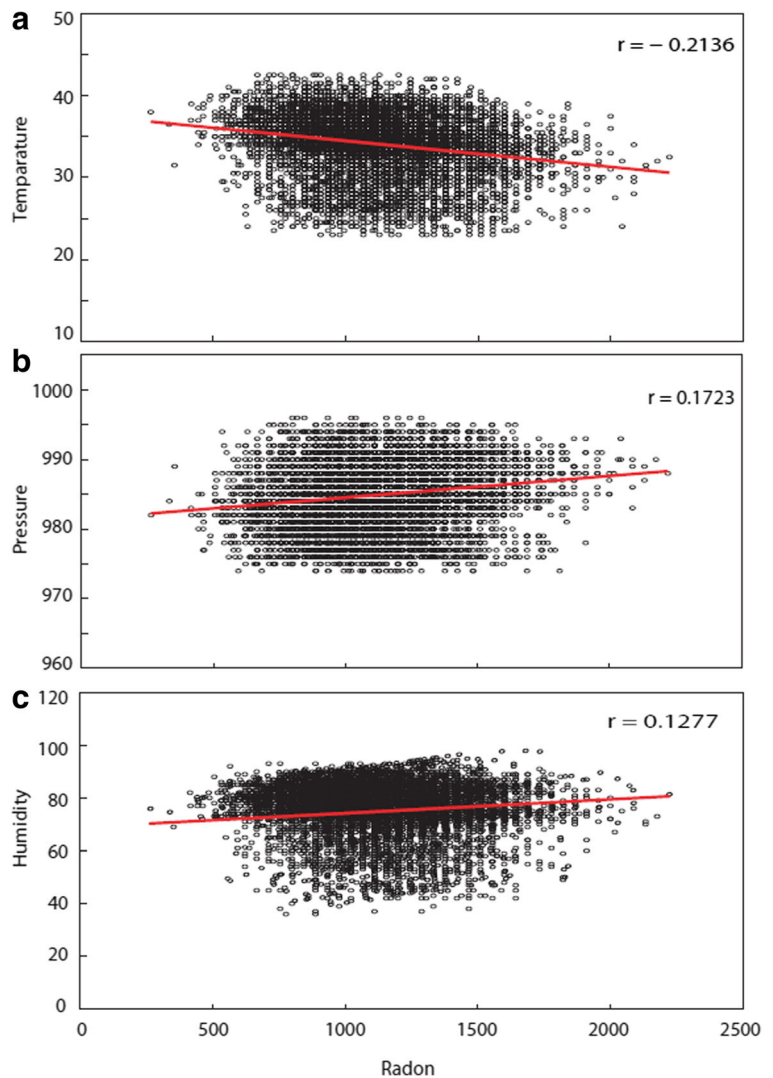

radon shows weak correlation ($< \pm 0.2$) with air temperature and the rainfall. These low levels of correlations are favorable for detecting the pre-earthquake radon anomalies as the influence of meteorological parameters are always taken as noise for locating radon anomalies before earthquakes. The scientific fraternity is now facing this biggest challenge of distinguishing the signals from noise.

Sources of radioactive emission

Identification of the source of the radioactive emission from the subsurface will be an important attribute in understanding the earthquake process. Several workers inferred the source of radioactive emission with the help of radon to thoron ratio (Giammanco et al. 2007; Yang et al. 2005). They attributed that if the radon level is high and the thoron level is low, the source of radon is deep, whereas the lower radon concentration with high thoron activity suggests a shallow source of radon phenomena. High ratio of radon to thoron suggests that the radon has been transported to the surface from deep sources by other carrier gases due to crustal stress/strain changes. Again, the low radon/thoron suggests the migration of radon from a shallow source due to micro fracturing before the moderate earthquakes (Yang et al. 2005). In order to understand the source characteristics of radon emission in Kutch, we calculated the radon to thoron ratio and shown in Fig. 13.

Fig. 10 Linear fitting of radon data of Desalpar with meteorological parameters. **a** Air temperature. **b** Pressure. **c** Relative humidity
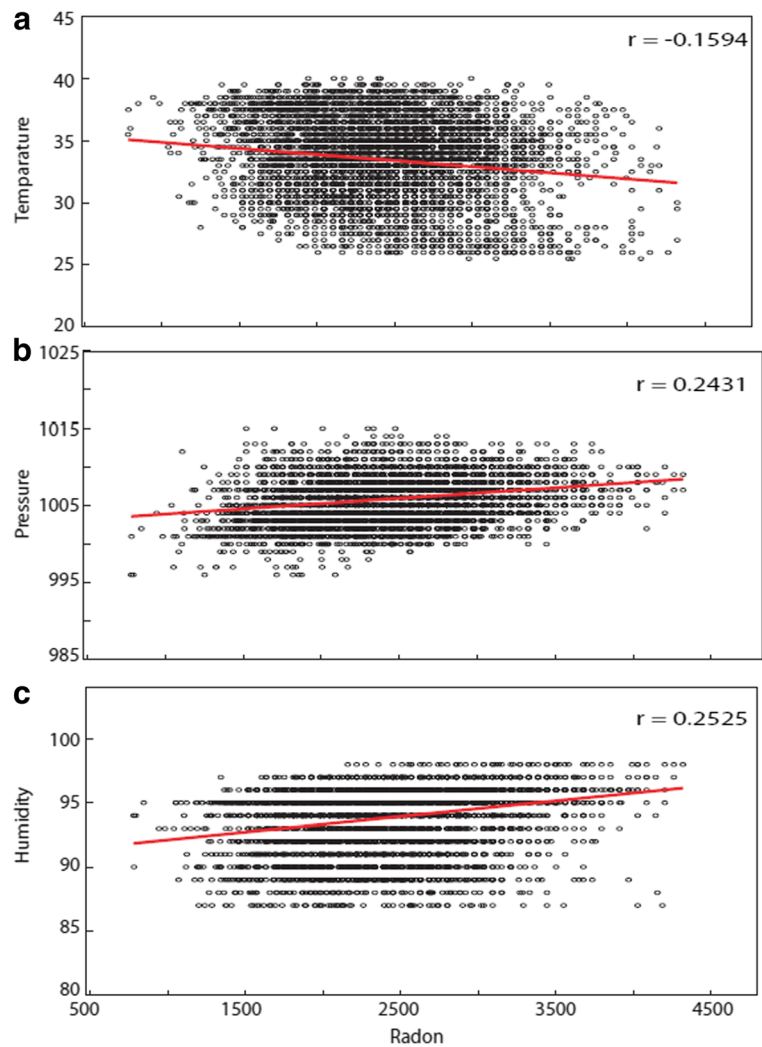

For the Desalpar observatory, the ratio varies between 0.45 and 17.2 with an average value of 6.45, whereas for the Badargadh observatory, the ratio varies between 1.35 and 17.4 with an average value of 6.17. For both the observatories, i.e., Desalpar and Badargadh, it can be depicted that radon is showing a moderate correlation with thoron which may imply that the emission of the radon is due to the contributions from both the deep and shallow sources (Padilla et al. 2013). The causative factors for radon transport from deep and shallow parts of the Earth can be explained as (i) due to stress/strain conditions within the earth, carrier gases present in the deeper part may transport the radon gases up to the surface and (ii) the micro fracturing in the shallow depth might influence the migration of radon. Incidentally, majority of earthquakes occurred at 12 to 27 km beneath the Kutch region. Linking this, we may assume that a deeper source may be prominent. However, the exact identification of a deep or shallow source is not within the scope of this paper. We may require long-duration data and a multiple number of earthquake occurrences near the measuring station with earthquake depths varying from shallow focus to deep focus.

Correlation with local earthquakes in Kutch

During the last few decades, several papers reported the increase of radon concentration before several earthquakes occurring at various environs all over the world (Ulomov and Mahashev 1968; Maldonado et al. 1996; Yang et al. 2005; Kumar et al. 2009; Baykut et al. 2010; Imme and Morelli 2012; Jaishi et al. 2014a; Deb et al.
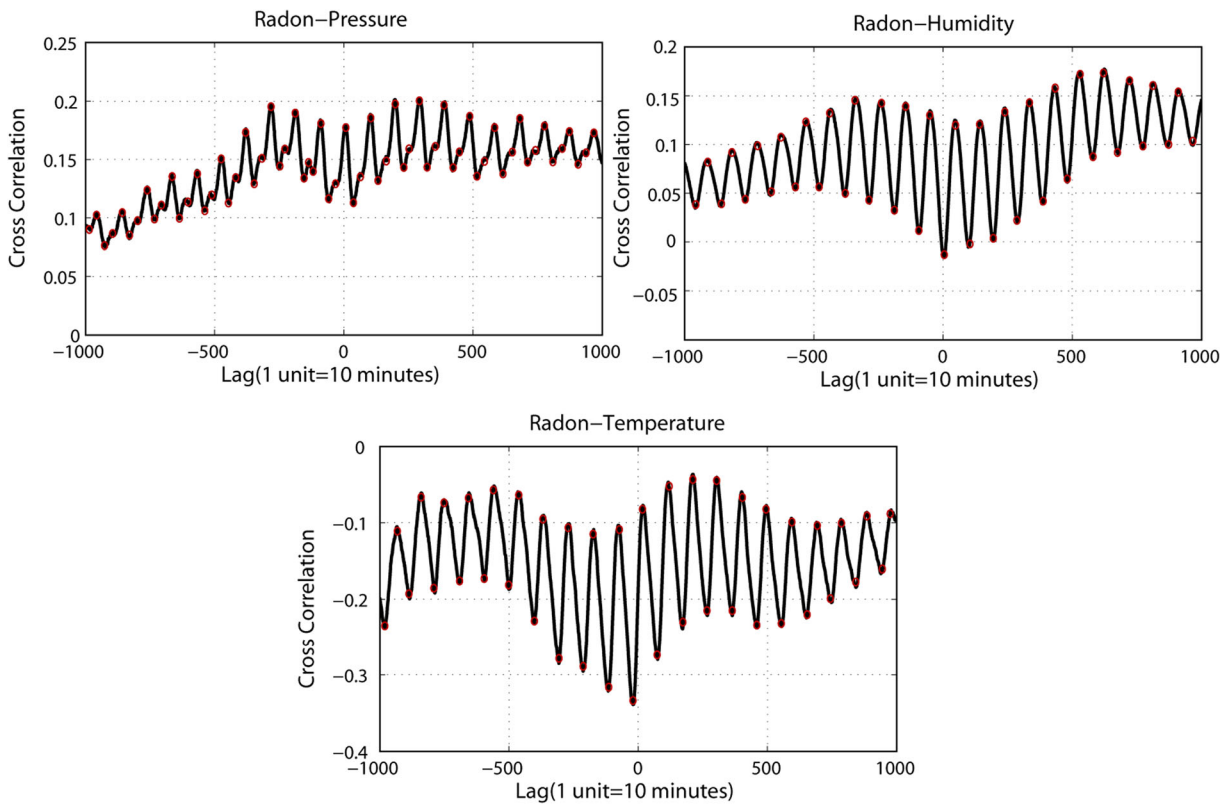
Fig. 11 Cross correlation of radon with humidity and temperature of Badargadh. The red circle is the local extrema point

2016; Neri et al. 2016; Fu et al. 2017). There are three models which describe this causal relationship between radon increase and earthquake occurrence, namely (1) dilatancy-diffusion model (Scholz et al. 1973), (2) stress corrosion model (Anderson and Grew 1977), and (3) compression mechanism model (King 1978). According to dilatancy-diffusion model, in the first stage, the opening of cracks and changes in ground water flow takes place; in the second stage, increase in new cracks, widening of old cracks, and diffusion of pore fluid takes place and this process modifies soil strength and increases pore pressure which will ultimately lead to significant changes in diffusion coefficient of radon and thus increases the radon gas emanation before occurrence of earthquakes. According to the stress corrosion model, in the first stage, mechanical cracks increases and wet environment creates; then, due to the control of the stress corrosion, crack growth reduces; this increases the radon anomalies before occurrence of earthquakes. Here, the stress corrosion depends on strain rate and local conditions such as rock type, porosity, elasticity, micro cracks, temperature, and stress intensity factor. According to the compression mechanism model, the

crustal compression increases first; then, it squeezes out the increased radon gas emanation into the atmosphere and this will increase the radon anomalies before occurrence of earthquakes. All these three models highlight the stress/strain changes which happen during the preparation stage of the earthquake.

In order to correlate the emission of radon with the occurrence of the earthquakes, the time series of radon, thoron and radon/thoron with mean + 2*sigma as dashed line along with the seismic events during the monitoring period were plotted for Badargadh (Fig. 14) and Desalpar (Fig. 15).

During the time period of the study, two earthquakes of M 3.7 on 26th March 2011 and M 4.2 on 17th May 2011 occurred in Kutch (Table 4). Both these earthquakes were near the Badargadh site and little far from the Desalpar site. The earthquakes were monitored by the Institute of Seismological Research with dense 60 broadband seismograph stations network in Gujarat (Kumar et al. 2012).

To identify the anomalies in the radon time series, mean ± 2*sigma technique was applied which is a very common practice in determining anomalies in radon
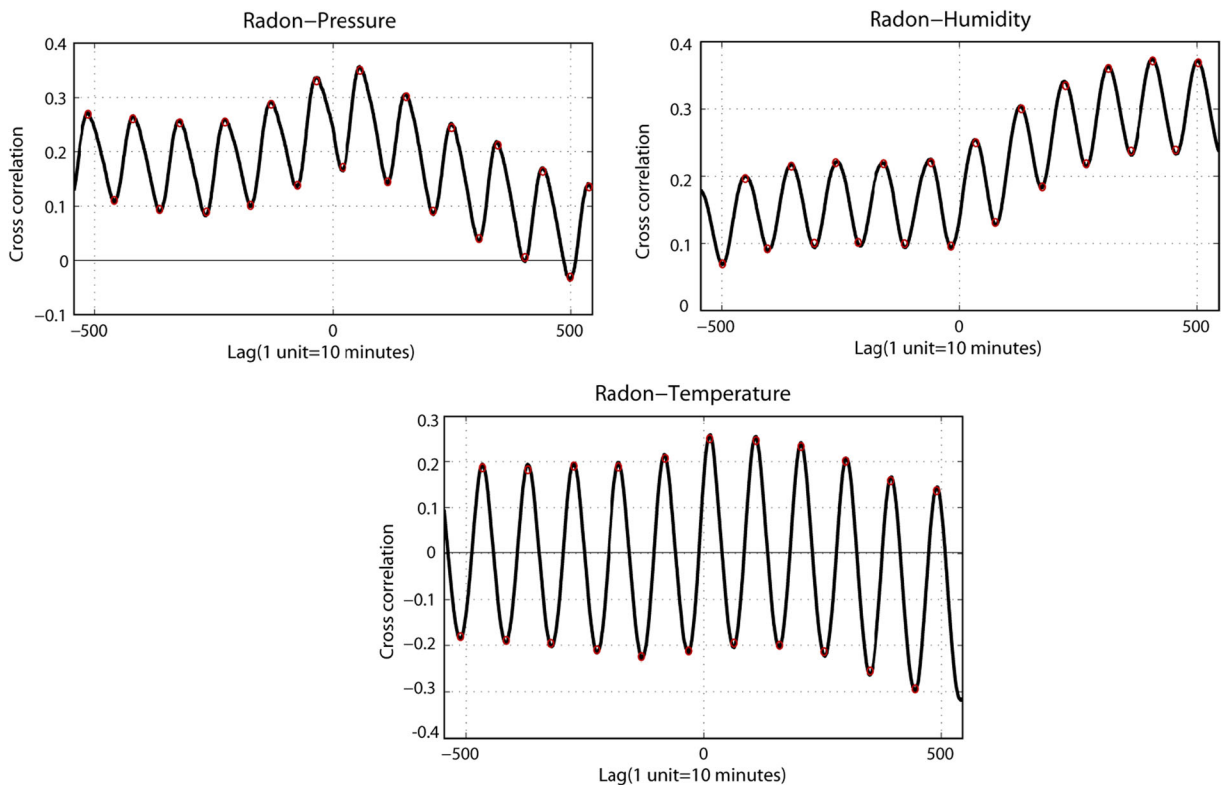
Fig. 12 Cross correlation of radon with humidity and temperature of Desalpar. The red circle is the local extrema point

time series (Virk et al. 2001). Mean, mean + 2*sigma were computed for time series of radon, thoron, and radon/thoron and plotted from upper to lower panel, respectively, as shown in Figs. 13 and 14. The highlighted line indicates the occurrence of the seismic events. At the Badargadh observatory, it can be observed that there was an increase in the radon concentration on 23rd Mar, 2011 just 4 days prior to the occurrence of the earthquake of magnitude 3.7 which occurred at a distance of 22 km from the measuring site with a focal depth of 26.7 km. Here, the radon emission crossed the mean + 2*sigma level. At the same time, an enhancement in the radon/thoron concentration was also observed. This rise of radon and radon/thoron continued till the occurrence of the earthquake. Based on this increase in radon/thoron ratio and the deeper focal depth, we may speculate a deeper source for radon emission. However, as the magnitude of this earthquake is small, it is difficult to conclude about the exact source of radon emission. Similarly, for the 17th May earthquake, the radon level did not cross mean + 2*sigma level before occurrence of this event. However, there is a rise of radon/thoron ratio on 14th May which crossed the mean + 2*sigma level.

This rise may be considered as an anomaly to this earthquake. At the Desalpar station, there was a rise in the radon level on 14th March onwards for about 4–5 days till 18th March, then the lower radon level was observed till the occurrence of the earthquake on 26th April. Due to this irregular pattern of radon level changes, it is difficult to correlate them with this earthquake. Moreover, the distance between the epicenter of the earthquake and this station is more which could also act as a limitation in obtaining the proper radon signatures. Further, for the event of magnitude 4.2 which occurred on 17th May 2011, the radon concentration crossed the mean + 2*sigma during 26–29 April followed by a decrease in its level below mean + 2*sigma till the occurrence of the earthquake. Thus, due to this irregular pattern of radon level changes, it is difficult to correlate them with this earthquake. For both the earthquakes, the radon time series of the Badargadh station has shown some anomalies prior to these earthquakes and anomalous variations were not seen in the radon time series of Desalpar.

Several success case studies were reported in India and other countries regarding radon anomalies before
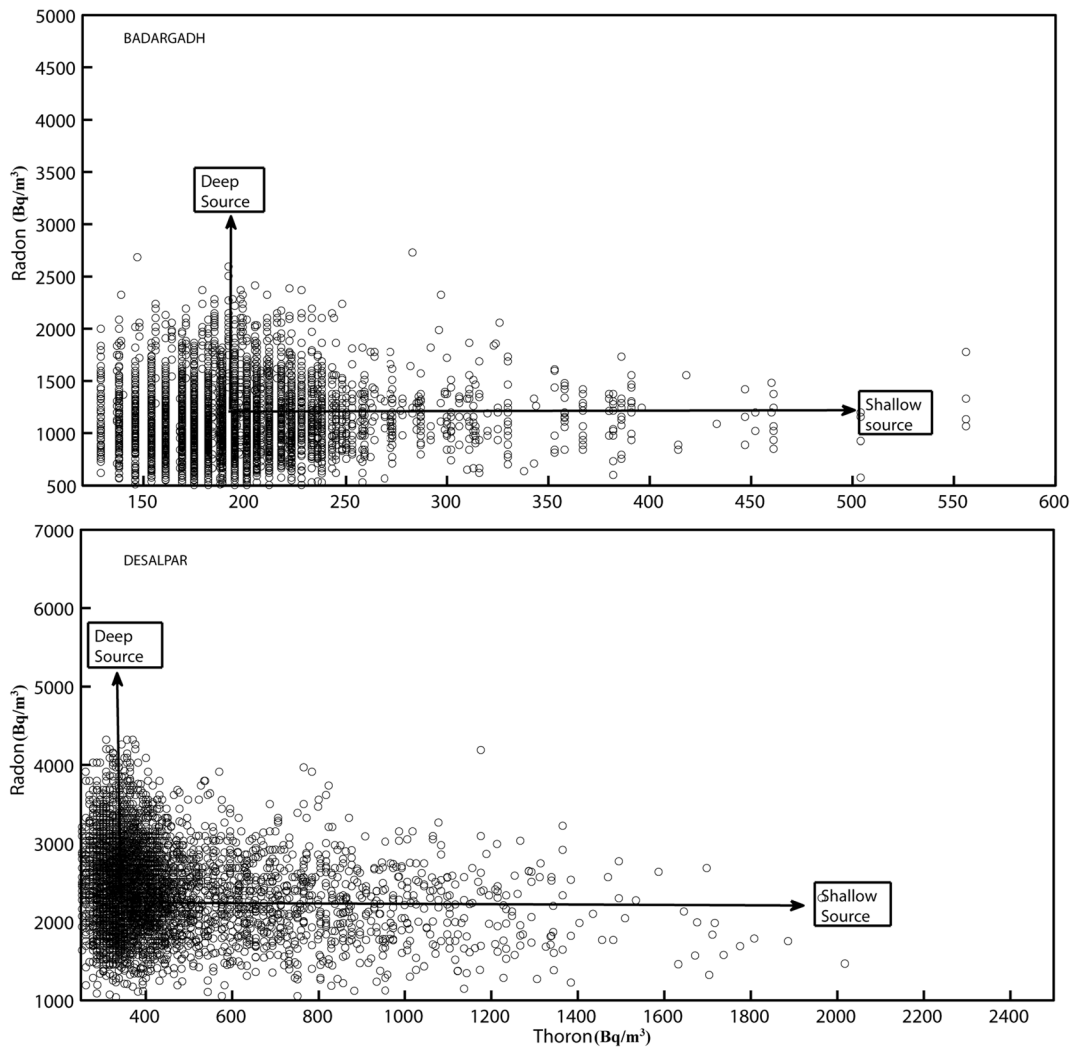
Fig. 13 Correlation between radon and thoron at Badargadh (upper panel) and Desalpar and Badargadh

occurrence of earthquakes. In India, first radon anomalies were observed by Rastogi et al. 1986 during their study of earthquakes in Bhatsa, Maharashtra, during August 1983 to July 1984. They observed an increase in radon concentration during March–April 1984 before high earthquake activity in that region. A significant contribution was made by Virk and Singh 1994 in radon studies during the Uttarakashi earthquake on October 20, 1991, of M 6.5. They found the radon precursory anomalies before 5 days of this earthquake. Walia et al. 2006 observed precursory signatures in radon time series during the earthquakes of M >5 in north western Himalaya. Jaishi et al. 2014a reported two peaks in the radon time series at Mat Bridge along Mat Fault in the Serchhip district, Mizoram, India, before the

earthquakes of M 6.0 on 29/07/2012 and M 6.7 on 11/11/2012. In both the cases, the anomaly was observed 15–16 days prior to the occurrence of earthquakes. Micro fracturing and the crustal deformation were attributed to be possible reasons for increase of radon before these earthquakes. Sanjay Singh et al. 2016 observed two radon peaks on 10/11/2013 and 10/25/2013 before an earthquake of M 4.7 on 29/10/2013. Chiranjib et al. 2016 reported the anomalous fluctuation pattern in radon time series 2–11 days before the earthquakes on February 19, 2013 (M 4.5), March 2, 2013 (M 5.2), April 16, 2013 (M 4.4), April 19, 2013 (M 4.2) and June 1, 2013 (M 4.1). Saheli Choudhary et al. 2017 reported two radon anomalies about 10 days prior to two earthquakes of M 5.0 on 19 November 2015 and M
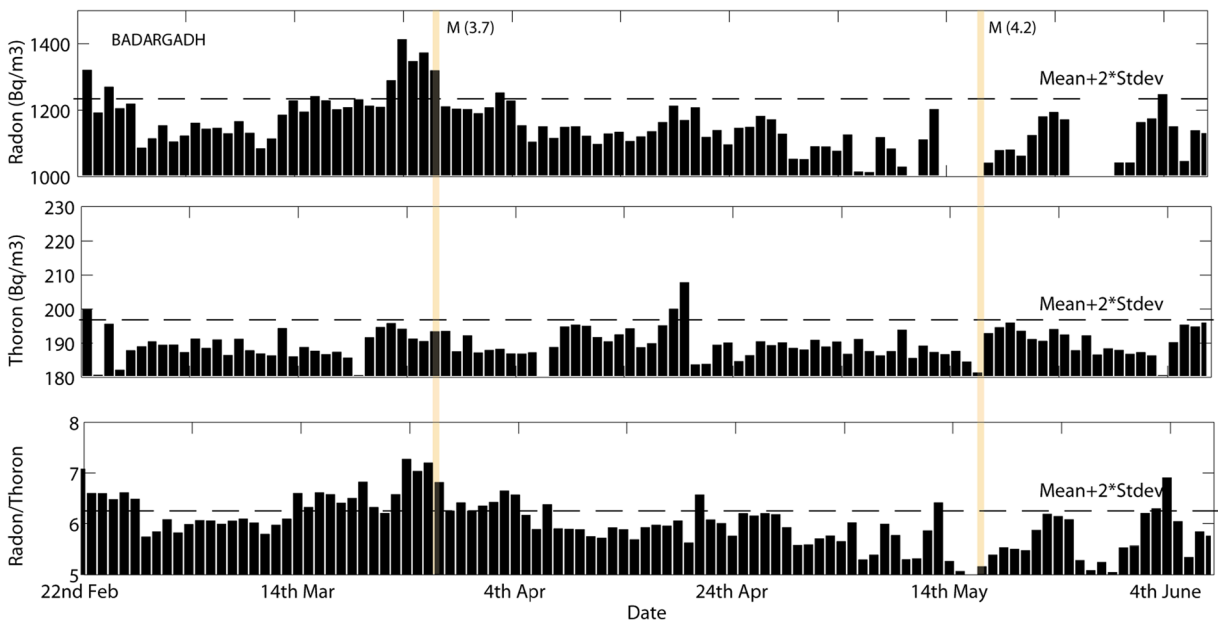
Fig. 14 Time series plot of radon, thoron, and radon/thoron at Badargadh
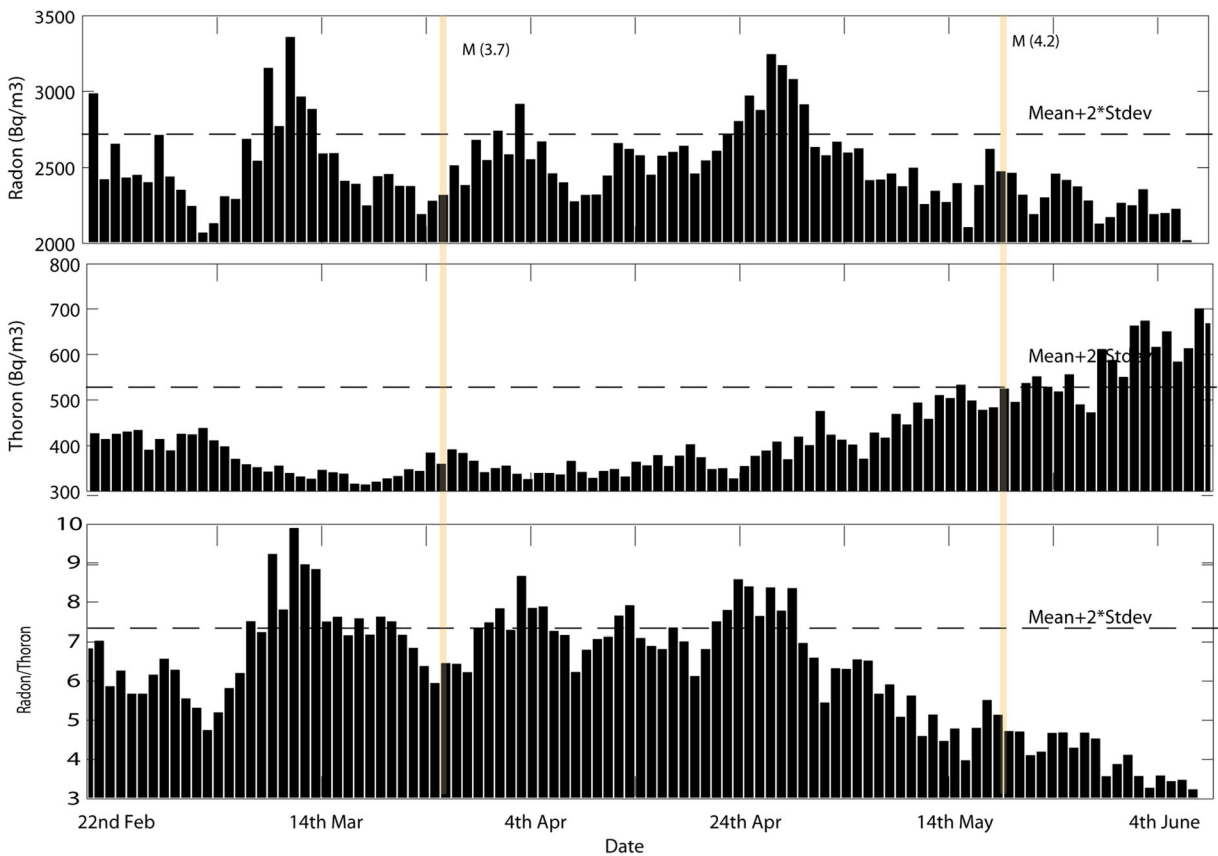
Fig. 15 Time series plot of radon (Rn^{222}), thoron (Rn^{22o}), and Rn^{222}/Rn^{22o} at Desalpar

Table 4 Details of earthquakes which occurred during the period of the study

Sr. no.	Year	Month	Day	Hour	Min	Sec	Lat	Lon	Depth	Mag
1	2011	3	26	2	23	29.3	23.375	70.307	26.7	3.7
2	2011	5	17	16	0	43.1	23.554	70.566	11.1	4.2

5.0 on 5 April 2016. Crustal deformation along Indo-Myanmar subduction zone is attributed to be possible reason for increase in radon concentration before these earthquakes. Naresh Kumar et al. 2017 observed a sharp increase in radon levels during 16 to 18 April then a slight decrease in radon level was observed till 20th April and again a rise in its level was observed till the Nepal earthquake of M 7.8 on 25th April 2017.

In other countries, Ulomov et al. 1967 reported the first evidence of radon precursors before the earthquake of M 5.2 on April 15, 1966. Igarashi and Wakita 1990 observed the precursory radon changes before Kobe earthquake in Japan. Hirotaka et al. 1988 reported about the remarkable increase in radon level 2 weeks prior to the earthquake of M 6.8 on September 14, 1984. Friedmann et al. 1988 observed an increase in radon levels during the earthquake of M 5.7 on July 5, 1983 in Turkey. Tarakci et al. 2014 reported the radon anomalies prior to the earthquakes in Western Turkey. Marco Neri et al. 2016 observed the gradual increase in radon concentration that reached highest values on March 29 just before the earthquake swarm during April 1–2 in the Piano Provenzana area. Progressive accumulation of tectonic stress on the fault plane, micro fracturing of rock and increased porosity and permeability were attributed to be possible reasons for increase in radon concentration before this earthquake swarm. Fu et al. 2017 reported anomalously high soil radon and thoron concentrations few hours to days prior to about 13 local earthquakes during 14 June 2006 to 9 September 2007 in northern Taiwan.

As the influence of meteorological parameters on radon emanation is less/moderate during the study period we can conclude that the observed anomalies in radon concentration recorded at Badargadh station were solely caused by the earthquakes on 29th March 2011 (M 3.7) and 17th May 2011 (M 4.2). The major likely causative factors for this increase in radon levels are micro fracturing of rocks, crustal deformation in the region (Walia et al. 2009) and strain build up in the area (Ramola et al. 2008). The findings of this study are prominent as no such studies were conducted in the past to study about the background values of radon, thoron, and other meteorological parameters and its influence on radon emanation and identification of precursors in Kutch, Gujarat, which is seismically active and lies in the highest level of seismic hazard, i.e., seismic zone V (BIS 2002). To establish this relationship more profoundly, we plan to establish 10 new radon gas monitoring stations in this region.

Conclusions

In the present study, the radon and thoron data recorded at two stations in Kutch, Gujarat, during Mar–June 2011 have been analyzed to correlate with earthquakes and meteorological parameters. Using descriptive statistics, the background values of radon and thoron are determined. The correlation between radon with temperature found to be negative and the correlation of radon with humidity and pressure is found to be positive. The ratio of radon/thoron is observed to be enhanced during this period which may indicate the deeper source contribution is prominent. Some considerable radon anomalies have been observed prior to local earthquakes on 29th March 2011 (M 3.7) and 17th May 2011 (M 4.2) at Badargadh. The radon monitoring near the epicentral zone is useful to understand the precursors of the earthquakes. Whereas, we did not notice considerable variations in the radon time series of Desalpar as this station is distant than that of Badargadh. However, longer duration and more number of stations will improve the correlations with meteorological parameters and earthquakes.

References

Ahrens, L. H. (1954). The lognormal distribution of the elements (a fundamental law of geochemistry and its subsidiary). *Geochimica et Cosmochimica Acta, 5*(2), 49–73. https://doi.org/10.1016/0016-7037(54)90040-X.

Anderson, O. L., & Grew, P. C. (1977). Stress corrosion theory of crack propagation with applications to geophysics. *Reviews of Geophysics and Space Physics, 15*(1), 77–104. https://doi.org/10.1029/RG015i001p00077.

Baykut, S., Akgul, T., Inan, S., & Seyis, C. (2010). Observation and removal of daily quasi-periodic components in soil radon data. *Radiation Measurements, 45*(7), 872–879. https://doi.org/10.1016/j.radmeas.2010.04.002.

BIS (2002). IS:1893-2002 (Part I): Indian standard criteria for earthquake resistant design of structures, Part 1- general provisions and buildings, Bureau of Indian Standards, New Delhi.

Biswas, S. K. (1987). Regional framework, structure and evolution of the western marginal basins of India. *Tectonophys, 135*, 302–327.

Chambers, S. D., Hong, S.-B., Williams, A. G., Crawford, J., Griffiths, A. D., & Park, S.-J. (2014). Characterizing terrestrial influences on Antarctic air masses using Radon-222 measurements at King George Island. *Atmospheric Chemistry and Physics, 14*(18), 9903–9916. https://doi.org/10.5194/acp-14-9903-2014.

Chambers, S. D., Williams, A. G., Crawford, J., & Griffiths, A. D. (2015). On the use of radon for quantifying the effects of atmospheric stability on urban emissions. *Atmospheric Chemistry and Physics, 15*(3), 1175–1190. https://doi.org/10.5194/acp-15-1175-2015.

Chaudhuri, H., Das, N. K., Bhandari, R. K., Sen, P., & Sinha, B. (2010). Radon activity measurements around Bakreswar thermal springs. *Radiation Measurements, 45*(1), 143–146. https://doi.org/10.1016/j.radmeas.2009.11.039.

Chaudhuri, H., Barman, C., Iyengar, A. N. S., Ghose, D., Sen, P., & Sinha, B. (2013). Long range correlation in earthquake precursory signals. *European Physical Journal Special Topics, 222*(3-4), 827–838. https://doi.org/10.1140/epjst/e2013-01886-y.

Chiranjib, B., Ghose, D., Sinha, B., & Deb, A. (2016). Detection of earthquake induced radon precursors by Hilbert Huang Transform. *Journal of Applied Geophysics, 133*, 123–131.

Crawford, J., Chambers, S., Kang, C. H., Griffiths, A., & Kim, W. H. (2015). Analysis of a decade of Asian outflow of PM 10 and TSP to Gosan, Korea; also incorporating Radon-222. *Atmospheric Pollution Research, 6*(3), 529–539. https://doi.org/10.5094/APR.2015.059.

Damkjaer, A., & Korsbech, U. (1985). Measurement of the emanation of radon-222 transport from Danish soils. *Science Total Environment, 45*, 343–350. https://doi.org/10.1016/0048-9697(85)90236-0.

Das, N. K., Bhandari, R. K., Ghose, D., Sen, P., Sinha, B. (2005). Anomalous fluctuation of radon, gamma dose and helium emanating from thermal spring prior to earthquake. *Current Science, 89*, 1399–1404.

Deb, A., Gazi, M., & Chiranjib, B. (2016). Anomalous soil radon fluctuations—signal of earthquakes in Nepal and eastern India regions. *Journal of Earth System Science, 125*(8), 1657–1665. https://doi.org/10.1007/s12040-016-0757-z.

Fleischer, R. L. (1981). Dislocation model for radon response to distant earthquakes. *Geophysical Research Letters, 84*, 77–480.

Fleischer, R. L. (1983). Theory of alpha recoil effects on radon release and isotopic disequilibrium. *Geochimica et Cosmochimica Acta, 47*(4), 779–784. https://doi.org/10.1016/0016-7037(83)90111-4.

Friedmann, H. (1991). Selected problems in Radon measurement for earthquake prediction proceedings of the second workshop on Radon monitoring in radioprotection, environmental and/or earth science. In: Furlan, G. and Tommasino, L. (Ed.) World Scientific 307–316.

Friedmann, H., Aric, K., Gutdeutsch, R., King, C. Y., Altay, C., & Sav, H. (1988). Radon measurements for earthquake prediction along the North Anatolian Fault Zone: a progress report. *Tectonophysics, 152*(3-4), 209–214. https://doi.org/10.1016/0040-1951(88)90047-9.

Fu, C.-C., Yang, T. F., Chen, C.-H., Lee, L.-C., Wu, Y.-M., Liu, T.-K., Walia, V., Kumar, A., & Lai, T.-H. (2017). Spatial and temporal anomalies of soil gas in northern Taiwan and its tectonic and seismic implications. *Journal of Asian Earth Sciences, 149*, 64–77. https://doi.org/10.1016/j.jseaes.2017.02.032.

Giammanco, S., Sims, K. W. W., & Neri, M. (2007). Measurements of 220Rn and 222Rn and CO2 emission in soil and fumaroles gases on Mt. Etna volcano (Italy): implications for gas transport and shallow ground fracture. *Geochemistry, Geophysics, Geosystems, 8*, Q10001.

Guerra, M., & Lombardi, S. (2001). Soil-gas method for tracing neotectonic faults in clay basins: the Pisticci field (Southern Italy). *Tectonophysics, 339*(3-4), 511–522. https://doi.org/10.1016/S0040-1951(01)00072-5.

Gupta, H. K., Harinaryana, T., Kousalya, M., Mishra, D. C., Mohan, I., Rao, N. P., Raju, P. S., Rastogi, B. K., Reddy, P. R., & Sarkar, D. (2001). Bhuj earthquake of 26 January 2001. *Journal of the Geological Society of India, 57*, 275–278.

Hirotaka, U. I., Moriuchi, H., Takemura, Y., Tsuchida, H., Fujii, I., & Nakamura, M. (1988). Anomalously high radon discharge from Atotsugawa Fault prior to the western Nagano Prefecture earthquake (M 6.8) of September 14, 1984. *Tectonophysics, 152*, 147–152.

Igarashi, G., & Wakita, H. (1990). Groundwater radon anomalies associated with earthquakes. *Tectonophysics, 180*, 2–4.

Imme G, Morelli D. (2012). Radon as earthquake precursor. In: Earthquake research and analysis-statistical studies, observation and planning (Dr. Amico S.D., Ed.), ISBN: 978–953–51-0134-5, In Tech, Available from: http://www.intechopen.com/books/earthquake-research-and-analysis-statistical-studies-observations-andplanning/radon-as-earthquake-precursor.

Jaishi, H. P., Singh, S., Tiwari, R. P., & Tiwari, R. C. (2014a). Analysis of soil radon data in earthquake precursory studies. *Annals of Geophysics, 57*(5), S0544. https://doi.org/10.4401/ag-6513.

Jaishi, H. P., Singh, S., Tiwari, R. P., & Tiwari, R. C. (2014b). Correlation of radon anomalies with seismic events along Mat fault in Serchhip District, Mizoram, India. *Applied Radiation and Isotopes, 86*, 79–84. https://doi.org/10.1016/j.apradiso.2013.12.040.

King, C. Y. (1978). Radon emanation on San Andreas Fault. *Nature, 271*(5645), 516–519. https://doi.org/10.1038/271516a0.

Klusman, R. W., & Jaacks, J. A. (1987). Environmental influence upon mercury, radon and helium concentrations in soil gas at a site near Denver, Colorado. *Journal of Geochemical Exploration, 27*(3), 259–280. https://doi.org/10.1016/0375-6742(87)90023-9.

Kovach, E. M. (1945). Meteorological influences upon the radon-content of soil-gas. *Eos Transactions American Geophysical Union, 26*, 241–248.

Kumar, A., Singh, S., Mahajan, S., Bajwa, B. S., Kalia, R., & Dhar, S. (2009). Earthquake precursory studies in Kangra valley of north-west Himalayas, India, with special emphasis on radon emission. *Applied Radiation and Isotopes, 67*(10), 1904–1911. https://doi.org/10.1016/j.apradiso.2009.05.016.

Kumar, S., Chopra, S., Choudhury, P., Singh, A. P., Yadav, R. B. S., & Rastogi, B. K. (2012). Ambient noise levels in Gujarat State (India) seismic network, Geomatics. *Natural Hazards and Risk, 3*(4), 342–354. https://doi.org/10.1080/19475705.2011.611952.

Kumar, N., Chauhan, V., Dhamodharan, S., Rawat, G., Hazarika, D., & Gautam, P. K. R. (2017). Prominent precursory signatures observed in soil and water radon data at multi-parametric geophysical observatory, Ghuttu for Mw 7.8 Nepal earthquake. *Current Science, 112*(5), 907–909.

I. Laskar, P. Phukon, A. K. Goswami, G. Chetry and U. C. Roy, (2011). A possible link between radon anomaly and earthquake, Geochemical Journal, Vol. 45, pp. 439 to 446.

Maldonado S.C., Monnin M., Segovia N. and Seidel J.L. (1996). A radon measurement network to study radon anomalies as precursors of strong earthquakes in the Guerrero seismic gap. 11 WCEE, CD-Rom, ISBN: 0080428223, Pergamon. Paper 1762, p.6.

Nazaroff, W.W., Nero, A.V. (1988). *Soil as a source of in-door radon: generation, migration and entry: radon and its decay products in indoor air.* Wiley-Inter-Science Publication, pp. 57–112.

Neri, M., Ferrera, E., Giammanco, S., Currenti, G., Cirrincione, R., Patanè, G., & Zanon, V. (2016). Soil radon measurements as a potential tracer of tectonic and volcanic activity. *Scientific Reports, 6*(1), 24581. https://doi.org/10.1038/srep24581.

Padilla, G. D., Hernandez, P. A., Padron, E., Barrancos, J., Perez, N. M., Melian, G., Nolasco, D., Dionis, S., Rodriguez, F., Calvo, D., & Hernandez, I. (2013). Soil gas radon emission and volcanic activity at El Hierro (Canary Island): the 2011–2012 submarine eruption. *Geochemistry, Geophysics, Geosystems, 14*(2), 432–447. https://doi.org/10.1029/2012GC004375.

Pispak, P., Dürrast, H., & Bhongsuwan, T. (2010). Soil-gas radon as a possible earthquake precursor: a case study from the Khlong Marui Fault Zone, Southern Thailand. *Kasetsart Journal (Natural Science), 44*, 1079–1093.

Prasad, Y., Prasad, G., Gusain, G. S., Choubey, V. M., & Ramola, R. C. (2009). Seasonal variation on radon emission from soil and water. *Indian Journal of Physics, 83*(7), 1001–1010. https://doi.org/10.1007/s12648-009-0060-9.

Ramola, R. C., Sandhu, A. S., Singh, M., Singh, S., & Virk, H. S. (1989). Geochemical exploration of uranium using radon measurement techniques. *Nuclear Geophysics, 3*, 57.

Ramola, R. C., Prasad, Y., Prasad, G., Kumar, S., & Choubey, V. M. (2008). Soil-gas radon as seismotectonic indicator in Garhwal Himalaya. *Applied Radiation and Isotopes, 66*(10), 1523–1530. https://doi.org/10.1016/j.apradiso.2008.04.006.

Rastogi, B. K., Chadha, R. K., & Raju, I. P. (1986). Seismicity near Bhatsa reservoir, Maharashtra, India. *Physics of the Earth and Planetary Interiors, 44*(2), 179–199. https://doi.org/10.1016/0031-9201(86)90044-0.

Rikitake, T. (1976). Earthquake prediction developments in solid earth. *Geophysics, 9*, 357.

Sac, M. M., Harmansah, C., Camgoz, B., & Sozbilir, H. (2011). Radon monitoring as the earthquake precursor in fault line in Western Turkey. *Ekoloji, 20*(79), 93–98.

Saheli C., Argha., Nurujjaman Md., & Chiranjib B, (2017). Identification of preseismic anomalies of soil radon-222 signal using Hilbert–Huang transform, *Nat Hazards, 87*(3), 1587–1606. https://doi.org/10.1007/s11069-017-2835-1

Scholz, C. H., Sykes, L. R., & Aggarwal, Y. P. (1973). Earthquake prediction: a physical basis. *Science, 181*(4102), 803–810. https://doi.org/10.1126/science.181.4102.803.

Schumann RR, Owen DE. (1988). *Relationship between geology, equivalent uranium concentration, and radon in soil gas*, Fairfax Country, Verginia: USGS open file report 88–18, p 28.

Singh, M., Ramola, R. C., Singh, S., & Virk, H. S. (1988). The influence of meteorological parameters on soil gas radon. *Expl. Geophys, IX*, 85–90.

Singh, S., Jaishi, H. P., Tiwari, R. P., & Tiwari, R. C. (2016). A study of variation in soil gas concentration associated with earthquakes near Indo-Burma Subduction zone. *Geoenvironmental Disasters, 3*(1), 22. https://doi.org/10.1186/s40677-016-0055-8.

Sundal A V, Vidar Valen, Oddmund Soldal, Terje Strand. (2008). The influence of meteorological parameters on soil radon levels in permeable glacial sediments. 418–428 doi: https://doi.org/10.1016/j.scitotenv.2007.09.001.

Tanner, A. B. (1964). *Radon migration in the ground: a review, symposium proceedings natural radiation environment, 161–190.* Chicago: University of Chicago Press.

Tarakci, M., Harmanşah, C., Saç, M. M., & Içhedef, M. (2014). Investigation of the relationships between seismic activities and radon level in western Turkey. *Applied Radiation and Isotopes, 83*, 12–17. https://doi.org/10.1016/j.apradiso.2013.10.008.

Ulomov, V. I., Zakharovc, A. I., & Ulomova, N. V. (1967). Tashkent earthquake of April 26, 1966, and its aftershocks. *Akad Nauk SSSR, Geophysics, 177*, 567–570.

Ulomov, V.I. & Marashev, B. Z. (1968). A precursor of a strong tectonic earthquake. *Dokl. Akad. Sci. USSR, Earth Sci. Sect., 176*, (l-6): 9–11.

Virk, H. S., & Singh, B. (1994). Radon recording of Uttarkashi earthquakes. *Geophysical Research Letters, 21*(8), 737–740. https://doi.org/10.1029/94GL00310.

Virk, H. S., Walia, V., & Kumar, N. (2001). Helium/radon precursory anomalies of Chamoli earthquake, Garhwal Himalaya, India. *Journal of Geodynamics, 31*(2), 201–210. https://doi.org/10.1016/S0264-3707(00)00022-3.

Walia, V., Bajwa, B. S., Virk, H. S., & Sharma, N. (2003). Relationships between seismic parameters and amplitudes of radon anomalies in N-W Himalaya, India. *Radiation*

Measurements, 36(1-6), 393–396. https://doi.org/10.1016/S1350-4487(03)00158-6.

Walia, V., Su, T. C., Fu, C. C., & Yang, T. F. (2005). Spatial variations of radon and helium concentrations in soil gas across Shan-Chaio fault, Northern Taiwan. *Radiation Measurements, 40*(2-6), 513–516. https://doi.org/10.1016/j.radmeas.2005.04.011.

Walia, V., Virk, H. S., & Bajwa, B. S. (2006). Radon precursory signals for some earthquakes of magnitude > 5 occurred in N–W Himalaya. *Pure and Applied Geophysics, 163*(4), 711–721. https://doi.org/10.1007/s00024-006-0044-z.

Walia, V., Lin, S. J., Hong, W. L., Fu, C. C., Yang, T. F., Wen, K. L., & Chen, C. H. (2009). Continuous temporal soil-gas composition variations for earthquake precursory studies along Hsincheng and Hsinhua faults in Taiwan. *Radiation Measurements, 44*(9-10), 934–939. https://doi.org/10.1016/j.radmeas.2009.10.010.

Weinlinch, F. H., Faber, E., Bouskova, A., Horalek, J., Teschner, M., & Poggenburg, J. (2006). Seismically induced variations in Marin-skLzn fault gas composition in the NW Bohemian swarm quake region, Czech Republic—a continuous gas monitoring. *Tectonophysics, 421*(1-2), 89–110. https://doi.org/10.1016/j.tecto.2006.04.012.

Yang, T. F., Walia, V., Chyi, L. L., Fu, C. C., Chen, C. H., Liu, T. K., Song, S. R., Lee, C. Y., & Lee, M. (2005). Variations of soil radon and thoron concentrations in a fault zone and prospective earthquakes in SW Taiwan. *Radiation Measurements, 40*(2), 496–502. https://doi.org/10.1016/j.radmeas.2005.05.017.