Anomalous soil radon fluctuations – signal of earthquakes in Nepal and eastern India regions

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The present paper deals with pre-seismic soil radon-222 recorded at two different locations 200 m apart, at Jadavpur University main campus, Kolkata, India. Solid state nuclear track detector method is used for detection of the radioactive radon gas. Two simultaneous 4-month long time series data have been analysed. Anomalous fluctuations in the radon datasets have been observed prior to recent earthquakes in Nepal and eastern India during the monitoring period, mainly, the massive 25th April 7.8 M Nepal earthquake. The simultaneous measurements assist in identifying seismogenic radon precursor efficiently.

1. Introduction

Earthquake is basically a large scale fracture phenomena, which causes tremendous devastation and loss of life. For enabling people to minimise such a loss of life and property, it is necessary to predict a potentially damaging earthquake. Over the last few decades, enormous efforts have been put forward, all over the world, to search for a possible precursory signal of an impending earthquake. Various methods have been adopted in monitoring different non-seismic parameters of both geophysical and geochemical in nature. Among all other methods, radon gas monitoring as a pre-seismic geochemical signal has been proved to be very promising due to various advantages in its detection, as well as its direct connection with the highly deformed tectonic region.

2. Efficacy of radon-222 as earthquake precursor

Radon (Rn^{222}) is an inert radioactive (alpha active) gas produced by the decay of radium, in the uranium

decay series. Radon gas, generated in rocks, remains partly in the solid matrix, but some move to pore fluids and migrate away through interconnected pores and aquifers by the method of diffusion and fluid flow. Tectonic deformation changes lead to changes in rock pressures and fluid convective flows. Prior to an earthquake, the build-up stress causes a change in strain field also. Deformation of rock mass under the tectonic stress opens up various pathways, and new surfaces become exposed when cracks open. The strain developed within the earth's crust before an earthquake leads to gas transportation and causes the rise of gases from the deep earth to the surface (Fleisher and Mogro-Campero 1978; Thomas 1988; Fleischer 1997). Several *in-situ* laboratory experiments have been performed and mathematical models have also been proposed by Clements (1974); Schery *et al.* (1984); Schery and Siegel (1986); and Holford *et al.* (1993). Reddy *et al.* (2006) have done significant work on the radon emanation process. However, the origin and mechanism of the radon anomalies and their relationship to earthquakes are not fully understood yet. Number of attempts have been made

Keywords. Geochemical; soil radon-222; earthquake; solid state nuclear track detector; time series.

worldwide to establish radon anomalies in soil (King 1980; Mogro-Campero *et al.* 1980; Reddy *et al.* 2004; Miklavčič *et al.* 2008; Ghosh *et al.* 2009), ground water (Hauksson 1981 and references therein, Virk and Singh 1993), hydrothermal system (Das *et al.* 2006; Chaudhuri *et al.* 2011) and mud-volcano (Chaudhuri *et al.* 2012), as precursors for earthquakes. The anomalous emission of radon-222 correlated with geophysical events may be considered as having two possible origins; either it is produced in-depth origin, or, once produced locally, it is transported by other terrestrial fluid motion triggered by geodynamical events. Both the two popular models, i.e., (i) the IPE model put forward by the Soviet scientists at the Institute of Physics of Earth (Mjachkin *et al.* 1972; Brady 1974; Mogi 1974; Stuart 1974) and (ii) the dilatancy–diffusion model by US scientists (Scholz *et al.* 1973; Mjachkin *et al.* 1975), extensively describe the physics behind the precursory features of radon in hydrothermal system, as well as sub-surface soil gas during the earthquake preparation phase. On the other hand, according to the compression mechanism proposed by King (1978), the anomalous radon concentration may be induced due to an increase in crustal compression that squeezes out the soil-gas into the atmosphere at an increased rate prior to an earthquake. Radon anomalies have been observed at larger distances from the earthquake epicentre, resulting from changes in the immediate vicinity of the monitoring station, rather than at the distant focal region. This is accomplished if it is assumed that changes in stress or strain are propagated from the rupture zone to the radon monitoring station, leading to variations in soil porosity–permeability, along with the groundwater flow rate near the radon monitoring station (King 1978). Considering the worldwide data set of 91 radon anomalies, Hauksson (1981) reported that radon anomalies occur at greater epicentral distances for earthquakes of larger magnitude, and the precursor time increases with the magnitude of the earthquake, but decreases with the distance between the epicentre and the radon monitoring station. Several empirical earthquake forecasting relations relating place, precursor time and magnitude of an earthquake are discussed in Ghosh *et al.* (2009) and Chaudhuri *et al.* (2011). However, while studying such anomalous radon fluctuations, one should keep in mind the fact that concentration of radon also changes significantly due to changes in meteorological parameters like atmospheric pressure, temperature, humidity, rainfall, etc. (Tanner 1964; Baykut *et al.* 2010). Hatuda (1953) performed an investigation on monitoring radon at an active fault zone for two years in Japan. He measured the radon concentration in soil

gas and reported anomalous radon concentration changes prior to the strong earthquake of magnitude M8.0 that occurred at Tonankai. Since then, the study of radon anomaly in sub-soil gas, thermal spring and ground water has been undertaken significantly by researchers all around the globe. Fleischer and Mogro-Campero (1985) reported their results associating soil radon anomalies with earthquakes in Alaska as well as in north-eastern United States. In Taiwan, Walia *et al.* (2005a) and Yang *et al.* (2005) carried out a study on the variation of radon-222 in sub-soil gas on a continuous basis and obtained encouraging results, which are of immense importance towards the prediction of earthquakes. Ulomov and Mavashev (1971), Sultankhodzhayev *et al.* (1976), Mogro-Campero *et al.* (1980), Linpei (1994) in China, Igarashi and Wakita (1990) in Japan, Segovia *et al.* (1995) in Central America and Mexico, Planinic *et al.* (2000) in Croatia studied the temporal variation of soil radon-222 concentration in search of earthquake precursory signal.

Several authors or investigators in different parts of India are also involved in radon fluctuation studies for earthquake prediction. Precursory phenomena of radon in earthquake sequence were observed at Osmansagar reservoir, Hyderabad, during January–February 1982 (Rastogi *et al.* 1987). In N–W Himalaya, Walia *et al.* (2003, 2005b) have found a strong relationship between radon anomalies with seismic parameters. Das *et al.* (2006) observed a distinct increase in radon-222 concentration in Bakreswar thermal spring gas prior to the great Indonesia tsunami in 2004 generated due to a 9.1 magnitude earthquake. Ramola *et al.* (2008) reported their earthquake precursor study associating soil as well as groundwater radon measurement. Barman *et al.* (2015) observed a pre-seismic signature in sub-soil radon gas in the lesser Himalayan region at an altitude of 800 meters above mean sea level. Reddy *et al.* (2010) performed continuous soil radon in the Koyna–Warna region, near the west coast of India to study reservoir-triggered earthquakes in that area.

The present group has been monitoring sub-soil radon gas in the Bengal basin for the last 10 years and has reported several radon anomalies prior to earthquakes that occurred within a 1000 km radial zone, centring Kolkata (Ghosh *et al.* 2007, 2009, 2012). Soil radon investigations were performed earlier using a single time series data. Radon emanation out of soil grains and its transport through interstitial spaces is affected appreciably by soil moisture content. To observe coherent responses, if any, this paper presents soil Rn²²² concentration profiles measured simultaneously at two nearby (~200 m apart) locations, A and B, having uniformly clayey soil, within the Jadavpur University premises (22.5667°N, 88.3667°E). Soil

moisture content at location A was lower, although location B was close to a pond, where the moisture content in the soil was relatively high. Simultaneous recording of radon time series at these two locations, it was expected, would add confidence in identifying pre-seismic responses. An attempt is made to examine anomalous fluctuations in the experimental data during the observation period March–June, 2015, with earthquake occurrences in eastern India, including Nepal, as shown in figure 1, to obtain correlations. The obtained data is expected to add useful information in the direction of soil radon responses preceding regional earthquakes.

3. Location and geology of the study area

Jadavpur is a southern neighbourhood of Kolkata metropolis, resting on the east bank of river Hooghly, on the lower Ganges Delta of eastern India. The entire region is positioned over the Bengal Basin,

one of the most extensive sediment reservoirs in the world and constitutes the lower floodplain and delta plain deposits of India and Bangladesh, at the mouth of the Ganga–Brahmaputra–Meghna River systems (Alam *et al.* 2003; Roy *et al.* 2010). Krishna *et al.* (2016) reported that the sedimentary pathways are an emergence of Himalayan source material in the Bengal Basin in greater detail. Due to the location of the basin at the juncture of three interacting plates, viz., the Indian, Burma and Tibetan (Eurasian) Plates, the basin-fill history of these geotectonic provinces varied considerably. The hinge zone and the shelf area are traversed by many faults, some of which may be tectonically active, at present.

The hinge zone is about 25 km wide and occurs at a depth of about 45,000 m, below Kolkata. The major fault systems in this region are the Garhomoyana–Khandaghosh Fault (GKF), Jangipur–Gaibandha Fault (GGF), Pingla Fault, Eocene Hinge Zone (EHZ), Debagram Bogra Fault (DBF), Rajmahal Fault (RF), Dauki Fault (DF),

Figure 1. Map indicating the monitoring sites in Kolkata and the earthquakes ($M \geq 5.0$) within 1000 km radial region centring Kolkata during the observation period from March 1 to June 30, 2015.

Sylhet Fault (SF), Sainthia Bahmani Fault (SBF), and Dhubri Fault (DHF) (Shiuly and Narayan 2012). This tectonic setting is shown in the geological map (figure 2). The total sedimentary thickness below Kolkata is of the order of 7500 m above the crystalline basement of this, the top 350–450 m is Quaternary, followed by 4500–5500 m of Tertiary sediments (Bhattacharya *et al.* 2012).

4. Experimental methods

The track etch method has been adopted here for radon monitoring. In our case, we have used CR-39 plate – a useful solid state nuclear track detector

Figure 2. Seismotectonic map of Kolkata city and surrounding region.

(SSNTD) for registering the alpha tracks generated from soil radon gas at both locations (locations A and B). A plastic cup of dimension 4.7 cm in height, 6.3 cm diameter at the open end and 5.9 cm diameter at the closed end is used for taping the CR-39 plate with a double-sided tape. A CR-39 plate of nearly square shape is attached at the lower closed end of the cup and the open face is covered with a semi-permeable membrane (figure 3). Except for radon-222, this membrane does not allow any other gas, water vapour or other radon progeny to enter into the cup. A metal container with its upper and lower face open is placed inside a hole of 70 cm deep below the earth surface. The metallic container with its two open faces is kept permanently in the experimental hole. The prepared plastic cup is placed within the metallic container in such a way that the open face, covered by the membrane, faces the earth's surface. The separation between the earth's surface and the covered cup surface is kept at nearly 1 cm with the help of two supports in order to avoid tearing of the membrane. To absorb excess moisture, some silica gel is kept surrounding the cup inside the hole. To reduce the influence from external atmospheric ^{222}Rn flow, the upper face of the metallic container is covered with a metallic lid. The upper end of the metal container remains almost in the same level of the ground surface. A schematic diagram of the experiment setup is shown in figure 3.

The CR-39 plate is kept uninterrupted under such conditions for one day (24 hrs). Once exposed, the plate is replaced by a new one following the same procedure. To enlarge the registered alpha tracks for making them visible under a microscope, the exposed plates are chemically etched in 6N NaOH solution at 70°C for 6 hrs. The temperature of the solution is maintained uniform throughout etching duration. The etched plates are washed under cold water for 20 min. The total number of registered tracks in the dried plates is counted with

Figure 3. Experimental arrangement for radon-222 monitoring.

Figure 4. (a) Combined graph for radon-222 anomalies at location A and the corresponding earthquakes (upper panel); meteorological parameters (ambient temperature, pressure, relative humidity and rainfall) recorded during March 1 to June 30, 2015 (consecutive lower panels). (b) Combined graph for radon-222 anomalies at location B and the corresponding earthquakes (upper panel); meteorological parameters (ambient temperature, pressure, relative humidity and rainfall) recorded during March 1 to June 30, 2015 (consecutive lower panels).

the help of a Carl-Zeiss Microscope with 10× ocular lens. Finally, the track density, i.e., count/cm², which is a measure of radon count is calculated for each plate.

5. Experimental results and discussions

The time series of soil radon concentration during March 1–June 30, 2015, at the two nearby monitoring sites were generated by the experimental technique described in the previous section. These two simultaneous datasets of locations A and B are presented in figure 4(a, b). During 4-month observation period from March 1 to June 30, 2015, the variation of local meteorological parameters (such as temperature, pressure, humidity and rainfall, shown in figure 4(a, b) lower panels) did not change significantly so that they can introduce seasonal changes in the soil radon emanation process. This is clearly visible in both the radon time series in figure 4(a, b).

To identify statistically significant radon anomaly, we have calculated average as well as standard deviation (σ) for the entire dataset. The solid lines in figure 4(a, b) indicate the average radon concentration ($\bar{A}_v$) and the dotted lines present $\bar{A}_v \pm n\sigma$ (where $n = -1, +1, 2$). In the present study, fluctuation beyond ($\bar{A}_v \pm 2\sigma$) is considered as an anomaly, as also observed by several authors such as King (1980), Ghosh *et al.* (2009, 2011), Chaudhuri *et al.* (2011). According to the above-mentioned definition of anomaly, four statistically significant anomalies are obtained on 20 April, 29 April, 19 May and 29 May, 2015, simultaneously at both locations A and B, during the observation period. However, on 12 May 2015, anomalous fluctuation beyond 2σ was recorded only at location B. With an aim to find out the source of these

anomalies, their earthquake source region connection is investigated here in the present paper. However, a correlation between earthquakes of any magnitude, at any epicentral distance from the measuring site, and geochemical radon anomaly is not expected. In other words, the zone of influence of an earthquake, where it can generate its precursory signal, is restricted in view of its magnitude and epicentral distance. In this aspect, two well-known models relating to earthquake magnitude (M) and maximum radial distance (D_m) up to which it can cause geochemical changes are provided by Dobrovolsky *et al.* (1979) and Fleischer and Mogro-Campero (1985).

According to the first model, the relation between the earthquake magnitude (M) and the maximum radial distance (D_m in km) at which radon anomaly can be significantly detected by pre-seismic effects is given by,

$$D_m = 10^{0.43M}, \quad M \geq 3. \quad (1)$$

On the other hand, considering the second model, the above relation is replaced by the following (Fleischer and Mogro-Campero 1985; Chaudhuri *et al.* 2011):

$$D_m = 10^{0.48M}, \quad M \geq 3. \quad (2)$$

Primarily, all moderate to large earthquakes of magnitude $\geq M5.0$, which are causes of concern due to their potential for destruction within 1000 km radial zone centering the monitoring sites at Kolkata, are considered. Details of these earthquakes are taken from the India Meteorological Department and the United States Geological Survey websites during the observation period. Four such events along with their seismic parameters are listed in table 1.

Table 1. Details of the radon-222 anomalies observed and the earthquakes that occurred during the observation period from March 1 to June 30, 2015.

Sl. no.	Date of EQ	EQ location	Magnitude (M)	Depth (km)	Location	Date of radon anomaly	Precursor time (day)	Epicentral distance (km)	Max. radius of influence (km) Dobrovolsky model	Max. radius of influence (km) Fleischer & Mogro-Campero model
1	25/4/2015	28.1°N; 84.6°E	7.8	10	A	20/4/2015	5	722	2259	6194
					B	20/4/2015	6			
2	26/4/2015	27.3°N; 88.1°E	6.9	10	A	20/4/2015	6	612	927	2015
					B	20/4/2015	13			
3	12/5/2015	27.7°N; 86.0°E	7.3	10	A	29/3/2015	13	618	1377	3191
					B	29/4/2015	29			
4	28/6/2015	26.5°N; 90.1°E	5.6	10	A	29/5/2015	29	470	256	488
					B	29/5/2015	29			

According to equation (1), three earthquakes ($M \geq 6$) in table 1 (Sl. nos. 1, 2 and 3) can cause anomalous fluctuation in radon concentration profile at the present monitoring site. Whereas, all the four earthquakes, including the M5.6 event, in table 1, occurred within the earthquake preparation zone according to the second model. Interestingly, the devastating 25 April 2015, Nepal earthquake (Sl. no. 1 in table 1) of magnitude M7.8 has shown a precursor before five days on 20 April 2015, at both locations A and B. On the very next day (26 April 2015), another earthquake of magnitude M6.9 occurred again in Nepal. No separate radon anomaly was recorded at any of the two locations. It may be noted that the separation distance between the two earthquakes on 25th and 26th April, 2015, is only 110 km. Thus, this earthquake (of magnitude M6.9) is considered as an aftershock of the previous earthquake of magnitude 7.8M (Mitra *et al.* 2015). Additionally, there were other several aftershocks of magnitude $\geq M5.0$, with similar source mechanisms, in next few days (Mitra *et al.* 2015). In the present study, all these aftershocks are kept aside and only the mainshock is taken under consideration. Again, radon anomalies (at both locations) on 29 April 2015 were observed 13 days prior to the M7.3 earthquake on 12 May 2015 (Sl. no. 3 in table 1) in Nepal. The earthquake (Sl. no. 4) of magnitude M5.6 in table 1 occurred at Kokrajhar, Assam, on 28 June 2015. Prior to this pre-seismic event, a radon signal appeared 29 days on 29 May 2015.

We found radon fluctuation $>2\sigma$ on 12 May 2015, only at location B and interestingly no earthquake of magnitude $\geq M5.0$ occurred within a distance according to both the models. The appearance of this single location anomaly may be considered as spurious pulse, which may be generated out of experimental limitations. Therefore, possibility of impending earthquake of considerable magnitude may be ruled out in the case of a single site radon anomaly unlike our earlier report (Ghosh *et al.* 2007) where some unusual radon anomalies ($>2\sigma$ to 3σ) were presented without any prominent seismic correlation. Again, radon fluctuation of magnitude $>2\sigma$ was registered on 19 May 2015 at both locations A and B. But after these radon anomalies, no earthquake occurred within 1000 km radial region centring the monitoring site in Kolkata. These 19th May anomalies may be caused due to other unknown parameter influencing the sub-soil radon emanation process. Further study for a longer period with statistical analysis of a large number of dataset is highly required for the explanation of all discrepancies present in the pre-seismic radon signal.

6. Conclusion

Monitoring of pre-seismic geochemical radon signal at Kolkata in Bengal Basin has been observed successfully. Radon anomalies followed by moderate to large earthquakes fit well in the maximum zone of influence model provided by Fleischer and Mogro-Campero (1985) in the region under study. Although, the Dobrovolsky *et al.* (1979) model worked perfectly for higher magnitudes, it may not be suitable for consideration in the case of the moderate size earthquakes, here in Kolkata in the Bengal basin, for the purpose of pre-seismic geochemical monitoring. Simultaneous anomalies at both the locations A and B are precursors of earthquakes in most cases. The present study lies in the fact that detection of genuine radon anomaly due to seismicity becomes more efficient by simultaneous measurement of soil radon concentration at two nearby locations. Finally, this data will add new information towards the pre-seismic geochemical research activity.

Acknowledgements

The authors acknowledge the financial support from UGC under UPE-II program. They are thankful to Mr Sadananda Pramanik, Lab Assistant, Biren Roy Research Laboratory for Radioactivity and Earthquake Studies, Jadavpur University, for his active support. CB is grateful to Prof. Bikash Sinha and Dr Debasis Ghose for their inspiration in carrying out this work.

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MS received 22 March 2016; revised 10 August 2016; accepted 25 August 2016

Corresponding editor: N V CHALAPATHI RAO