A study on the anomalous behaviour of Radon in different depths of soil at a tectonic fault and its comparison with time-series data at a distant continuous monitoring station

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Abstract

The present study reports the anomalous behaviour of Radon isotope pairs (^{222}Rn , ^{220}Rn) in different soil depths at Mat fault, Mizoram (India). The measurement was taken for six occasions between November 2017 and April 2018 under dry soil condition in majority of the occasions. The Radon isotope pair's data were generated in situ online at depths of 5 cm, 50 cm and 1 m from ground surface in nine selected grid locations at Mat fault. At the same time, to identify geophysical phenomena Radon data were generated at Mizoram University (MZU) in a continuous monitoring station (CMS), located about 57 km from Mat fault. A ZnS/Ag scintillation-based continuous Radon monitor (Model: *SMARTnDuo*, BARC, India) was deployed for monitoring Radon at Mat fault as well as in MZU. Correlation study shows that ^{222}Rn data at 5 cm and 50 cm depths of Mat fault region vary in the same manner with ^{222}Rn data at the CMS during all geophysical and non-geophysical process as identified by the CMS ^{222}Rn data. However, ^{222}Rn data at 1 m depth in the fault region does not show any definite correlation with CMS data. The variation of ^{220}Rn data at 50 cm depth in Mat fault also match the CMS ^{220}Rn data but deviated from it at 5 cm and 1 m depth. The influence of meteorological parameters on ^{222}Rn and ^{220}Rn data monitor at the CMS and Mat fault was also reported, and comparison was made with observation reported by other authors in the region.

Keywords Radon · Fault · Continuous monitoring · In situ · Meteorological factors · Correlation

1 Introduction

Radon studies draw attention to many scientists and researchers from the twentieth century to till date, due to its premonitory potential to a seismic event and health hazard. Observation of Radon anomaly before the Tashkent earthquake [1] induced Radon studies as a possible precursor in soil and groundwater across the globe [2–13]. Tectonic fault lines are the regions where soil is loosely formed and packed; as a result, they are the regions where sub-terrestrial and inert gases like CO_2 , CH_4 , Rn, etc., easily seep out to the surface, as it forms a medium of preferential pathway during stress release and other geophysical processes [14, 15]. In the present study, anomalous behaviours of Radon pairs (^{222}Rn , ^{220}Rn) at a tectonic fault due to

geophysical phenomena have been investigated by correlating with a real-time CMS Radon data. Radon is a radioactive noble gas with three naturally occurring isotopes, viz. Radon (3.8 days), thoron (55.6 s) and actinon (3.6 s) from the decay series of ^{238}U , ^{232}Th and ^{235}U , respectively. Radon is emanated to the pore space of the soil matrix from the solid grain by the process of recoil effect due to the decay of ^{226}Ra ; from there, it gets transported to the surface by the process of diffusion or advection for exhalation to the atmosphere. Typical diffusion length is 1 m and 1 cm for ^{222}Rn and ^{220}Rn , respectively [16]. The diffusion equation for Radon in soil is given by:

$$\frac{\partial C_p}{\partial t} = S - \nabla \cdot F_p - \lambda C_p \quad (1)$$

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where C_p is the Radon activity per volume of the pore space, S is the Radon activity released into a unit volume of the pore space per unit time, F_p is the activity of Radon crossing per unit pore area per unit time and λ is the decay constant.

The main objective of this study was to investigate the anomalous behaviour of ^{222}Rn and ^{220}Rn pairs during geophysical phenomena (identified by the CMS data at MZU) in Mat fault at Zawlpui (23.3°N, 92.9°E), Serchhip District, Mizoram (India). A grid (1000 m × 400 m) with nine locations/spots was selected at Mat fault to perform the measurement at various occasions as shown in Fig. 1. At the same time, a continuous monitoring station (CMS) was set up at Mizoram University (23.4°N, 92.3°E) to detect the anomalous and non-anomalous periods of Radon data due to geophysical phenomena. This station is located at a distance of about 57 km from Mat fault. Random field visits to the fault region were carried out at various occasions with a frequency of once in a month from November 2017 to April 2018 to generate in situ Radon pair data at different depths from the selected nine grid spots of the fault region. The Radon monitoring was carried out using a ZnS/Ag scintillation-based continuous Radon monitor (Model: *SMARTRnDuo*, BARC, India) in the fault as well as

in the continuous monitoring station. Mat fault obliquely cuts the Indo-Burmese arc and is the most prominent fault in Mizoram state. It trends in the NW–SE direction and was traceable by satellite throughout the entire state as shown in Fig. 1 [10]. Correlation of seismic activity with Radon in the region has been studied by Jaishi et al. [4, 17–20] and Singh et al. [10, 21, 22] particularly at Mat fault by Jaishi et al. using LR-115 passive system, which lacks the real-time behaviour of Radon during geophysical and non-geophysical processes in the earth crust. In the present study, continuous monitoring, as well as in situ grid-based study, provides a better picture of Radon behaviour at the fault.

Correlation study shows that in situ online generated ^{222}Rn data at depths of 5 cm and 50 cm in Mat fault region vary, in the same manner, with ^{222}Rn data at the CMS, during geophysical and non-geophysical phenomena. The presence and absence of geophysical processes in the earth crust were identified by the peak and non-peak periods of the ^{222}Rn data monitored at the CMS, respectively. While ^{222}Rn data at 1 m depth in the fault region do not show any definite correlation with time-series ^{222}Rn data monitored at the CMS during the said phenomena, ^{220}Rn data monitored at the CMS below 5 cm the ground surface vary intervally and reveal that its variation was in

Fig. 1 Location map of the study area, showing the location of the continuous monitoring station (CMS), grid and formation of the grid at Mat Fault

similar trend with ^{220}Rn data generated at depth of 50 cm in Mat fault, while the 5 cm and 1 m depth ^{220}Rn data of the fault region deviated from the CMS data in trend. The influence of meteorological parameters on emission of the isotope pair (^{222}Rn , ^{220}Rn) was studied and compared with the finding of Jaishi et al. [17, 18, 20] and Singh et al. [22] at Mat fault and Chite fault, respectively, and also with other reports from different locations.

2 Materials and methods

2.1 Continuous Radon monitor—SMARTnDuo and continuous Radon monitoring station (CMS)

SMARTnDuo a ZnS/Ag scintillation-based counter was developed and calibrated by Bhabha Atomic Research Centre, Mumbai, India. The instrument is capable of operating in Radon mode, thoron mode and alpha mode. In thoron mode, the instrument presents counts (sum of ^{222}Rn and ^{220}Rn counts), background counts (counts of ^{222}Rn only) and thoron (^{220}Rn) concentrations, while in Radon mode the instrument presents only ^{222}Rn counts and ^{222}Rn concentrations. The instrument is operated by internal battery as well as by solar power, and most importantly it does not require drying of air sample, and hence, it is best-suited for field use and continuous unattended operation. The sample is drawn from a sampling spot to the scintillation cell of the instrument by a built-in pump with a flow rate of 0.5–0.7 L/min following a preset pump *ON* and *OFF* period. The scintillation cell (153 cm³) was internally coated with ZnS/Ag, such that ^{222}Rn and ^{220}Rn sensitivity of the scintillation cell was 1.2 counts per hour (CPH)/(Bq/m³) and 0.8 CPH/(Bq/m³), respectively. The measurement range of the monitor varies from 8 Bq/m³ to 50 MBq/m³ and 15 Bq/m³ to 50 MBq/m³ for ^{222}Rn and ^{220}Rn , respectively [23].

A station for continuous monitoring of Radon pairs (^{222}Rn and ^{220}Rn) data was set up at the Physics Department of Mizoram University, India (23.4°N, 92.3°E). The station was shaded to minimise the external atmospheric effect on the Radon time-series data and to detect anomalous period originated from any geophysical processes in the earth crust. Soil gas at a depth of 5 cm below the ground surface was transported into the scintillation volume of the *SMARTnDuo* through tubing connected to the soil probe and the *SMARTnDuo* in a closed-loop manner as shown in Fig. 2a. The built-in pump sucks in the Radon gas inside the soil probe at depth of 5 cm below the ground surface for about 5 min of a 15-min cycle. The sample gas before entering the scintillation cell passed through a progeny filter, which filtered out both ^{222}Rn and

^{220}Rn progenies but could not differentiate the ^{222}Rn and ^{220}Rn gases. Hence, the first 5-min counts of the 15-min cycle during the sampling gives the sum of ^{222}Rn and ^{220}Rn counts. The built-in pump *OFF* automatically after the first 5 min; the following 5 min was delayed without any counting so that the entire short-lived ^{220}Rn decays off; the last 5 min gives the counts of ^{222}Rn along with a marginal fraction of fixed background counts due to the long-lived alpha emitter in the cell. However, any change in the last 5-min counts from interval to interval is attributable to variation in ^{222}Rn concentration. At the end of the 15-min interval, the ^{220}Rn counts were obtained by subtracting the last 5-min counts from the first 5-min counts. In this way, Radon pairs (^{222}Rn , ^{220}Rn) were monitored online at every 15-min cycle interval at the station and online stored to a data logging PC connected to *SMARTnDuo* through the serial data communication.

2.2 Procedure for measurement of Radon at different soil depths in Mat fault

For measurement of soil gas in the fault, a grid (1000 m × 400 m) containing nine spots within 1 km from the fault line was formed at Mat fault. The first six spots form a 200-m square grid, where three of them lie within and along the fault line, while the other three lie at a distance of 200 m from the fault line adjacent to the first three spots. The last three 200 m apart spots lie at a distance of 1 km from the fault line adjacent to the first two groups as shown in Fig. 1. Now starting from spot 1, Radon gases (^{222}Rn and ^{220}Rn) at three different depths were generated by inserting soil probe of length 1 m at three different depths, viz. 5 cm, 50 cm and 1 m depths, respectively (Fig. 2b). The instrument was operated in thoron mode with 15-min cycle for all the depths, the operation was done in order of depths and a time of 15 min was spent for each depth. Now the tube connecting between the pump outlet of the instrument and sample outlet of the soil probe was removed, and the sample outlet of the soil probe was closed so that no atmospheric gases may be sampled during the sampling process. By turning *ON* the instrument in thoron mode with 15-min cycle, the built-pump sucks in the sample gas at that particular depth in that particular spot through the tube connecting the sample inlet of the soil probe and sample inlet of the instrument. At the same time, it draws out all the gases which were already counted in the scintillation cell volume through the tube connecting the sample outlet and pump inlet of the instrument and releases to the atmosphere through the opening pump outlet. The gases obtained in thoron mode as discussed above were the sum of ^{222}Rn and ^{220}Rn counts, background counts (^{222}Rn counts), ^{220}Rn concentrations and ^{220}Rn counts (difference of counts and

Fig. 2 Sketch diagram of the experimental set-up of SMART-RnDuo for **a** measurement at continuous monitoring station (CMS) and **b** measurement at the grid (Mat fault) using a soil probe

background counts). After completion of process of generating Radon data at different depths in spot 1, we moved to spot 2 and so on in order of their serial number away from the fault line (Fig. 1) and generated Radon data for three different depths (5 cm, 50 cm and 1 m) at each spot with the same method discussed above.

2.3 Method for selecting peak period and the non-peak period from Radon data monitored at the continuous monitoring station

Radon data generated in the continuous monitoring station at Mizoram University were plotted against the real time. It has been observed that the ^{222}Rn counts rise with

temperature, reach its maximum value and then return back to its minimum value called local minimum for each day during the whole observation period (Fig. 3a). This entire local minimum for each of the day was not equal and distinct in majority of the cases. So, in the present study, the highest local minimum of diurnal variation was sorted out and the average of all the Radon counts below it was taken by using the equation:

$$\frac{\sum_{i=C_{\min}}^{C_{\text{hlm}}} C_i}{n} \quad (2)$$

where C_i is the ^{222}Rn counts, $C_{\min}$ is the lowest ^{222}Rn count, C_{hlm} is the highest local minimum of diurnal variation ^{222}Rn

Fig. 3 Plot of **a** real-time 5-cm-depth ^{222}Rn data monitored at the CMS showing categorisation of in situ generated ^{222}Rn data at Mat fault (represented by vertical dash line on its date of generation) into peak and non-peak period data (indicated by interval of two vertical solid lines) between October 15, 2017 and May 15, 2018, **b** real-time 5-cm-depth ^{220}Rn data monitored at the CMS between October 15, 2017 and May 15, 2018, showing categorisation of in situ generated Mat fault ^{220}Rn data (represented by vertical dash line on its date of generation) into five different groups on the condition that their time of generation belong to the interval

counts and n is the total number of counts below the highest local minimum.

This average ^{222}Rn count was taken as the base count for ^{222}Rn , which is considered the counts of ^{222}Rn in its equilibrium state in the absence of any atmospheric factors and geological process in that measurement region. Now every raise of the ^{222}Rn count is with respect to this base count and is called Radon frequency (count base times of Radon counts). When this Radon frequency remains above a certain value called Radon peak period factor (RPF) for some days, the period is called a peak period indicating a geophysical process in the measurement region. It is a non-peak period (absence of geophysical process) when it remains below the peak period factor for some continuous days. For calculating the Radon peak period factor (RPF) for continuous peaks, the Radon frequency value by the time it starts raising above the normal repeated diurnal peaks and the Radon frequency value by the time it falls back very close to the diurnal peak after remaining above these two values for several days were noted. The same was done for all the other groups of the continuous peak during the measurement period. Now the noted Radon frequency values were averaged, and this average Radon frequency value is taken as the peak period factor which was 1.3 times the base count in the present study and represented by a horizontal line parallel to the X-axis passing through it as shown in Fig. 3a. All the ^{222}Rn data generated at Mat fault during the time when the monitored ^{222}Rn frequencies at the CMS lie above the peak period factor for several days were considered a peak period data (^{222}Rn data generated at the fault by the time of geophysical process as detected by the CMS ^{222}Rn data). Otherwise, they were

taken as a non-peak period data if they were generated by the time when the Radon frequencies were below the peak period factor for several days.

In case of ^{220}Rn data monitored at the CMS, its counts change by intervals while its daily variation, unlike the Radon, was unnoticeable during the whole observation period (Fig. 3b). In each of the respective intervals, the thoron counts were constant until a transition to another interval. Five ^{220}Rn intervals were observed during the whole observation period such that the in situ online generated Mat fault ^{220}Rn data of different depths were also categorised into five groups on the condition that its time of generation at the fault must fall within intervals of the CMS data intervals. Now the average of the generated Mat fault data belonging to each interval was taken and compared with ^{220}Rn data of the CMS.

Meteorological parameters, viz. temperature ($^{\circ}\text{C}$), barometric pressure (mbar), rainfall (mm), relative humidity (%) and wind speed (Kmh^{-1}) were obtained from IMD-Regional Meteorological Centre, Guwahati, Assam (India). Since the meteorological parameters recorded at the two centres were an average of 24 h (1 day); the generated ^{222}Rn and ^{220}Rn data at the CMS and Mat fault were also averaged with 24 h with respect to the meteorological data. For calculating the correlation coefficient excel, 2017 was used.

3 Results and discussion

Radioisotope pair (^{222}Rn and ^{220}Rn) data, at depths of 5 cm, 50 cm, and 1 m from ground surface in nine selected grid locations/spots at Mat fault were generated for six

occasions between November 2017 to April 2018, with the procedure discussed in Materials and Methods section. Field visit dates were: November 16, 2017, December 15, 2017, January 17, 2018, February 27, 2018, March 27, 2018, and April 18, 2018, and were represented by vertical dash line in Fig. 3. After downloading the in situ online generated Radon data of the three depths from the *SMARTRnDuo*, the ^{222}Rn data were separated into two groups, that is, peak period data and non-peak period data, on the condition that their time of generations at the fault belongs to the peak period or non-peak period time of ^{222}Rn data monitored at the CMS. The peak period of ^{222}Rn data generated at the CMS corresponds to the presence of geophysical process, and hence, the non-peak period corresponds to its absence in that region. On the basis of this condition imposed the in situ online generated ^{222}Rn data of November 16, 2017, December 15, 2017, February 27, 2017 and April 18, 2018 belong to the peak period data and that of January 17, 2018 and March 27, 2018 belong to the non-peak period data. The generated ^{220}Rn data at Mat fault were grouped into five with respect to the five counts interval variations of ^{220}Rn data at the CMS, such that the behaviour of ^{220}Rn at the fault and CMS was compared.

3.1 Analysis of the exhalation process for the in situ online generated Mat fault Radon isotope pair data by correlating with their continuous monitoring station data

During the whole observation periods, it was observed that the ^{222}Rn data counts at depths of 5 cm and 50 cm in average were always higher during the peak period than the non-peak period in each of the nine spots as shown in Fig. 4a, b. But in case of 1 m depth, though ^{222}Rn counts were higher in majority of the spots during peak periods, we also observed two cases (Spot 1 and Spot 9) where the ^{222}Rn counts were higher during the non-peak period (Fig. 4c). So, in this study, we observed that ^{222}Rn data generated under control meteorological factors at the CMS 57 km away from the fault line vary exactly in the same manner as that of ^{222}Rn data at 5 cm and 50 cm depths in an active fault (Mat fault) during geophysical processes. But the 1 m depth ^{222}Rn data at Mat fault does not show an exact trend with the CMS data.

On the other hand, ^{220}Rn data generated continuously at the CMS vary intervally, having first, second, third, fourth and fifth intervals between November 1, 2017–November 23, 2017; November 23, 2017–December 25, 2017; December 25, 2017–February 19, 2018; February 19, 2018–March 27, 2018 and March 27, 2018–April 30, 2018, respectively. Such that the ^{220}Rn

data generated at the fault on November 16, 2017, December 15, 2017, January 17, 2018, February 27, 2018 belong to the first interval, second interval, third interval and fourth interval of the CMS data, respectively, while those generated on March 27, 2018 and April 18, 2018 belong to the fifth interval (Fig. 3b). Now, the generated ^{220}Rn were correlated with ^{220}Rn data of the CMS. From Fig. 5a, b, we observed that the 5 cm depth ^{220}Rn data at Mat fault does not show an exact trend with ^{220}Rn data monitored at the CMS, as the third and fourth interval ^{220}Rn data generated at Mat fault deflect from the CMS data variation. Again on comparing the 50 cm depth (Fig. 5c) and 1 m depth (Fig. 5d) Mat fault ^{220}Rn data with CMS ^{220}Rn data (Fig. 5a), the 50 cm depth ^{220}Rn data were exactly in similar trend with the CMS ^{220}Rn data in each of the intervals during the whole observation period. The 1 m depth Mat fault ^{220}Rn data in the fifth interval again did not show the same trend with the CMS ^{220}Rn data, while all the other four intervals correspond exactly with the CMS data. In general, we can say that during this observation period the generated ^{220}Rn data at Mat fault in 50 cm depth exactly vary in the same manner with ^{220}Rn data monitored at the CMS, while at 5 cm and 1 m depth deflect from the CMS data. The correlation of ^{220}Rn data with the geophysical phenomena was neglected as the daily variation of ^{220}Rn data at the CMS at depth of 5 cm was unrecognisable instead varies in an interval fashion which was quite unreliable for studies of the geophysical process.

3.2 Peak period to non-peak period ratios of the ^{222}Rn data and sampling depth profile of ^{222}Rn and ^{220}Rn for the three different depths and their comparison

The ratios of ^{222}Rn peak period and non-peak period data of Mat fault (shown in Fig. 4a–c) in each spot separately were taken for all the three depths as shown in Fig. 6a. The ratio averages from the nine spots for each depth were again taken as shown in Fig. 6b. From Fig. 6b, we found that the variation of ^{222}Rn gas at a depth of 50 cm was most pronounced during the peak period/geophysical process (identified by the CMS data), which was caused by Radon fluctuation due to stress release and other geophysical processes in the earth crust.

In Table 1, it was observed that the ratio of ^{222}Rn to ^{220}Rn counts per minute (Counts m^{-1}) in the three successive sampling depths (5 cm, 50 cm and 1 m) at Mat fault was 0.5, 0.8 and 1.4, respectively. The ratio of ^{222}Rn to ^{220}Rn Counts m^{-1} monitor at the CMS (5 cm depth) located at 75 km away from Mat fault was also found to be 0.8. The observed ratio of the isotope pair and the calculated average counts per minute (Counts m^{-1}) of the two gases

Fig. 4 Plot of in situ online generated ^{222}Rn data for each of the nine spots of the grid at Mat fault between November 2017 and April 2018: **a** average ^{222}Rn counts at depth of 5 cm during peak period and non-peak period of ^{222}Rn data at the CMS, **b** average ^{222}Rn counts at depth of 50 cm during peak period and non-peak period of ^{222}Rn data at the CMS, **c** average ^{222}Rn counts at depth of 1 m during peak period and non-peak period of ^{222}Rn data at the CMS

at each sampling depth reveals that ^{220}Rn concentration was higher at a sampling depth closer to the ground surface (Table 1). It was also observed that ^{222}Rn counts increase gradually with sampling depth [24] while ^{220}Rn counts increase from 5 to 50 cm and then decreases at 1 m depth. Using the calculated average Counts m^{-1} of the two gases at each sampling depth during the study period, the authors estimate the rate with which the two gases change with depth by the equation:

$$\frac{C_i - C_n}{n - i} \quad (3)$$

where i is the i th sampling depth in cm, n is the n th sampling depth in cm successive to the i th sampling depth, C_i

is the observed Counts m^{-1} of ^{222}Rn or ^{220}Rn data at the i th sampling depth and C_n is the Counts m^{-1} of ^{222}Rn or ^{220}Rn at the n th sampling depth.

Using Eq. (3), it was estimated that ^{222}Rn increases with the rate of $3.9 \text{ Counts m}^{-1}\text{cm}^{-1}$ and $3.6 \text{ Counts m}^{-1}\text{cm}^{-1}$ from sampling depths of 5–50 cm and 50 cm–1 m, respectively, with an average of $3.8 \text{ Counts m}^{-1}\text{cm}^{-1}$ from 5 cm to 1 m depth. On the other hand, ^{220}Rn changes from a sampling depth of 5–50 cm with the rates of $2.9 \text{ Counts m}^{-1}\text{cm}^{-1}$ and then changes with the rate of $-0.3 \text{ Counts m}^{-1}\text{cm}^{-1}$ from 50 cm to 1 m (Table 1). Despite having a higher concentration than ^{222}Rn at sampling depth of 5 cm in the CMS as well as at Mat fault, ^{220}Rn anomaly peaks were absent in the CMS while it was observed for

Fig. 5 Plot of in situ online generated ^{220}Rn data at Mat fault between November 2017 and April 2018: **a** ^{220}Rn counts at depth of 5 cm w.r.t the five different interval counts variation of ^{220}Rn data at the CMS, **b** ^{220}Rn counts at depth of 50 cm w.r.t the five different interval counts variation of ^{220}Rn data at the CMS, **c** ^{220}Rn counts at depth of 1 m w.r.t the five different interval counts variation of ^{220}Rn data at the CMS

^{222}Rn . This suggests the absence or lack of enhancement in ^{220}Rn gases from the bottom during geophysical phenomena, which may be due to their small half-life (55.6 s) enabling them to reach the surface during geophysical phenomena. Since no ^{220}Rn peaks were observed for reference at the CMS, correlation of ^{220}Rn data with geophysical phenomena was neglected in the present study. On the other hand, ^{222}Rn data increase with sampling depth [24] and exhibit sharp and noticeable peaks at the CMS. The observed ^{222}Rn peaks were assumed to be only due to geophysical phenomena occurring in the region (see Sect. 3.3) and were correlated with ^{222}Rn data generated at Mat fault.

3.3 Meteorological factors and the isotope pair (^{222}Rn , ^{220}Rn) data

The trend of meteorological parameters versus ^{222}Rn and ^{220}Rn data is shown in Figs. 7 and 8. Details of correlation between meteorological factors and the isotope pair (^{222}Rn , ^{220}Rn) data are given in Table 2. The observed correlations were compared with the findings of Jaishi et al. [17, 18, 20] and Singh et al. [22] at Mat fault and Chite fault (54 km from Mat fault), respectively, and also with other reports.

In case of ^{222}Rn data monitored at the CMS, its correlative coefficient with meteorological factors was very weak (Table 2) except for relative humidity where the correlative

Fig. 6 Plot of **a** peak period to non-peak period ^{222}Rn counts ratio at depths of 5 cm, 50 cm and 1 m below the ground surface for each of the nine spots of the grid at Mat fault, **b** average of peak period to non-peak period ^{222}Rn counts ratio at depths of 5 cm, 50 cm and 1 m below the ground surface of Mat fault

Table 1 ^{222}Rn and ^{220}Rn concentration profile at different sampling depths, their ratio at those sampling depths and estimated rate with which the two gases changes with depth

Location/depth	Average counts per minute (Counts m^{-1})		$^{222}\text{Rn}/^{220}\text{Rn}$ counts ratio
	^{222}Rn	^{220}Rn	
CMS (5 cm depth)	35.4	41.7	0.8
5 cm depth (Mat fault)	113.2	222.0	0.5
50 cm depth (Mat fault)	288.5	354.8	0.8
1 m depth (Mat fault)	467.9	339.4	1.4
Sample gas	Average counts per minute per centimetre (Counts $\text{m}^{-1}\text{cm}^{-1}$)		
	5–50 cm	50 cm^{-1} m	5 cm^{-1} m
^{222}Rn	3.9	3.6	3.7
^{220}Rn	3.0	-0.3	1.3

Fig. 7 Plot of **a** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus air temperature at the CMS (5 cm depth), **b** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus air temperature at Mat fault (5 cm depth), **c** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus air temperature at Mat fault (50 cm depth), **d** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus air temperature at Mat fault (1 m depth), **e** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus pressure at the CMS (5 cm depth), **f** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus pressure at Mat fault (5 cm depth), **g** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus pressure at Mat fault (50 cm depth), **h** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus pressure at Mat fault (1 m depth)

Fig. 8 Plot of **a** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus rainfall at the CMS (5 cm depth), **b** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus rainfall at Mat fault (5 cm depth), **c** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus rainfall at Mat fault (50 cm depth), **d** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus rainfall at Mat fault (1 m depth), **e** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus relative humidity at the CMS (5 cm depth), **f** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus relative humidity at Mat fault (5 cm depth), **g** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus relative humidity at Mat fault (50 cm depth), **h** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus relative humidity at Mat fault (1 m depth), **i** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus wind speed at the CMS (5 cm depth), **j** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus wind speed at Mat fault (5 cm depth), **k** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus wind speed at Mat fault (50 cm depth), **l** $^{222}\text{Rn}/^{220}\text{Rn}$ counts versus wind speed at Mat fault (1 m depth)

strength was -0.3 with ^{222}Rn emission. The observation reveals that ^{222}Rn data monitored at the CMS were negligibly affected by meteorological factors when shaded by insulated materials from all sides. The zero correlation

coefficients of wind speed with ^{222}Rn emission indicate the absence of significant influence on ^{222}Rn emission by wind speed inside the CMS as the change in wind speed was minimised by the shading and hence maintain a uniform

Table 2 Details of correlation of meteorological parameters with ^{222}Rn and ^{220}Rn data generated at the CMS and Mat fault

Meteorological parameters	CMS		5 cm		50 cm		1 m	
	Slope	r	Slope	r	Slope	r	Slope	r
^{222}Rn								
Temperature ($^{\circ}\text{C}$)	-1.7	-0.1	-5.6	-0.2	-8.3	-0.1	5.5	0.1
Pressure (mbar)	3.2	0.1	9.0	0.5	25.7	0.5	24.9	0.4
Rainfall (mm)	-1.1	-0.1	-1.4	-0.3	-4.5	-0.4	-3.4	-0.3
Humidity (%)	-2.0	-0.3	3.5	0.6	7.7	0.5	12.2	0.7
Wind Velocity (Kmh^{-1})	-2.0	0.0	-16.6	-0.8	-39.7	-0.7	-47.4	-0.7
^{220}Rn								
Temperature ($^{\circ}\text{C}$)	15.0	0.4	-18.1	-0.3	27.4	0.4	65.0	0.8
Pressure (mbar)	-19.9	-0.5	-4.8	-0.1	-20.4	-0.6	-39.3	-0.8
Rainfall (mm)	1.0	0.0	-2.0	-0.2	0.2	0.0	3.0	0.3
Humidity (%)	-4.6	-0.3	-7.1	-0.6	-6.9	-0.7	-3.7	-0.3
Wind velocity (Kmh^{-1})	33.4	0.4	1.4	0.0	31.0	0.8	47.8	0.9

speed of wind inside the CMS. Above all, it confirmed the assumption made by the authors in the present study that ^{222}Rn anomaly peaks observed under minimised meteorological factors in the CMS were only due to geophysical phenomena and not by meteorological factors. ^{220}Rn , on the other hand, shows a moderate correlation with meteorological factors except for rainfall where its correlation coefficient with the parameter was zero. In general, it can be concluded that by insulated shading of the CMS the influence of meteorological factors on the emission of the isotope pair could greatly be reduced.

Since the influence of meteorological factors on emission ^{222}Rn was observed to be non-significant and highly reduced for ^{220}Rn data monitored at the CMS. Inclusion of the isotope pair data monitored at the CMS might hamper in observing the real correlation with meteorological factors and might be excluded. So for displaying the influence of meteorological factors on the emission of ^{222}Rn and ^{220}Rn gas in the region, only the isotope pair data generated at Mat fault were considered.

The 24-h averaged ^{222}Rn data generated at Mat fault has a very weak negative correlation coefficient (-0.1) with air temperature at depths of 5 cm and 50 cm, while the two parameters show a weak positive correlation (0.1) at a depth of 1 m from the ground surface. The weak reverse correlation between the above two parameters was also observed by Jaishi et al. [17, 18] at a depth of 80 cm in the same fault. At the same time, Singh et al. [22] measuring ^{222}Rn data at Chite fault (54 km from Mat fault) and several authors [25–29] observed a positive correlation between the two parameters. ^{220}Rn data generated at Mat fault on the other hand exhibit a moderate negative and positive correlation with temperature at depths of 5 cm (-0.3) and 50 cm (0.4), respectively, but at a depth of 1 m from the ground surface the two parameters exhibit a strong positive correlation coefficient of 0.8 . The moderate reverse

correlation between ^{220}Rn and temperature was also observed by Jaishi et al. [17] in the same fault at 80 cm depth from the ground surface, while it was observed at 5 cm depth in the present study. In another report, Jaishi et al. [18] also observed a non-significant positive correlation between the two parameters at the same measuring depth and location. In general, it can be concluded that the emission of ^{222}Rn gas at Mat fault has a very weak correlation with temperature, while ^{220}Rn seems to have a moderate correlation with temperature.

Barometric pressure exhibits a moderate positive correlation with ^{222}Rn data at Mat fault in all the three successive sampling depths with a correlation coefficient of 0.5 , 0.5 and 0.4 , respectively, but show a weak and strong reverse correlation (-0.1 , -0.6 and -0.8) with ^{220}Rn data in the three respective successive sampling depth. The observation contradicts the observation of Singh et al. [22] studying at Chite fault and other investigators [25, 26, 28, 30–32] where ^{222}Rn concentration was supposed to decrease due to the pumping effect of atmospheric pressure. Though a reverse correlation was observed between pressure and ^{220}Rn emission in all the sampling depths, the observed positive correlation between pressure and ^{222}Rn was currently not understood by the authors with the presently available data. Generation of data is in progress, and the authors hope to explain the reason in the upcoming report as it could possibly be the local characteristic of the study area.

A moderate reverse correlation was observed between rainfall and ^{222}Rn data at Mat fault in all the three successive sampling depths with respective correlation strength of -0.3 , -0.4 and -0.3 . The finding was in accordance with observation reported by Jaishi et al. [17, 18] and by some other authors [26, 28]. Singh et al. [22] studying in the same area (54 km from Mat fault) observed a positive correlation between the two parameters where they

suggested capping effect [27, 31, 33, 34] due to a mild rainfall hindered the exhalation process of ^{222}Rn gas to the atmosphere. ^{220}Rn data at Mat fault with rainfall show a weak negative correlation (-0.2) at 5 cm depth, zero correlation at 50 cm depth and a moderate positive correlation (0.3) at 1 m depth. The weak negative and moderate positive correlation of rainfall with ^{220}Rn emission was already reported by Jaishi et al. [17, 20] at depths of 80 cm in Mat fault in two separate reports.

Relative humidity shows a strong and moderate positive correlation coefficient (0.6 , 0.5 , 0.7) with ^{222}Rn emission in all the three respective sampling depths at Mat fault. The positive correlation between the two parameters has been reported by Jaishi et al. [18] at Mat fault and Singh et al. [22] at Chite fault. Increase in moisture content of the soil increases emanating power of ^{222}Rn into the soil pore, hinders adsorption of ^{222}Rn gas on the material surface and results in active transport of ^{222}Rn on water molecule [35]. A moderate reverse and strong correlation (-0.3 , -0.6 and -0.7) was observed between humidity and ^{220}Rn emission at the three respective successive sampling depths at Mat fault. This finding was in accordance with Guedalia et al. [36] where they observed increased soil moisture and decreased ^{220}Rn emission within 5 cm soil depth but contradict the observation made by Jaishi et al. [17, 18] at Mat fault.

A strong reverse correlation was observed for wind speed and ^{222}Rn concentration at Mat fault with relative strength of -0.8 , -0.7 and -0.7 at depths of 5 cm, 50 cm and 1 m, respectively. The speeding wind was found to remove ^{222}Rn gas in the upper surface of the soil, hence decreasing its concentration [27, 29, 30], while Singh et al. [26] and Virk and Singh [28] reported the opposite. The observed correlation strength for wind speed and ^{220}Rn concentration was 0 , 0.8 and 0.9 at the above respective mention sampling depths at Mat fault. The absence of correlation between wind speed and ^{220}Rn emission at depth of 5 cm in Mat fault supports the observation made by Guedalia et al. [36] where they observed for a wind circulated at the speed of $0.02\text{--}0.05\text{ ms}^{-1}$ using a circulating pump which has no influence on ^{220}Rn emission at the ground surface.

The influence of meteorological factors on the emission of ^{222}Rn and ^{220}Rn for the three sampling depths at Mat fault can be generalised as follows: the influence of air temperature on emission of ^{222}Rn is negligible but shows effective influence on emission of ^{220}Rn . Barometric pressure and relative humidity moderately tend to raise ^{222}Rn concentration but tend to decrease the ^{220}Rn concentration. Rainfall moderately tends to lower ^{222}Rn emission and shows the same effect on ^{220}Rn at the surface. Wind speed strongly tends to lower ^{222}Rn concentration, while it shows a reverse effect for ^{220}Rn concentration.

4 Conclusion

The Radon (^{222}Rn , ^{220}Rn) exhalation process studies reveals that ^{222}Rn data continuously monitored at depth of 5 cm below the ground surface in a continuous monitoring station (CMS) correspond to it and vary in the same manner as that of ^{222}Rn data generated at depths of 5 cm and 50 cm below the ground surface in an active fault (Mat fault) during geophysical and non-geophysical processes. The absence and presence of geophysical phenomena were identified from the CMS data. But the 1 m depth Mat fault ^{222}Rn data show no definite correlation with the CMS data. The influence of meteorological factors on ^{222}Rn data monitored at the CMS were observed to be non-significant except for relative humidity, confirming that the observed ^{222}Rn anomaly at the CMS was only due to geophysical phenomena. This implies that ^{222}Rn data monitored at Mizoram University response to geophysical phenomena occurring in the region like those measured at depths of 5 cm and 50 cm in an active fault (Mat fault) with sharp and noticeable ^{222}Rn spikes and vice versa. Hence, it could be a suitable location for permanent set-up of continuous monitoring station for ^{222}Rn signal studies. We also observed that the ratio of peak period to non-peak period ^{222}Rn data was highest at 50 cm depth in Mat fault showing the best sampling depth for observing ^{222}Rn fluctuation during geophysical phenomena. The 5-cm-depth CMS ^{220}Rn data changes intervally which made it difficult for correlation with geophysical studies; its variations exactly were in analogous with the 50-cm-depth Mat fault ^{220}Rn data. While the 5-cm- and 1-m-depth ^{220}Rn data of Mat fault did not show an exact similar trend with the CMS data during the observation period. The correlation studies of meteorological factors with ^{222}Rn and ^{220}Rn data at Mat fault show that finding was highly in accordance with the observation made by Jaishi et al. [17, 18, 20] at depths of 80 cm in Mat fault but contradict the finding of Singh et al. [22] except for humidity at Chite fault located at 54 km from Mat fault.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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