Journal of Radioanalytical and Nuclear Chemistry (2019) 319:23–32
https://doi.org/10.1007/s10967-018-6286-2

Study of variation of soil radon exhalation rate with meteorological parameters in Bakreswar–Tantloi geothermal region of West Bengal and Jharkhand, India

Saheli Chowdhury[1,2] · Chiranjib Barman[3] · Argha Deb[1,2] · Sibaji Raha[3] · Debasis Ghose[3]

Received: 2 July 2018 / Published online: 30 October 2018
© Akadémiai Kiadó, Budapest, Hungary 2018

Abstract
Radon gas is the predominant ionizing radiation on earth. Its occurrence is controlled by the presence of uranium in all types of rocks in the earthcrust, apart from local geological features and atmospheric factors which influence its release into the atmosphere. The present work deals with 24 h observation of the dependence of radon exhalation rate from soil on local meteorological parameters at four locations in Bakreswar–Tantloi geothermal region, located in the highly faulted Chhotanagpur Plateau of eastern India. This study is the primary step towards the determination of soil radon exhalation dynamics in this geothermal area.

Keywords Soil^{222}rn exhalation rate · Meteorological parameters · Geothermal region

Introduction

Radon is a radioactive noble gas produced by alpha decay of radium in the natural radioactive decay chains in the earth's crust. Of the 39 isotopes of radon, ^{222}Rn, the progeny of ^{226}Ra by α-decay, is most abundant in our environment due to its comparatively longer half-life of 3.82 days. A fraction of ^{222}Rn produced in the crust enters into the air-filled pore spaces in soil by diffusion or by alpha recoil. This process is called radon emanation. As diffusion coefficient of gases in dry soil is less than two metres, and it decreases as the soil type changes from dry to moist and clayey [1], it may be assumed that a significant part of radon emanation occurs due to recoil between ^{222}Rn atoms and α-particles produced by decay of ^{226}Ra. The emanated radon can migrate away from its site of production, either by advection along joints, faults and intergranular pathways in the crust, or being carried by carrier gases like carbon dioxide, methane, etc. or by groundwater circulating deep inside the crust, and can eventually reach the surface layers of soil [2–4]. A part of this radon is finally exhaled into the atmosphere before decay.

The process of emission, migration and exhalation of radon is very complex; subjected to several geophysical and geochemical factors including average uranium concentration in rocks and sediments [5], local geology such as presence of faults and shears [6–8], soil composition and structure like grain size, porosity and permeability [9–11], and prevalent atmospheric and weather conditions including air temperature, atmospheric pressure, wind flow and precipitation [12–17]. ^{222}Rn exhalation from soil, rocks, building materials, etc. has been studied extensively all over the world due to the negative impact of radon on human health [18, 19]. Moreover, the release of radon gas from soil as well as from hydrothermal systems has been studied globally over the last few decades as an important precursor of earthquakes [20, 21]. But in most of the radon exhalation studies, soil or rock samples were collected from sites and exhalation rates were measured in

✉ Saheli Chowdhury
sahelichowdhury2492@gmail.com;
sahelichowdhury.rs@jadavpuruniversity.in

1 School of Studies in Environmental Radiation and Archaeological Sciences, Jadavpur University, 188 Raja S.C. Mallick Road, Kolkata 700032, India

2 Department of Physics, Jadavpur University, 188 Raja S.C. Mallick Road, Kolkata 700032, India

3 Centre for Astroparticle Physics and Space Science, Bose Institute, College More, Block-EN, Sector-V, Bidhannagar, Kolkata 700091, India

laboratories [5, 22–26]. Hence, such studies do not take into account the meteorological factors affecting the exhalation rates at the sites or their daily and seasonal variations. Again, some workers have performed short-term and long-term in situ measurements of radon exhalation from soil, but there is considerable confusion and argument regarding the influence of meteorological and soil parameters on radon exhalation rate. One of the earliest in situ radon exhalation studies was by Kraner [27], who reported influences of wind and rainfall on radon exhalation rates from soil. Moses et al. [12] and Pearson and Moses [13] studied the effect of wind velocity on radon exhalation and vertical distribution of radon in the environment. Fleischer et al. [28] observed temporal variation of radon emanation at a site of uranium deposits. Singh et al. [29] studied the time variation of soil radon emanation with meteorological parameters for one year at a non-mineralised site, and observed positive correlation of radon exhalation from soilwith temperature and wind velocity, and weak negative correlation with rainfall, humidity and atmospheric pressure. Walia et al. [7] conducted a study of variation of radon concentration in soil and groundwater along the main boundary thrust of north-western Himalayas, whereas Vaupotič et al. [30] observed soil radon exhalation rate along the Ravne fault in Slovenia, but their works were mainly concerned with the effect of seismicity and local geological features on soil radon exhalation. Ashok et al. [16] observed radon exhalation rate from soil continuously for one year in Bangalore city, India, and Zhang et al. [31] carried out similar one year study in the city of Beijing, China. Both studies reported higher radon exhalation rates during night and early morning hours when air temperature was low and lower exhalation rates when air temperature peaked in the afternoon. According to Kojima and Nagano [14] who studied the dependence of soil radon exhalation rate on environmental factors in Tokyo, radon exhalation rate shows poor correlation with atmospheric pressure but is considerably affected by rainfall. They observed significant reduction in radon exhalation from soil during heavy rainfall, and after rain the exhalation rate was found to increase gradually. When water content of soil became higher than 35% by volume, radon exhalation rate from soil was found to decrease with increasing water content, whereas at soil water contents lower than 35%, radon exhalation rate decreased with decreasing water content. The authors concluded that lower radon exhalation rates at very high soil water content may be due to capping effect at ground surface caused by heavy rainfall, and reduction of soil permeability due to the presence of huge amount of moisture. Radon emanation coefficient, and hence radon exhalation rate from soil, is highest at moderate soil moisture content (around 35% by volume). Kulali et al. [11], who studied the effect of meteorological parameters on radon exhalation from soil during different seasons in Karahayıt region of Turkey, have reported similar observation regarding the relation between soil radon exhalation and rainfall. Various authors have observed positive correlation between atmospheric pressure and radon exhalation from soil [32–34]. Sahoo et al. [17] have reported negative correlation of soil radon exhalation rate with air temperature and positive correlations of soil radon exhalation rate with relative humidity and atmospheric pressure in their study on temporal variation of radon exhalation from soil with meteorological parameters and seismic activities in Kutch region of western India.

In the present work, diurnal variation of radon exhalation rate from soil with a few meteorological parameters has been studied in situ at four locations in Bakreswar–Tantloi geothermal region of the states of West Bengal and Jharkhand, India. Soil gas, as well as groundwater of this region contains large concentration of radon [35–37]. For comparison, similar measurements were conducted at one location in Kolkata, West Bengal. This spot, 170 km away from Bakreswar, is in the campus of Jadavpur University, Kolkata. The geological setting of this region is completely different from that of Bakreswar because Kolkata is located in a non-geothermal region, in the alluvial plain of the Ganga Basin.

Bakreswar–Tantloi region experiences several incidents of lightning and thunder throughout the year. It has been reported by several workers that radon emission from the earth's crust is related to the atmospheric global electric circuit (GEC) and formation of thunderclouds and occurrence of lightning flashes [38, 39]. High levels of radioactivity in regions of high soil radon exhalation can cause increased charging of the GEC, which leads to enhanced thunderstorm activity. We have proposed to set up a monitoring station for study of interrelation between soil radon emission and occurrence of thunder and lightning in Bakreswar–Tantloi region. The aim is to monitor how increased electrical conductivity of the local atmosphere caused due to higher volume of radon in air leads to enhanced occurrence of lightning and thunder conditions in this region. The present work has been undertaken in order to determine the meteorological and seasonal influences on soil radon exhalation in the region of study, which is a first step towards this goal.

Geology of the study area

Bakreswar–Tantloi geothermal region is located along the extreme eastern fringe of the Son-Narmada-Tapti (SONATA) lineament, the mega mid-continent lineament extending from Gujarat in the west to West Bengal in the east (Fig. 1a) [40, 41]. This region geologically belongs to the Archaean Chhotanagpur Gneissic Complex (CGC) which is composed of Precambrian granites and gneisses, Gondwana sedimentary rocks and Rajmahal volcanic rocks [42, 43]. The basement is predominantly composed of granite and gneiss with minor enclaves of calc-silicate, amphibolite, gabbro, pegmatite and dolerite belonging to Pre-Cambrian CGC. The gneiss and calc-silicate are regionally folded to form asymmetric anticlinical and synclinical structures trending NE–SW [44]. The Chhotanagpur Plateau experienced a series of fissure eruptions over years during Rajmahal volcanic activity in early Cretaceous age [44, 45]. Therefore, Bakreswar–Tantloi region is criss-crossed by a number of fractures and faults, most of which are partly or fully buried by sediments or silica. The distribution of faults and fractures in this region has been shown in Fig. 1b. The average crustal thickness of this region is about 23 km [41]. This geothermal area is characterized by high crustal heat flow of 230 mW/m^2 [46]. There are seven hot springs in Bakreswar (23°52'30" N, 87°22'30" E) in Birbhum district of West Bengal and four in Tantloi (24°02'25"N, 87°17'30"E) in Dumka district of Jharkhand. All these make Bakreswar–Tantloi geothermal region an ideal spot for study of radon emanation from the earth crust.

Experimental method

Radon exhalation rate from soil was measured with AlphaGuard PQ 2000 PRO radon monitor and AlphaPump together with a radon exhalation chamber manufactured by Saphymo, Germany (Fig. 2). The AlphaGuard is a pulse counting ionisation chamber with active volume of 0.56 l. It is designed to monitor continuous radon concentrations in a large range from 2 to 2 × 10^6 Bq/m^3. The exhalation chamber is a rectangular box of dimensions 0.57 m × 0.37 m × 0.165 m with an open base. At first, a rectangular hole was dug in the ground at the chosen location and the exhalation chamber was kept inverted on it so that radon exhaled from beneath could accumulate in the covered volume. The top face of the box has two corrugated nozzles. These nozzles were initially closed with tygon tubing provided with pinchcock to shut communication of the internal volume with outside air. The box was left undisturbed in this state for 1 h to allow radon exhaled out of the soil to accumulate in the enclosed volume. Then Alphaguard and Alpha pump were connected with the exhalation chamber with tygon tubes as shown in Fig. 2. The AlphaGuard was set in 10 min diffusion mode. The Alpha pump was set at a slow displacement capacity of 0.03 L/min. Radon concentration readings were noted every 10 min for 1 h. Then the AlphaGuard was disconnected, and soil gas accumulated in the exhalation chamber

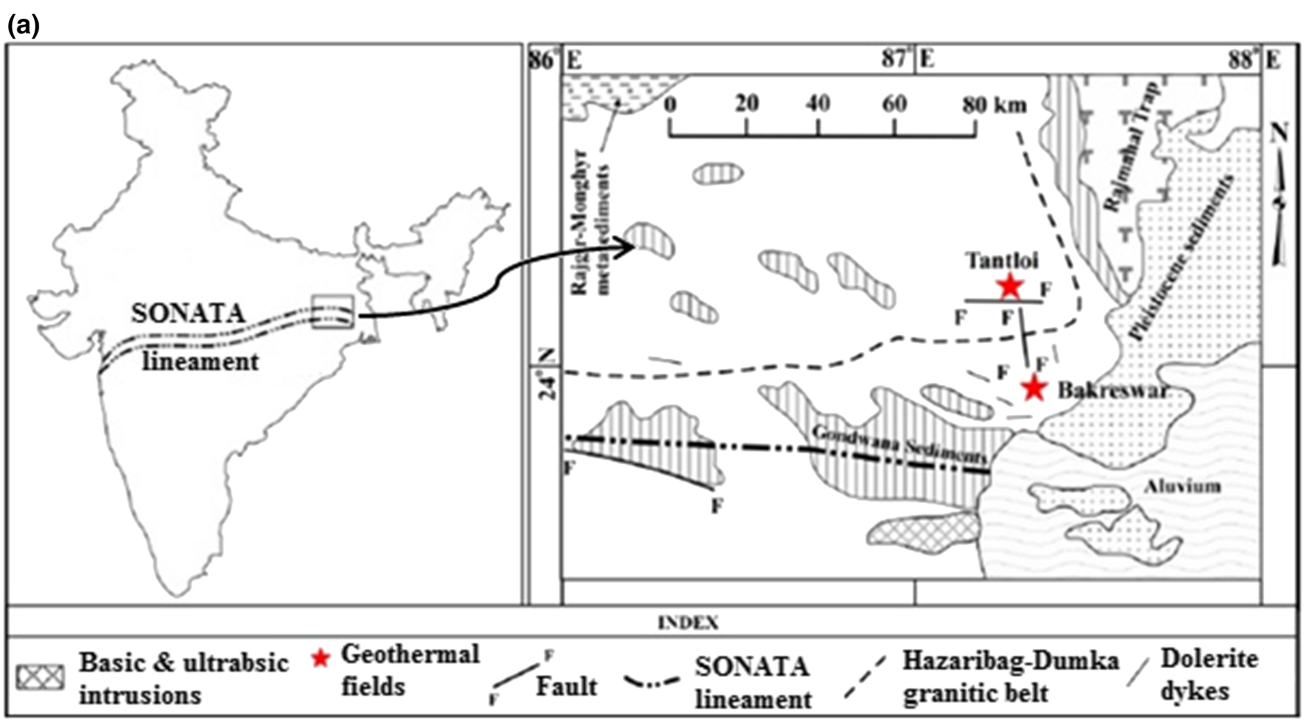

Fig. 1 **a** Location and geology of study area (after Singh et al. 43). **b** Distribution of faults and fractures in Bakreswar–Tantloi geothermal region

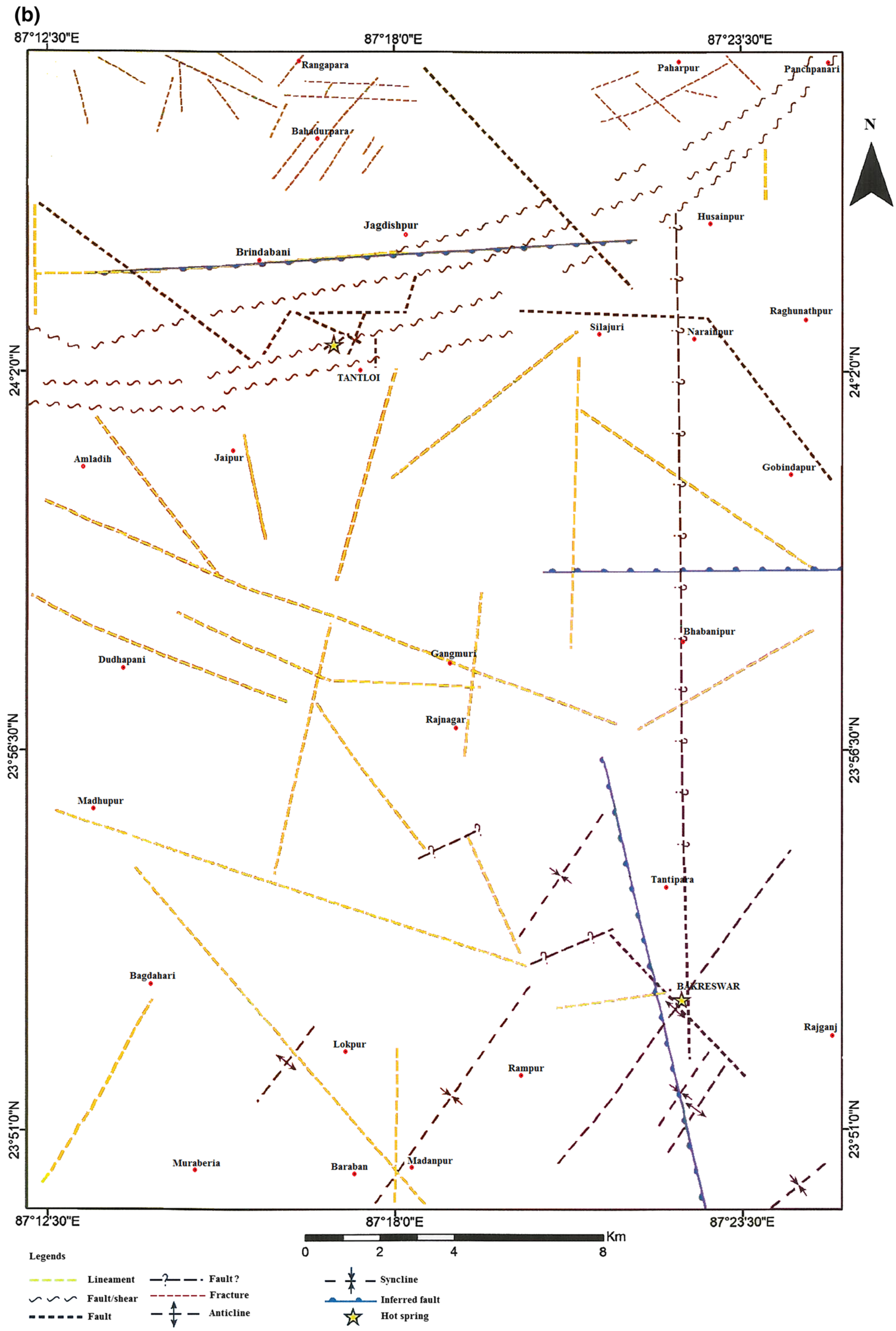

Fig. 1 continued

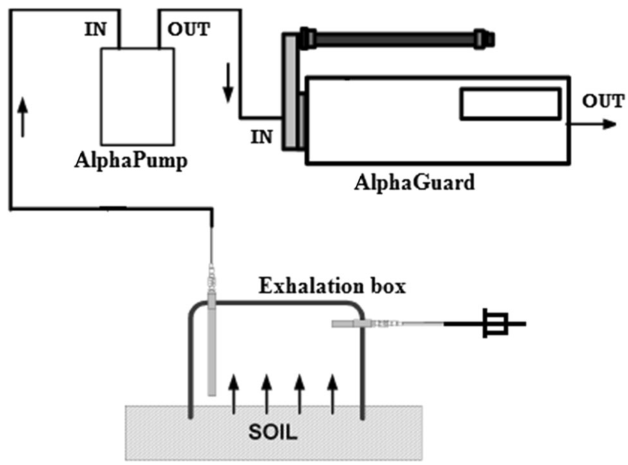

Fig. 2 Experimental set-up for determination of soil ^{222}Rn exhalation

was pumped out by operating the AlphaPump at a higher rate of 1 L/min for half an hour. Then, soil gas was again allowed to accumulate in the exhalation chamber for 1 h, and the same procedure was followed. This was continued for 24 h at each location studied.

Radon exhalation rate E_{Rn} from soil is calculated according to the following relation [30]:

$$E_{Rn} = \frac{C_{avg} \times V}{t_{acc} \times S} \qquad (1)$$

where, C_{avg} = Average Rn concentration, t_{acc} = Accumulation time, V = Volume of radon exhalation chamber (0.035 m^3), S = Surface area covered by the chamber (0.211 m^2).

Result and discussion

The diurnal variation of radon exhalation rate from soil and its dependence on meteorological parameters were observed at three locations in Bakreswar and one location in Tantloi, as shown in Fig. 3 (locations plotted on Google map). In Bakreswar, the three chosen spots, designated as Location A (23.8871°N, 87.3773°E), Location B (23.8794°N, 87.3751°E) and Location C (23.8786°N, 87.3638°E), are on three sides of the hot spring Agnikunda. The spot at Tantloi, designated as location D (24.04008°N, 87.27802°E), is also beside a hot spring. This study was carried out in early January 2017 when this region experienced winter. Maximum and minimum temperatures were around 30 and 7 °C respectively. No rainfall occurred during this period.

In order to understand the effects of meteorological parameters on soil radon exhalation rate, simultaneous measurements of ^{222}Rn concentration in soil gas, ambient temperature, relative humidity and atmospheric pressure were carried out continuously for 24 h at each location. Although it is ideal to carry out such observations at all locations simultaneously, it could not be done in this case due to lack of resources. At location A, observations began at 12:30 PM on January 05, 2017 and ended at 12:30 PM on the next day. At location B, the time of start of observations was 3:30 PM on January 06, 2017, and the time of completion was 3:30 PM the following day, whereas at location C observations were started at about 5:00 PM on January 12, 2017 and completed at the same time on January 13, 2017. At location D in Tantloi, the times of start and end of the measurements were 8:00 PM of January 14, 2017 and 8:30 PM of January 15, 2017 respectively.

The diurnal variations of ^{222}Rn exhalation rate from soil along with temperature, pressure and relative humidity at the four locations have been shown in Fig. 4. At location A in Bakreswar, radon exhalation rate from soil varied between 198 and 688 Bqm^{-2} h^{-1}, at location B between 138 and 530 Bqm^{-2} h^{-1}, and at location C it varied between 577 and 1408 Bqm^{-2} h^{-1}; whereas at location D in Tantloi it varied between 5310 and 8426 Bqm^{-2} h^{-1}. These values show that soil radon exhalation rate is generally higher in Tantloi than in Bakreswar. This may be due to differences in local geology of the two places, including soil structure and location of faults. The topsoil of Tantloi contains more sand and small stones than that of Bakreswar, and there is a fault very close to the monitoring location at Tantloi, through which the river Siddheswari flows. Location D at Tantloi is at a distance of 628 m from a hot spring, whereas Location A, Location B and Location C are respectively 708 m, 184 m and 1.183 km away from Agnikunda hot spring. All these factors may contribute to the difference in soil radon exhalation rate between Tantloi and Bakreswar.

From Fig. 4 it can be seen that at all four locations, soil ^{222}Rn exhalation rate increases after sunset, becomes highest during night hours from 9:00 PM to 1:00 AM, and then decreases until it reaches a minimum around noon. This may be due to the fact that the ground gets heated during the day and cooled during the night, causing a large diurnal temperature variation at the earth surface, whereas the temperature underneath the top-soil layer remains more or less constant. Bakreswar–Tantloi region, being a geothermal area with crustal heat flow about 230 mW/m^2, is expected to have quite high sub-surface soil temperature. During evening, night and early morning, the temperature of topsoil layer is lower than that of the subsurface soil layer, while around midday the surface temperature is higher than subsoil temperature. Thus, during nighttime there exists a positive temperature gradient between the soil at a depth of about 1 m and the ground surface, and during midday and afternoon a negative temperature gradient exists between subsurface and ground

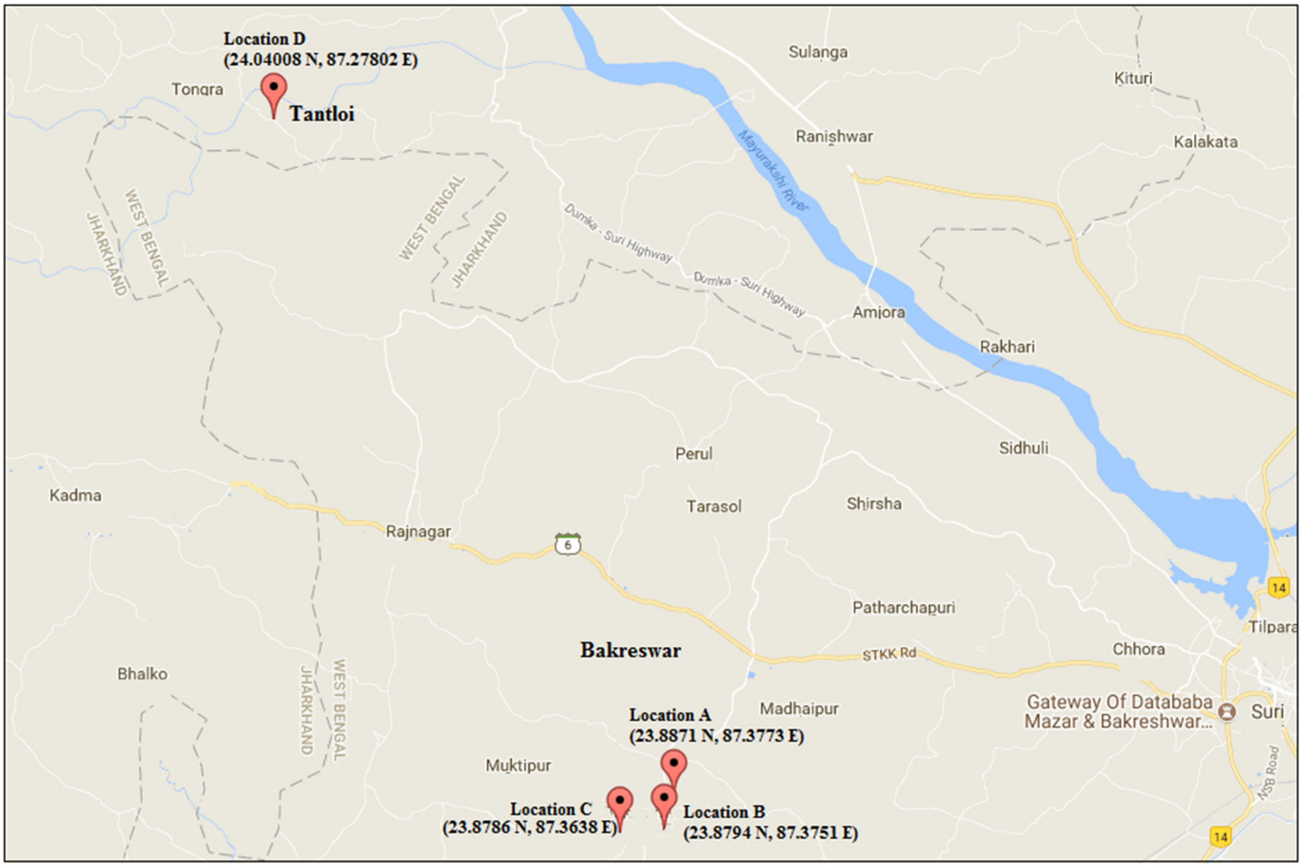

Fig. 3 Locations in Bakreswar–Tantloi region where soil radon exhalation was studied

surface. According to Klusman and Jaacks [47], positive temperature gradient between subsoil layer and ground surface assists the upward movement of radon from inside the earth's crust to the atmosphere, whereas a negative temperature gradient hinders the upward movement of radon. The reversal of the temperature gradient between day and night in Bakreswar–Tantloi region may be the main reason behind the appreciable diurnal variation of radon exhalation rate. Similar observations have been reported by several researchers [17, 48–50]. Also, the cracks and pores in the soil get heated throughout the day and are dilated considerably by sunset. Hence, radon gas trapped underneath the top-soil can find larger exhalation pathways after sunset.

Convection currents in atmosphere may be another factor that can cause diurnal variations of radon exhalation rates, with calmer atmosphere during late evening hours gradually increasing radon concentration in top-soil layers [51]. Moreover, it is known that radon exhalation from soil increases with increase of the radon emanation factor, which in turn increases with moisture content of soil [52–54]. In the region of study, relative humidity was found to increase gradually after sunset and reach above 95% around midnight and in early morning, as Fig. 4 shows. Also, there was dew throughout the night. These factors increased moisture level in soil, and hence radon exhalation, at night. It may be observed from Fig. 4 that soil radon exhalation rate is generally lower during the daytime when atmospheric pressure is higher. However, during the observation period, atmospheric pressure did not vary much throughout the day. Therefore, from such a small data set it cannot be concluded with certainty whether any negative correlation exists between radon exhalation from soil and atmospheric pressure.

In order to find out how soil radon exhalation depends on meteorological parameters in a non-geothermal region, similar 24 h measurements were carried out at another location in Kolkata, far away from Bakreswar, designated as location E (22.4993°N, 88.3718°E). The location of this spot is shown in Fig. 5. Here, observation started at 10:00 AM on January 21, 2017 and ended the following day at 10:30 AM. The results have been shown in Fig. 6. As there are no highly mineralised rocks in this region, radon exhalation rate from soil is much lower than that in Bakreswar–Tantloi region, as can be seen from Fig. 6. However, soil radon exhalation rate shows similar dependence on local meteorological factors, that is, radon exhalation appears to be negatively related with air temperature and

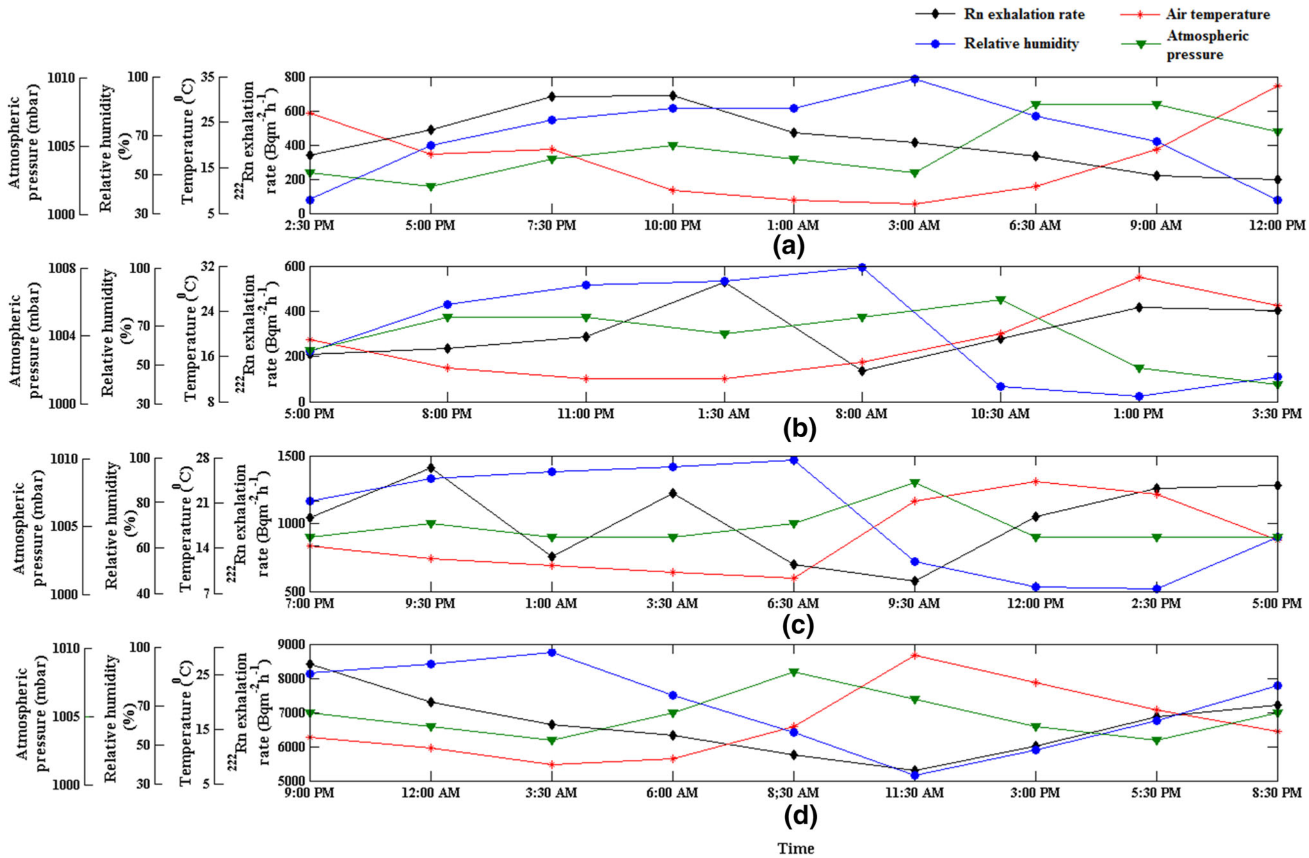

Fig. 4 Diurnal variation of soil radon exhalation rate with ambient temperature, atmospheric pressure and relative humidity at **a** Location A, **b** Location B, **c** Location C, **d** Location D

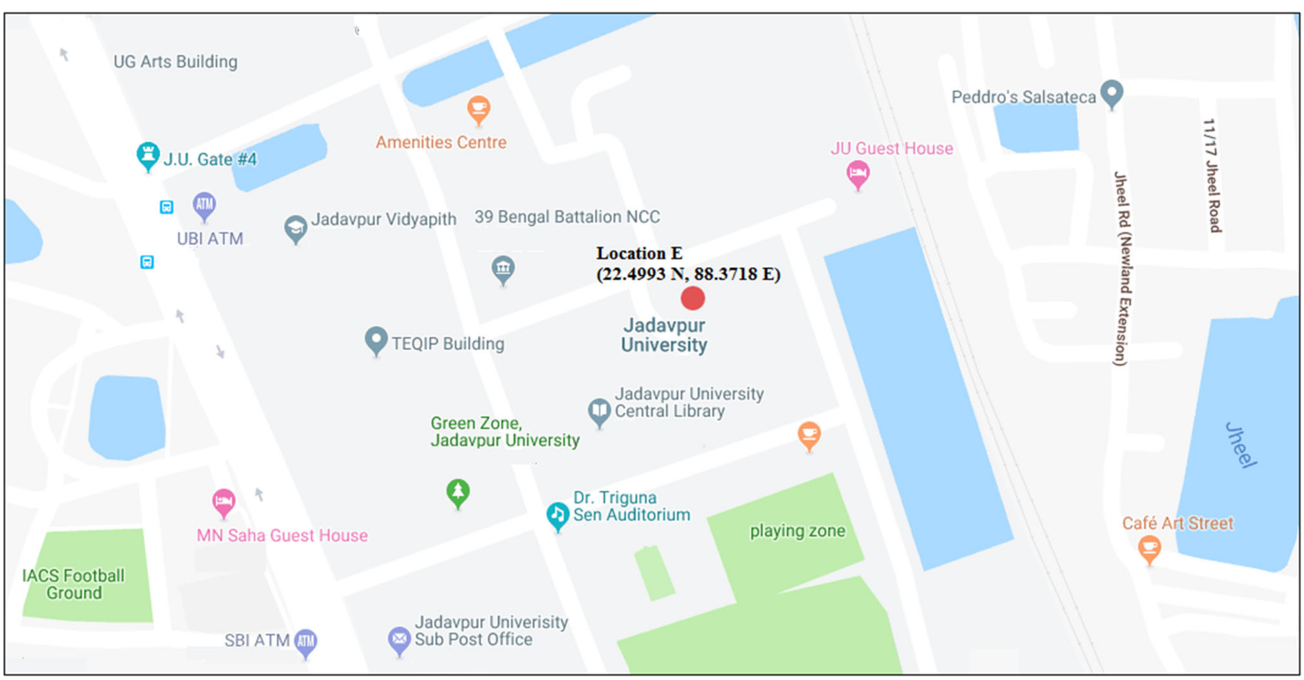

Fig. 5 Location in Kolkata where soil radon exhalation was studied

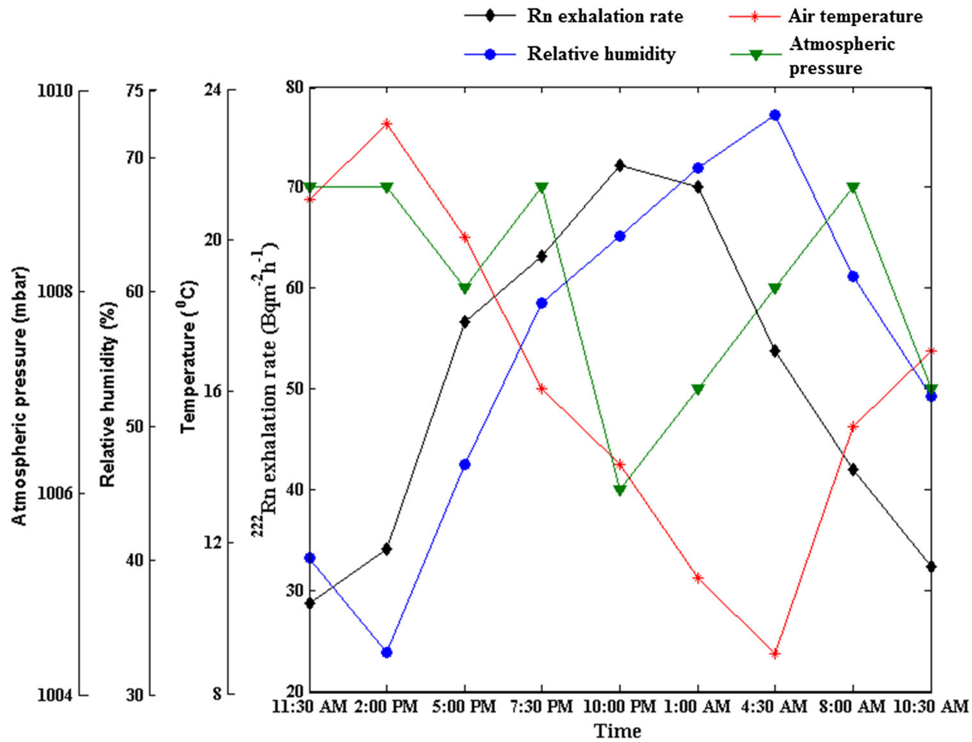

Fig. 6 Diurnal variation of soil radon exhalation rate with ambient temperature, atmospheric pressure and relative humidity at Position E

positively related to relative humidity of air. Also, slight negative correlation seems to exist between soil radon exhalation rate and atmospheric pressure. This shows that the presence of geothermal energy fields and crystalline rocks in a region increases the radon exhalation rate from soil; however, it does not affect how the exhalation rate depends on meteorological parameters.

Although this work shows that exhalation of radon gas from soil at a place depends significantly on local meteorological parameters, there are a few other issues that need to be addressed. Firstly, dependence of soil radon exhalation on rainfall must be studied, because moisture content of soil is known to affect significantly the radon emission rate from soil. Also, soil radon exhalation rates at all these locations were estimated in winter only. Similar work should be carried out in other seasons in order to determine any seasonal variation in radon exhalation from soil. It would be better if variations in radon exhalation rate at any location be studied continuously for a considerable period of time, preferably throughout a year. Moreover, long-term studies should be conducted at a considerable number of locations in Bakreswar–Tantloi geothermal region in order to have a complete picture of soil radon exhalation in this region.

Conclusion

Radon exhalation rates were estimated for 24 h at four locations in Bakreswar–Tantloi geothermal region of the Indian states of West Bengal and Jharkhand. For the sake of comparison, similar study was performed at one location in Kolkata also, which is located in the alluvial Gangetic plain, a non-geothermal region. It has been observed that radon exhalation rates from soil are much higher in the geothermal region. However, soil radon exhalation rate at all locations has been found to depend significantly on ambient temperature and relative humidity. Atmospheric pressure seems to have slight effect on soil radon exhalation, but the nature of this effect cannot be determined with absolute certainty. Radon exhalation rates from soil should be measured at more locations in Bakreswar–Tantloi geothermal region, and also during different seasons, so that there would be adequate information to study the influence of the presence of geothermal energy sources on soil radon exhalation in this region.

Lightning and thunder are common occurrences in Bakreswar–Tantloi geothermal region throughout the year. A monitoring station has been proposed for the study of the influence of soil radon emanation on thunder and lightning events in this geothermal region. The data collected from this primary study would be useful and valuable for the installation of the proposed monitoring station in this region in near future.

Acknowledgements The authors acknowledge the logistic support of Bose Institute for carrying out this work at Bakreswar, as it has been conducted under the joint collaboration between Bose Institute and Jadavpur University. The authors are grateful to the staff of the Helium Laboratory at Bakreswar for their invaluable help. SC and AD acknowledge the financial help of the Department of Science and Technology (DST), Govt. of India, for the fellowship of SC and the UPE-II programme for Jadavpur University which provided funds for instruments.

References

1. Tanner AB (1980) In: Gendsell TF, Lowder WM (eds) The natural radiation environment III. University of Chicago Press, Chicago, p 5
2. Nazaroff WW, Moed BA, Sextro RG (1988) Soil as a source of indoor radon: Generation, migration and entry. In: Nazaroff WW, Nero AV (eds) Radon and its decay products in indoor air. Wiley-Interscience, New York, pp 57–112
3. Rogers VC, Nielson KK (1991) Multiphase radon generation and transport in porous materials. Health Phys 60:807
4. Nazaroff WW (1992) Radon transport from soil to air. Rev Geophys 30(2):137–160
5. Elzain AA, Mohammed YSh, Mohamed KS, Mohamed-Ali AM (2016) A study of radium concentration and radon exhalation rate in soil samples from Kassala Town, Sudan Using SSNTDs. Am J Phys Appl 4(4):84–89
6. Sohrabi M (1998) The state of the art on worldwide studies in some environments with elevated naturally occurring radioactive materials (NORM). Appl Radiat Isot 49(3):169–188
7. Walia V, Su TC, Fu CC, Yang TF (2005) Spatial variations of radon and helium concentrations in soil-gas across the Shan-Chiao fault, Northern Taiwan. Radiat Meas 40:513–516
8. Sun X, Yang P, Xiang Y, Si X, Liu D (2017) Across-fault distributions of radon concentrations in soil gas for different tectonic environments. Geosci J. https://doi.org/10.1007/s12303-017-0028-2
9. Schweikani R, Giaddui TG, Durrani SA (1995) The effect of soil parameters on the radon concentration values in the environment. Radiat Meas 25:581–584
10. Sun K, Guo Q, Cheng J (2004) The effect of some soil characteristics on soil radon concentration and radon exhalation from soil surface. J Nucl Sci Technol 41(11):1113–1117
11. Kulali F, Akkurt I, Özgür N (2017) The effect of meteorological parameters on radon concentration in soil gas. Acta Phys Pol, A 132:999–1001
12. Moses H, Stehney AF, Lucas HF Jr (1960) The effect of meteorological variables upon the vertical and temporal distributions of atmospheric radon. J Geophys Res 65(4):1223–1238
13. Pearson JE, Moses H (1966) Atmospheric radon-222 concentration variation with height and time. J Appl Meteorol 5:175–181
14. Kojima H, Nagano K (1999) The influence of meteorological and soil parameters on radon exhalation. In: Proceedings of radon in the living environment, Athens, Greece
15. Riley WJ, Robinson AL, Gadgil AJ, Nazaroff WW (1999) Effects of variable wind speed and direction on radon transport from soil into buildings: model development and exploratory results. Atmos Environ 33:2157–2168
16. Ashok GV, Nagaiah N, Prasad NGS, Ambika MR (2011) Study of radon exhalation rate from soil, Bangalore, South India. Radiat Prot Environ 34:235–239
17. Sahoo S, Katlamundi M, Shaji JP, Murali Krishna KS, Udaya Lakshmi G (2018) Influence of meteorological parameters on the soil radon (Rn^{222}) emanation in Kutch, Gujarat, India. Environ Monit Assess 190:111. https://doi.org/10.1007/s10661-017-6434-0
18. Nikolopoulos D, Louizi A (2008) Study of indoor radon andradon in drinking water in Greece and Cyprus: implications to exposure and dose. Radiat Meas 43(7):1305–1314
19. Martín Sánchez A, de la Torre Pérez J, Ruano Sánchez AB, Naranjo Correa FL (2012) Radon in workplaces in Extremadura (Spain). J Environ Radioact 107:86–91
20. Barman C, Ghose D, Sinha B, Deb A (2016) Detection of earthquake induced radon precursors by Hilbert Huang Transform. J Appl Geophys 133:123–131
21. Chowdhury S, Deb A, Nurujjaman Md, Barman C (2017) Identification of pre-seismic anomalies of soil radon-222 signal using Hilbert-Huang transform. Nat Hazards 87:1587–1606
22. Ramola RC, Choubey VM (2003) Measurement of radon exhalation rate from soil samples of Garhwal Himalaya, India. J Radioanal Nucl Chem 256(2):219–223
23. Faheem M (2008) Radon exhalation and its dependence on moisture content from samples of soil and building materials. Radiat Meas 43:1458–1462
24. Gupta M, Mahur AK, Verma KD (2012) Indoor radon levels in some dwellings surrounding the National Thermal Power Corporations (NTPCs), India. Adv Appl Sci Res 3(3):1262–1265
25. Modzelewska D, Dołhańczuk-Śródka A, Ziembik Z (2014) Issues of radon (Rn-222) exhalation measurements. In: Proceedings of ECOpole’14 conference, Jarnoltowek. https://doi.org/10.2429/proc.2014.8(2)049
26. Harb S, Ahmed NK, Elnobi S (2015) Radon exhalation rate and radionuclides in soil, phosphate, and building materials. IOSR J Appl Phys 7(2):41–50
27. Kraner HW (1964) Measurements of the effects of the atmospheric variables on Rn-222 flux and soil gas concentrations. In: The natural radiation environment. University of Chicago Press, Chicago, pp 191–215
28. Fleischer RL, Fisk MD, Hart Jr. HR, Likes RS, Mogro-Campero A (1979) Anomalies in concentrations of radon in the earth. Bendix Field Engineering Corporation, CJBX-97
29. SinghM Ramola RC, Singh S, Virk HS (1988) The influence of meteorological parameters on soil gas radon. J Assoc Explor Geophys IX 2:85–90
30. Vaupotič J, Gregorič A, Kobal I, Zvab P, Kozak K, Mazur J, Kochowska E, Grzadziel D (2010) Radon concentration in soil gas and radon exhalation rate at the Ravne Fault in NW Slovenia. Nat Hazards Earth Syst Sci 10:895–899
31. Zhang L, Guo Q, Sun K (2015) Continuous measurement of radon exhalation rate of soil in Beijing. J Radioanal Nucl Chem 303:1623–1627
32. Clements WE, Wilkening MH (1974) Atmospheric pressure effects on ^{222}Rn transport across the earth-air interface. J Geophys Res 79:5025–5029
33. Schery SD, Gaeddert DH, Wilkening MH (1984) Factors affecting exhalation of radon from a gravelly sandy loam. J Geophys Res 89:7299–7300
34. Dueñas C, Fernández MC, Carretero J, Liger E, Pérez M (1997) Release of ^{222}Rn from some soils. Ann Geophys 15:124–133
35. Ghose D, Chowdhury DP, Sinha B (2002) Large-scale helium escape from earth surface around Bakreswar–Tantloi geothermal area in Birbhum district, West Bengal, and Dumka district, Jharkhand, India. Curr Sci 82(8):993–996
36. Majumdar RK, Majumdar N, Mukherjee AL (2010) Geological, geochemical and geoelectric studies for hydrological characterization and assessment of Bakreswar thermal springs in hard rock areas of Birbhum district, West Bengal, India. In: Proceedings of 8th Biennial international conference and exposition on petroleum geophysics, Hyderabad, India

37. Naskar AK, Gazi M, Barman C, Chowdhury S, Mondal M, Ghose D, Sinha B, Deb A (2017) Estimation of underground water radon danger in Bakreswar and Tantloi geothermal region, India. J Radioanal Nucl Chem 315:273–283
38. Pulinets AA, Leyva Contreras A, Gaivoronska TB, Safronova IA (2004) Ionospheric day-to-day variability and spatial;-temporal correlation. IRI Taks Force Activity Workshop, ICTP, Trieste, Italy
39. Morozova LI (2011) Clouds as forerunners of earthquakes. Sci First-Hand 4:80–91
40. Shanker R (1988) Heat-flow of India and discussion on its geological and economic significance. Indian Mineral 42:89–110
41. Majumdar RK, Majumdar N, Mukherjee AL (2000) Geoelectric investigations in Bakreswar geothermal area, West Bengal, India. J Appl Geophys 45:187–202
42. GSI Kolkata (1991) Geological Survey of India. Geothermal Atlas of India, Spl Publ 19: 110–113
43. Singh HK, Chandrasekharam D, Vaselli O, Trupti G, Singh B, Lashin A, Al Arifli N (2014) Physicochemical characteristics of Jharkhand and West Bengal thermal springs along SONATA mega lineament, India. J Earth Syst Sci 124(2):419–430
44. Nagar RK, Vishwanathan G, Sagar S, Sankaranarayanan A (1996) Geological, geophysical and geochemical investigations in Bakreswar–Tantloi thermal field, Birbhum and Santhal Parganas districts, West Bengal and Bihar, India. Proc. Sem. on Geothermal Energy in India. In: Pitale UL, Padhi RN (eds) Geological Survey of India—Special Publication 45, pp 349–360
45. Valdiya KS (2016) Cretaceous volcanism. In: The making of India. Society of Earth Scientists Series. Springer, Cham
46. Mukhopadhyay DK, Sarolkar PB (2012) Geochemical appraisal of Bakreshwar-Tantloi Hot Springs, West Bengal and Jharkhand, India. In: Proceedings, thirty-seventh workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, USA
47. Klusman RW, Jaacks JA (1987) Environmental influences upon mercury, radon and helium concentrations in soil gases at a site near Denver, Colorado. J Geochem Explor 27(1–2):259–280
48. Schubert M, Schulz H (2002) Diurnal radon variations in the upper soil layers and at the soil-air interface related to meteorological parameters. Health Phys 83:91–96
49. Jaishi H, Singh S, Tiwari RP, Tiwari RC (2014) Analysis of soil radon data in earthquake precursory studies. Ann Geophys 57(5):S0544. https://doi.org/10.4401/ag-6513
50. Crawford J, Chambers S, Kang CH, Griffiths A, Kim WH (2015) Analysis of a decade of Asian outflow of PM 10 and TSP to Gosan, Korea; also incorporating Radon-222. Atmos Pollut Res 6(3):529–539
51. Chambers SD, Hong SB, Williams AG, Crawford J, Griffiths AD, Park SJ (2014) Characterizing terrestrial influences on Antarctic air masses using Radon-222 measurements at King George Island. Atmos Chem Phys 14(18):9903–9916
52. Damkjaer A, Korsbech U (1985) Measurement of the emanation of radon-222 transport from Danish soils. Sci Total Environ 45:343–350
53. Sheng TK, Jer HS (2003) Indoor radon radioactivity at the University of Brunei Darussalam. Pure appl Geophys 160:75–80
54. Qiuju G, Sun K, Cheng C (2004) Methodology study on evaluation of radon flux from soil in China. Radiat Prot Dosim 112:291–296