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*Full Length Research Paper*

# Earthquake precursory studies at Amritsar Punjab, India using radon measurement techniques

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**The continuous soil gas radon and daily monitoring of radon concentration in water is carried out at Amritsar (Punjab, India), a well known seismic zone to study the correlation of radon anomalies in relation to seismic activities in the study area. In this study, radon monitoring in soil was carried out by using barasol probe (BMC2) manufactured by Algade France whereas the radon content in water was recorded using RAD7 radon monitoring system of Durridge Company USA. The radon anomalies observed in the region have been correlated with the seismic events of M ≥ 2 recorded in NW Himalayas by Wadia Institute of Himalayas Geology Dehradun and Indian Meteorological Department, New Delhi. The effect of meteorological parameters; temperature, pressure, wind velocity and rainfall on radon emission has been studied. The correlation coefficient between radon and meteorological parameters has been calculated. Correlation coefficients (R) between radon anomaly (A), epicentral distance (D), earthquake magnitude (M) and precursor time (T) are evaluated. The constants in the empirical equations between earthquake magnitude, epicentral distance and precursor time has been calculated in the present study and compared with the earlier studies in NW Himalayas.**

**Key words:** Radon, NW Himalayas, barasol probe, RAD7 and earthquake precursor.

## INTRODUCTION

In the present state of science, predicting earthquakes is a distant goal since too many parameters would need to be known parallel to securely predict such events. However, during the past decades' improvement in measurement, technology made it possible to measure certain rare gases being present in traces. The measurement of these gases may contribute to a better understanding of the mechanism of earthquakes, together with the complex processing of more geo-chemical and geo-physical parameters. Among these gases, radon monitoring are probably the most frequently used for earthquake monitoring/predicting purposes. The changes in subsurface radon concentration have been observed to precede earthquake occurrence and therefore radon has potential use in earthquake prediction studies (Hartmann and Levy, 2005; Italiano et al., 2008; Walia et al., 2009).

The first evidence of a correlation between radon and earthquake occurrence came from observation of radon concentration in well water, prior to the Tashkent earthquake of 1966 (Ulomov and Mavashev, 1967). This evidence stimulated research work in this area soon afterwards in many countries. Radon observations, both in soil-gas and in groundwater, revealed many precursory changes in its concentration before an earthquake (Fleischer, 1981; Liu et al., 1984, 1985; King et al., 1993; Igarashi et al., 1995; Chyi et al., 2005; Yang et al., 2005; Einarsson et al., 2008; Kumar et al., 2009). Due to such observed correlation, radon is considered as one of the

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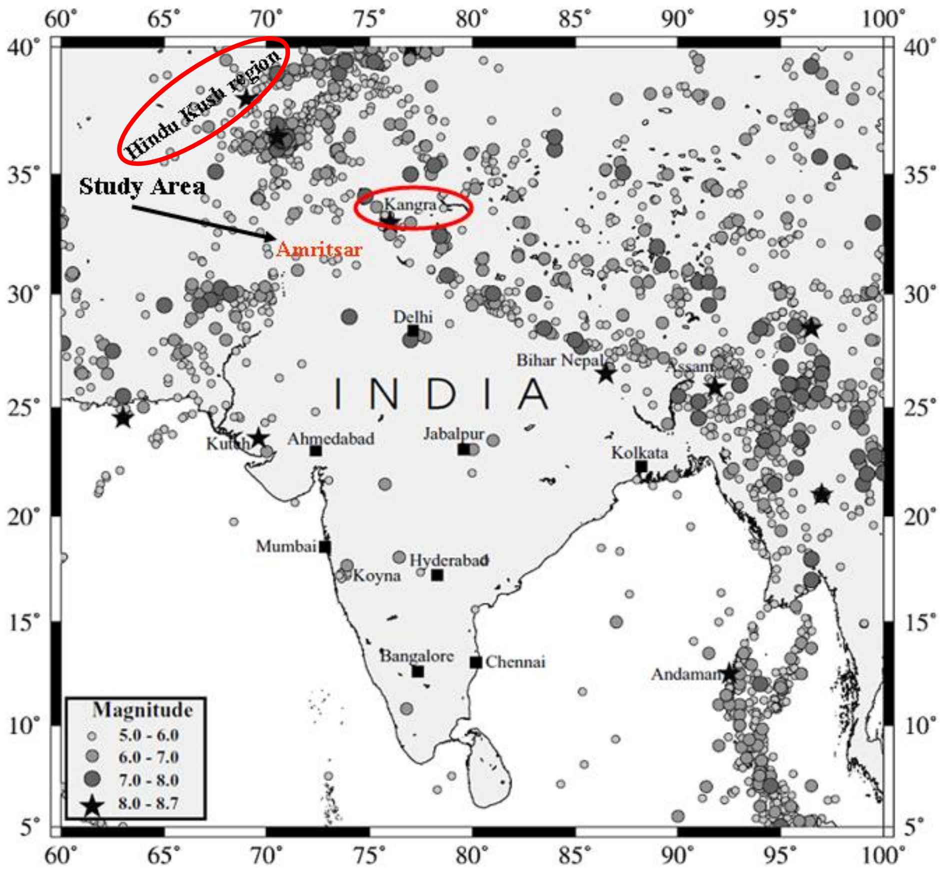

**Figure 1.** Map showing location of radon monitoring station Amritsar.

few promising precursors for earthquakes.

Radon ($^{222}$Rn) is a daughter nuclide of radium ($^{226}$Ra), which in turn comes from the long lived antecedent, uranium ($^{238}$U). The short half-life of $^{222}$Rn (3.82 days) limits its diffusion in soil, so the radon measured at the ground surface cannot be released from a deep origin, unless there exists a driving mechanism other than mere diffusion. Radon is a marker of convection process, fault interaction and of uranium, thorium mineral rocks (Quattrocchi et al., 2000). The movement of radon through rocks under the earth largely depends on lithology, compaction, porosity and fractural and tectonic features like faults, thrust, joints or fractures (Choubey et al., 1997; Walia et al., 2005a).

Amritsar is located in the northern part of Punjab state (Figure 1) and lies between 31º 28’ 30” to 32º 03’ 15” north latitude and 74º 29’ 30” to 75º 24’ 15” east longitude. Geologically, the Punjab sediments are derived from Shivalik Himalayas. The Amritsar lie in zone IV of seismic zoning map of India. The seismicity of the study area is because of its closeness to the seismically active areas; Kangra and Hindukush areas of NW Himalayas. This may be due to the presence of active faults in NW Himalayas. Keeping above facts, the continuous soil gas radon and daily monitoring of radon concentration in water is carried out at Amritsar (Punjab, India) to study the correlation of radon anomalies in relation to seismic activities in the study area. The effect of meteorological variables on the radon concentration in soil-gas is taken into consideration.

## MATERIALS AND METHODS

### Radon monitoring in soil

For continuous monitoring of radon, temperature and pressure in soil gas, barasol probe (BMC2) manufactured by Algade France is used. It consists of radon sensor (Silicon alpha sensitive detector) that records the radon gas which enters into the detection chamber. The BMC2 probe is composed of a detection unit, electronics and a battery unit fitted inside a mechanism consisting of a tube made of an epoxy glass material 61 mm in diameter and 500 mm long. As standard, an 8 pin connector provides the probe interconnection and control. The connector has an air and water tight index of IP 68 when covered by the cap. The battery unit holds 2 × 1.5 V alkaline batteries. Two good quality alkaline batteries give the probe more than 6 months independent operation. The radon probe is installed vertically in about 1 m long and 10 cm diameter polyvinylchloride (PVC) tube, with the detector at the lower end. The tube is opened at its bottom end and airtight at the surface (Figure 2). The probe

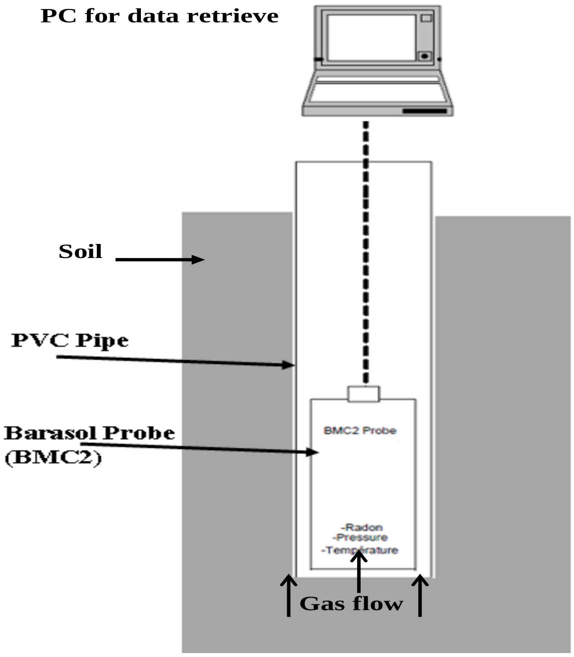

**Figure 2.** Sketch of BMC2 radon probe.

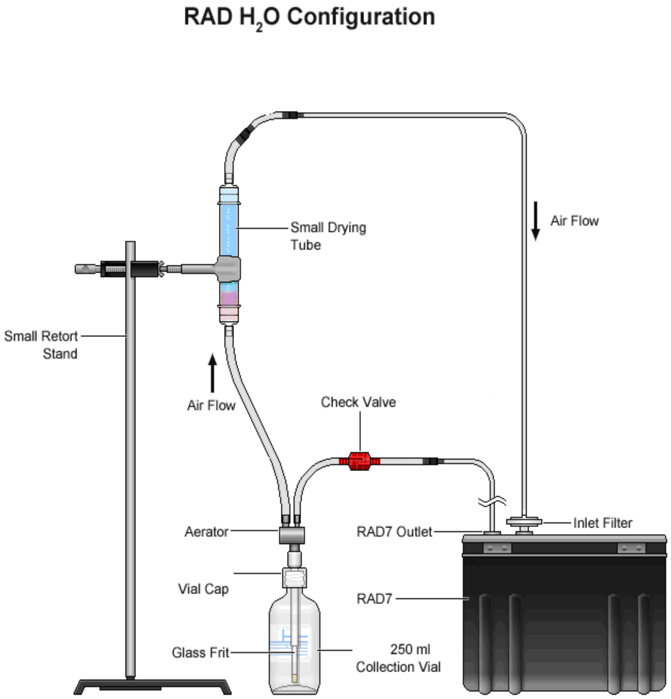

**Figure 3.** Sketch of RAD7 aerating a 250 ml water sample.

allows long continuous recordings with a sampling interval as short as 15 min, up to several hours (data storage capacity amounts to 8000 measurement points). In the present experiment, half hourly rate was consistently selected. The wind velocity and rainfall data of the study area has been collected from Indian Meteorological Department New Delhi.

### Radon monitoring in water

RAD 7 (Figure 3) procured from Durridge Company U.S.A has been used for monitoring radon concentration in water. The method employs a closed loop aeration scheme whereby both the air and water volume are constant and independent of the flow rate. The air recirculates through the water and continuously extracts the radon until a state of equilibrium develops. The RAD-$H_2O$ system reaches this state of equilibrium within about 5 min, after which no more radon can be extracted from the water. The setup consists of three components, the RAD7, on the right, the vial, center front, and the tube of desiccant, top left. During the five minutes of aeration, more than 95% of the available radon is removed from the water. For the measurement of radon concentration, a sample of 250 ml water is collected at the same time daily from natural ground water source in Amritsar. The radon sampling is complicated by the fact that the gas easily escapes from water and therefore has to be done without any aeration which might lead to out gassing. So, the water sample was collected in such a way that there was no bubbling. Before making a measurement, the RAD7 must be free of radon, and dry. To achieve this, it has been purged for some time so that it shows less than 6% humidity. Drierite desiccant was used for this process.

## RESULTS AND DISCUSSION

### Effect of meteorological parameters on radon exhalation

The values of correlation coefficients of radon exhalation in soil at Amritsar with different meteorological parameters are summarized in Table 1. The average value of radon for soil-gas at Amritsar is reported to be 14450.8 Bq/m$^3$ with a standard deviation (Std) of 9175.4 Bq/m$^3$. The percentage variation coefficient (Std/Avg) of radon is 63.5% (Table 1). Radon shows positive correlation with temperature that is, the value of radon concentration increases as temperature increases and decreases with decrease in temperature (Figure 4). The correlation coefficient between radon and temperature is found to be 0.75 (Table 1). The average value of temperature for the given time window was 22.7ºC with a standard deviation of 6.3ºC and percentage variation coefficient of 27.8% (Table 1).

Negative correlation (correlation coefficient -0.71) between radon and pressure has been found that is, radon decreases with increase in pressure and increases with decreases in pressure. The average value of pressure for the given time window was 983.5 mbar with a standard deviation of 9.1 mbar and percentage variation coefficient of 93% (Table 1). The average value of wind velocity was found to be 2.2 km h$^{-1}$ with a standard deviation of 1.4 km h$^{-1}$ and percentage variation coefficient of 63%. Wind velocity causes a decrease in soil-gas radon concentration because soil-gas is being diluted or removed at the surface (Kraner et al., 1964; Miller and Ostle, 1973; Jaacks, 1984; Hesselbom, 1985; Walia et al., 2005b).

A positive correlation has been observed between radon and rainfall in the study area during the present

**Table 1.** Correlation coefficient of radon concentration in soil-gas with different meteorological parameters at Amritsar.

| Parameter | Average (Avg) | Standard deviation (Std) | % Variation coefficient (Std/Avg) | Correlation coefficient |
|---|---|---|---|---|
| Radon (Bq/m$^3$) | 14450.8 | 9175.4 | 63.5 | - |
| Soil temperature (ºC) | 22.7 | 6.3 | 27.8 | 0.75 |
| Soil pressure (mbar) | 983.5 | 9.1 | 0.93 | -0.71 |
| Rainfall (mm) | 1.8 | 6.7 | 372.0 | 0.11 |
| Wind velocity (km/h) | 2.2 | 1.4 | 63.0 | -0.15 |

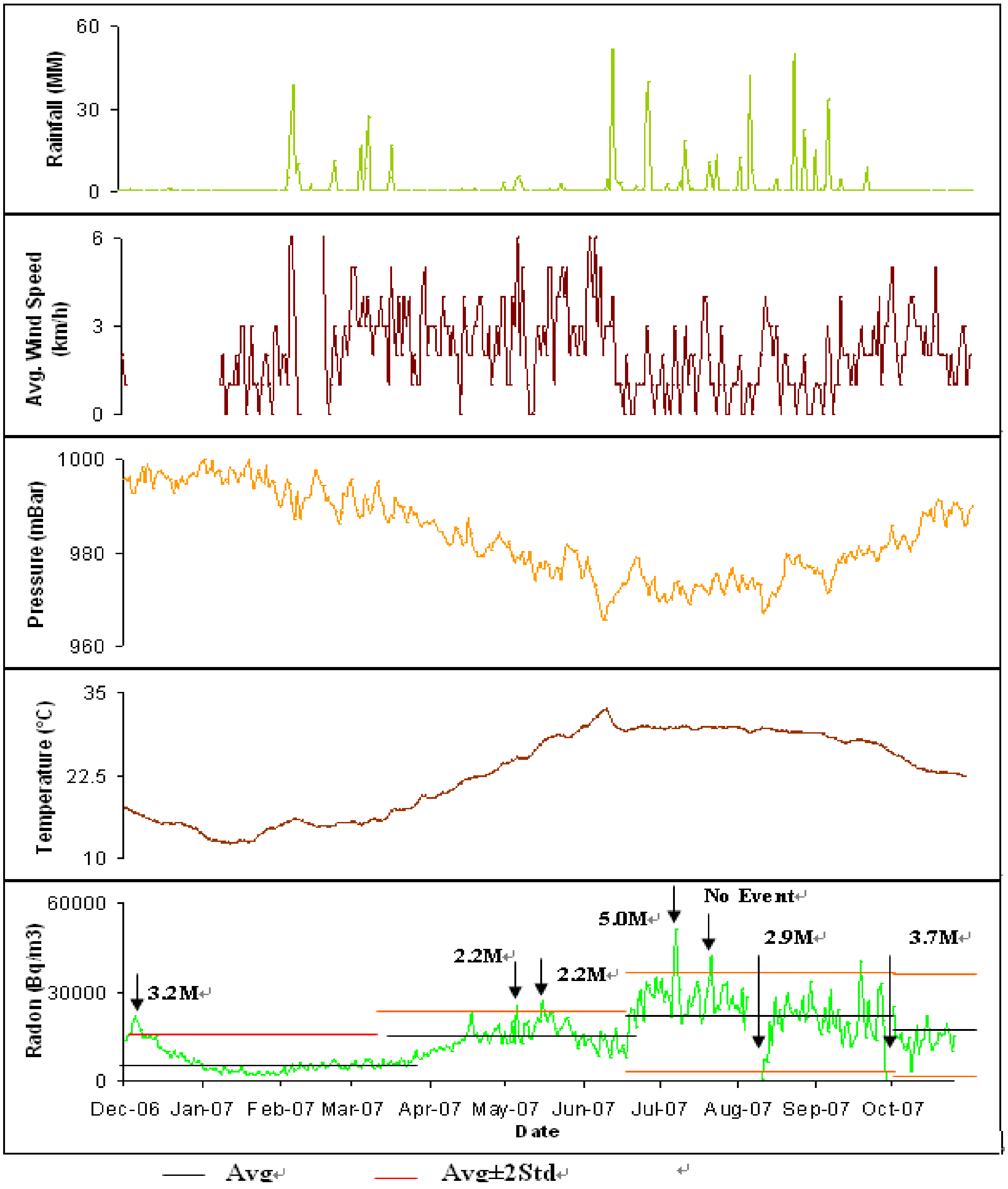

**Figure 4.** Daily variation of radon concentration in soil along with meteorological parameters; temperature, pressure, average wind speed and rainfall at Amritsar from 7th December, 2006 to 31st October, 2007.

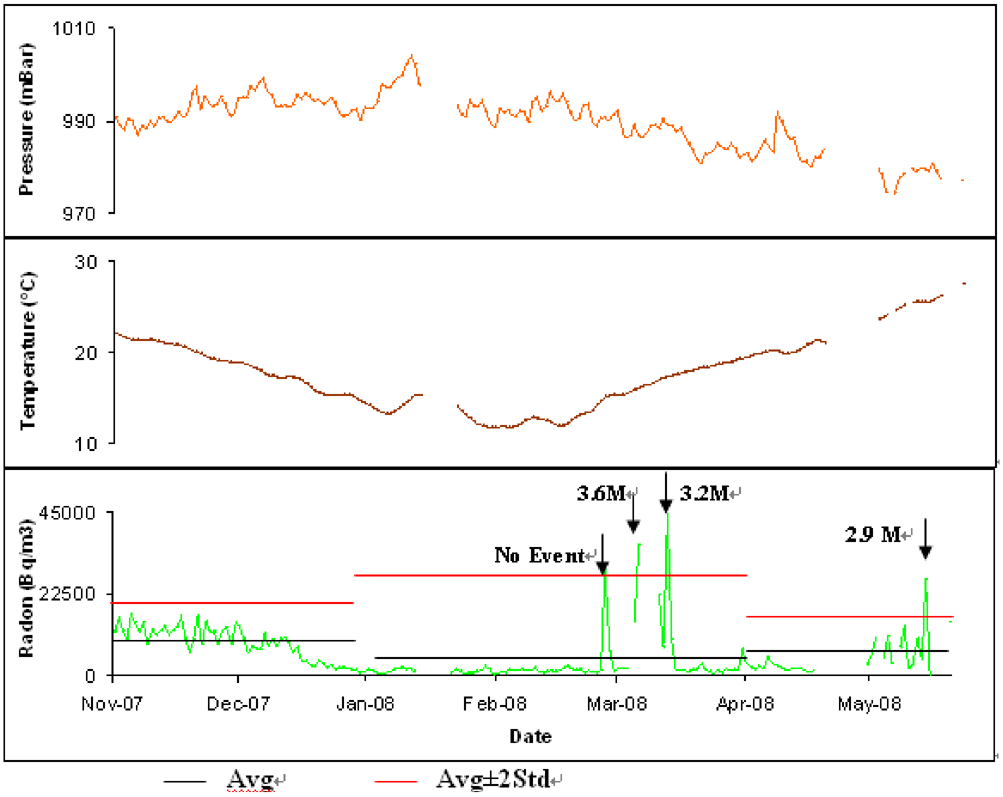

**Figure 5.** Daily variation of radon concentration in soil along with meteorological parameters; temperature and pressure at Amritsar from 1st November, 2007 to 20th May, 2008.

investigations. The average value of rainfall was found to be 1.8 mm with a standard deviation of 6.7 mm and percentage variation coefficient of 372 mm (Table 1). The variation of radon concentration in soil gas with meteorological parameters; temperature, pressure at Amritsar from 1st November, 2007 to 20th May, 2008 is shown in Figure 5. A similar trend of the variation of soil gas radon with temperature and pressure is also observed during earlier period of observation (Figure 4). Our results for the effects of meteorological parameters; temperature, pressure, wind velocity and rainfall on radon release corroborate the findings of the other authors (King and Minissale, 1994; Walia et al., 2005b; Mukherji et al., 2001).

## Correlation of radon anomalies in soil and water with seismic events

In order to identify possible threshold values of the anomalous radon concentration, various statistical methods have been used by different authors in the past (Klusman, 1993; Lepeltier, 1969; Guerra and Lombardi, 2001; Fu et al., 2005; Yang et al., 2005: Walia et al., 2005b). The very common practice of considering the mean plus ‘n’ standard deviation is generally accepted as an anomaly in soil gas and is found to be convenient for soil gas survey interpretations (Guerra and Lombardi, 2001; Fu et al., 2005; Walia et al., 2005b). In our context of radon concentration, the statistical threshold value of gas anomalies is fixed at the average plus two standard deviation (2σ) for positive anomaly and average minus two standard deviation (2σ) for negative anomalies in soil and ground water. For defining the mean and standard deviation, the anomalously high and anomalously low value was neglected, which may cause unnecessary high deviation and perturb the real anomalies.

Radon anomalies recorded in soil gas at Amritsar are shown in Table 2. Eleven radon anomalies were recorded, out of which nine were positive and two were negative anomalies. The first radon anomaly was recorded on 11th December, 2007 which was followed by event of 3.2 M (30.8°N, 76.6°E) in NW Himalayas. The second radon anomaly was observed on 11th May, 2007 followed by the event 2.2 M (31.0°N, 76.6°E) a week before the event which occurred on 18th May, 2007. The third anomaly was recorded on 21st May, 2007 followed by the event 2.2 M (31.1°N, 76.8°E) occurred on 26th May, 2007 five days after the anomalous radon value. The fourth radon anomaly was recorded on 13th July, 2007. This anomaly was correlated with Uttarakashi earthquake of 5.0 M which occurred on 22nd July, 2007,

**Table 2.** Listing of radon anomalies recorded at Amritsar in soil gas with seismic event.

| Date of anomaly | Date of event | Latitude (ºN) | Longitude (ºE) | Depth (kms) | Magnitude | Epicenter distance (kms) | % Variation from (Avg±2б) | Precursor time (Day) |
|---|---|---|---|---|---|---|---|---|
| 11/12/06 | 25/12/06 | 76.6 | 30.8 | 10.0 | 3.2 | 168 | 47.1 | 14 |
| 11/05/07 | 18/05/07 | 31.0 | 76.6 | 28.6 | 2 .2 | 157 | 0.5 | 7 |
| 21/05/07 | 26/05/07 | 31.1 | 76.8 | 10.0 | 2.2 | 171 | 6.8 | 5 |
| 13/07/07 | 22/07/07 | 33.0 | 78.2 | 15.0 | 5.0 | 330 | 26 | 9 |
| 27/07/07 | | | | No event | | | 4.5 | - |
| 16/08/07* | 28/08/07 | 30.7 | 76.1 | 14.8 | 2.9 | 138 | 97 | 12 |
| 4/10/07* | 4/10/07 | 32.5 | 76.2 | 4.5 | 3.7 | 144 | 64 | 0 |
| 27/02/08 | | | | No event | | | 62.9 | - |
| 06/03/08 | 11/03/08 | 32.8 | 76.2 | 11.9 | 3.6 | 169 | 94.6 | 5 |
| 13/03/08 | 24/03/08 | 32.8 | 76.2 | 16.8 | 3.2 | 169 | 139.4 | 11 |
| 14/05/08 | 14/05/08 | 32.4 | 76.5 | 9.3 | 2.9 | 159 | 68.5 | 0 |

*Negative anomaly.

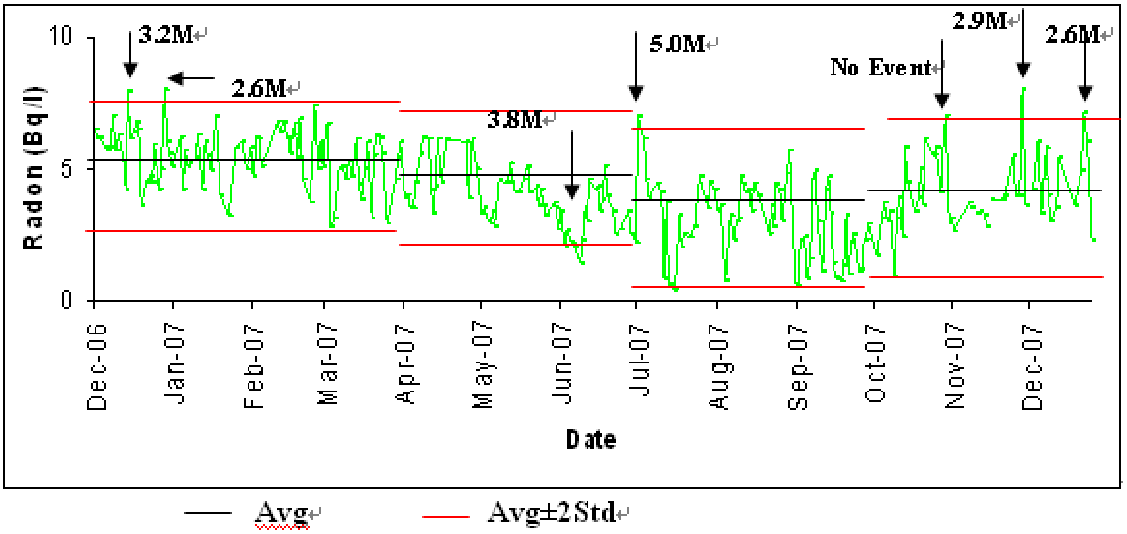

**Figure 6.** Daily variation of radon concentration in ground water at Amritsar from 7th December, 2006 to 31st December, 2007.

nine days after the anomalous radon value. The fifth anomaly was recorded on 22nd July, 2007. This anomaly was not followed by any seismic event in NW Himalayas. The sixth radon anomaly was recorded in the month of August on 16th, 2007 which was followed by the event 2.9 M which occurred on 28th August, 2007. The seventh anomaly was recorded on 4th October, 2007 followed by 3.7 M in NW Himalayas on the same day. The nature of six and seventh anomaly was negative. The eighth radon anomaly was recorded 27th February, 2008 not followed by any event in NW Himalayas. In the month of March, 2008, two anomalies were recorded followed by 3.6 and 3.2 M events in NW Himalayas. The eleventh anomaly recorded on 14th May, 2008 was followed by the event 2.9 M in NW Himalayas.

The daily variation of radon concentration in water at Amritsar from 7th December, 2006 to 31st July, 2008 is shown in Figures 6 and 7, respectively. Radon anomalies observed in ground water at Amritsar are shown in Table 3. Fourteen radon anomalies were recorded, out of which one anomaly was negative. The first radon anomaly in ground water was recorded on 20th December, 2006 followed by event of 3.2 M (30.8ºN, 76.6ºE) in NW Himalayas. These events are also correlated with the radon anomaly recorded in soil gas on 11th December, 2006 also. The second anomaly was recorded on 3rd January, 2007, followed by the event 2.6 M in NW Himalayas. The third anomaly was recorded on 14th June, 2007, followed by the event 3.8 M in NW Himalayas. The nature of this anomaly was negative. The

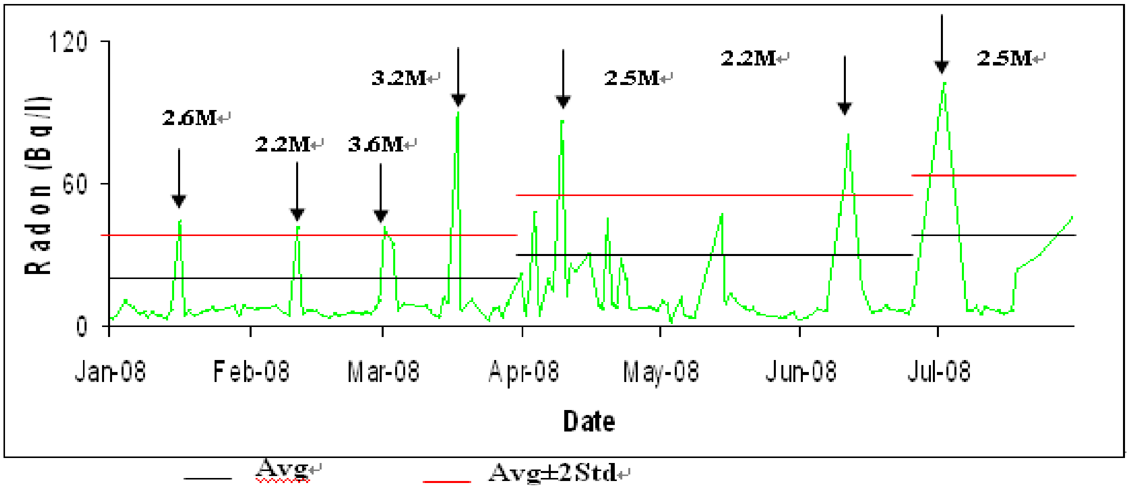

**Figure 7.** Daily variation of radon concentration in ground water at Amritsar from 1st January to 31st July, 2008.

**Table 3.** Listing of radon anomalies recorded at Amritsar in ground water with seismic event.

| Date of anomaly | Date of event | Latitude (ºN) | Longitude (ºE) | Depth (kms) | Magnitude | Epicentral distance (kms) | % Variation from (Avg±2σ) | Precursor time (Day) |
|---|---|---|---|---|---|---|---|---|
| 20/12/06 | 25/12/06 | 76.6 | 30.8 | 10.0 | 3.2 | 168 | 3.9 | 5 |
| 03/01/07 | 12/01/07 | 31.5 | 77.5 | 10.0 | 2.6 | 228 | 5.3 | 9 |
| 14/06/07* | 14/06/07 | 33.4 | 75.4 | 44.6 | 3.8 | 202 | 17.6 | 0 |
| 07/07/07 | 22/07/07 | 33.0 | 78.2 | 15.0 | 5.0 | 330 | 16.7 | 15 |
| 04/11/07 | | | No event | | | | 1.4 | - |
| 04/12/07 | 06/12/07 | 32.5 | 76.3 | - | 2.9 | 151 | 15.9 | 2 |
| 28/12/07 | 07/01/08 | 31.2 | 77.3 | 4.3 | 2.6 | 213 | 2.8 | 10 |
| 16/01/08 | 19/01/08 | 31.3 | 77.4 | 6.0 | 2.6 | 221 | 15.9 | 3 |
| 11/02/08 | 15/02/08 | 31.5 | 77.6 | 6.1 | 2.2 | 237 | 10.8 | 4 |
| 01/03/08 | 11/03/08 | 32.8 | 76.2 | 11.9 | 3.6 | 169 | 10.8 | 10 |
| 17/03/08 | 24/03/08 | 32.8 | 76.2 | 16.8 | 3.2 | 169 | 140 | 7 |
| 09/04/08 | 09/04/08 | 30.1 | 76.8 | 20.7 | 2.5 | 233 | 62 | 0 |
| 11/06/08 | 13/06/08 | 77.1 | 31.6 | 4.2 | 2.2 | 189 | 50.9 | 2 |
| 02/07/08 | 03/07/08 | 77.5 | 31.4 | 7.6 | 2.5 | 228 | 9.6 | 1 |

*Negative anomaly.

fourth radon anomaly was recorded on 7th July, 2007. This anomaly was correlated with Uttarakashi earthquake of 5.0 M which occurred on 22nd July, 2007, fifteen days after the anomalous radon value. This event is also correlated with soil gas radon anomaly recorded on 13th July, 2007. The fifth radon anomaly was recorded on 4th November, 2007, not followed by any event in NW Himalayas.

In the month of December 2007, two anomalies were recorded which were followed by 2.9 and 2.6 M events in NW Himalayas, respectively. The eighth radon anomaly was recorded on 16th January, 2008, followed by 2.6 M (31.3ºN, 77.4ºE) three days prior to the event that occurred on 19th January, 2008. The ninth anomaly was recorded on 11th February, 2008, followed by the event 2.2 M in NW Himalayas. Two anomalies were recorded in the month of March on 1st and 17th March, 2008, followed by the events 3.6 and 3.2 M in NW Himalayas, respectively. These events are also correlated with soil gas anomalies recorded on 11th and 24th March, 2008, respectively. The twelfth radon anomaly was recorded on 9th April, 2008 followed by event 2.5 M in NW Himalayas. The last two anomalies were recorded on 11th June and 2nd July, 2008, followed by 2.2 and 2.5 M events in NW Himalayas, respectively.

Micro seismic events correlated in the present studies were within the epicentral distance of 250 km from the monitoring site, which is within the radon sensitive range

**Table 4.** Correlation coefficients (R) between radon anomaly (A), epicentral distance (D), earthquake magnitude (M) and precursor time (T).

| Seismogeochemical parameter | Correlation coefficient |
|---|---|
| M-D | 0.46 |
| M-A | 0.07 |
| D-A | -0.04 |
| M-T | .0.38 |
| D-T | 0.22 |
| A-T | 0.08 |

and only one major earthquake of 5 magnitude are correlated with the epicentral distance of 330 km from the monitoring site. About 75% of the earthquakes that occurred in NW Himalayas have successfully been correlated with the recorded radon anomalies. Correlation coefficients (R) between radon anomaly (A), epicentral distance (D), earthquake magnitude (M) and precursor time (T) are evaluated (Table 4) from the above data. The magnitude of earthquake and epicentral distance has moderate correlation (0.46) whereas these parameters show low correlation with amplitude of radon anomaly. The amplitude of radon anomaly is positively correlated (0.07) with magnitude and negatively correlated (-0.04) with epicentral distance. The amplitude of anomaly is also controlled by other parameters like meteorological, geophysical and geological variables. Both the amplitude of anomaly and the epicentral distance in general increase with the increase in the magnitude of the earthquake, whereas the amplitude decreases with increase in epicentral distance. The same trend was also observed for radon by Walia et al. (2005b) and for other geochemical precursors by Kissin (1992).

In the present studies, the precursor time and magnitude of earthquake has shown a moderate correlation (0.38). The amplitude of radon anomaly and epicentral distance is positively correlated with precursor time with the values of 0.08 and 0.22, respectively. Although, radon concentration has shown higher correlation coefficient with metrological parameters like temperature and pressure but still radon anomalies show a good correlation with distant seismicity of NW Himalayas. Most of the events correlated in the present study are having epricentral distance from hundred to few hundred kilometers from the monitoring site. The entire events correlated in the present study are micro seismic except only one major earthquake of 5 magnitudes. An attempt has been made to find the constant ‘a’ and ‘b’ in the empirical equations between earthquake magnitudes, epicentral distance and precursor time (Wattananikorn et al., 1998; Planinic et al., 2004; Miklavcic et al., 2008; Singh et al., 2010).

In order to find the constant a and b, the earthquake of every magnitude at the distance (D) less than or equal to10 km from the monitoring site is selected; Also, in case of $M \geq 2$; $10 < D \leq 100$; for $M \geq 3$; $100 < D \leq 200$ and for $M \geq 4$; $D > 200$. In the case of spatially and temporally clustered earthquakes, the largest earthquake is assumed to precede the radon anomaly in the present studies (Hartmann and Leavy, 2005). The value of “a” obtained from the present data varies from 2.2 to 6.8, with an average value of 4.8. The value of “a” in NW Himalayas calculated by Singh et al. (2010) varied from 1 to 8, with an average of 2.7. The value of “b” obtained from the present data varied from -0.3 to 1.0, with an average value of 0.5. The value of “b” in NW Himalayas calculated by Singh et al. (2010) varied from -0.4 to 1.2 with an average of 0.3. The difference in the range of values of the constant a and b in the present investigation compared with those calculated by Singh et al. (2010) may be due to the difference in the geological formations of the studied areas. The present monitoring station is lying in the foothill of NW Himalayas, India, where as the area studied by Singh et al. (2010) is lying in the NW Himalayas.

## Conclusion

About 75% of the radon anomalies observed in soil gas and ground water in the study area correlates with the micro seismic events that occurred in the North West Himalayas, but the influence of meteorological parameters on radon exhalation cannot be neglected. The difference in the range of values of the constant a and b in the present investigation compared with earlier studies in NW Himalayas may be due to the difference in geological formations of the studied areas. From the present and earlier studies, we can conclude that the earthquake is a dynamic phenomenon and till date there has been no model univocally linking earthquakes and radon anomalies. The analysis of other carrier gases in addition to radon may help in better understanding the phenomena of earthquake precursory studies.

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### REFERENCES

Choubey VM, Sharma KK, Ramola RC (1997). Geology of radon occurrence around Jari in Parvati valley, Himachal Pradesh, India. J. Environ. Radioact. 34(2):139-147.

Chyi LL, Quick TJ, Yang TF, Chen CH (2005). Soil gas radon spectra and earthquakes. Terr. Atmos. Ocean. Sci. 16:763-774.

Einarsson P, Theodorsson P, Hjartardottir AR, Guojonsson GI (2008). Radon changes associated with the earthquake sequence in June

2000 in the South Iceland Seismic Zone Pure Appl. Geophys. 165: 63-74.

Fleischer RL (1981). Dislocation model for radon response to distant earthquakes. Geophys. Res. Lett. 8:477-480.

Fu CC, Yang TF, Walia V, Cheng CH (2005). Reconnaissance of soil gas composition over the buried fault and fracture zone in southern Taiwan. Geochem. J. 39:427-439.

Guerra M, Lombardi S (2001). Soil-gas method for tracing neotectonic faults in clay basins: the Pisticci field (Southern Italy). Tectonophys, 339:511-522.

Hartmann J, Levy KJ (2005). Hydrogeological and gasgeochemical earthquake precursors - A review for application, Natural Hazards 34: 279-304.

Hesselbom A (1985). Radon in soil gas: A study of methods and instruments for determining radon concentrations in the ground. Uppsala, Sweden. Sveriges Geologiska Undersokning, Ser. C. 803: 1-58.

Igarashi G, Sacki S, Takahata N, Sumikawa K, Tasaka S, Sasaki Y, Takahashi M, Sano Y (1995). Groundwater radon anomaly before the Kobe earthquake in Japan. Science 269:60-61.

Italiano F, Martinelli G, Plescia P (2008). $CO_2$ degassing over seismic areas: The role of mechanochemical production at the study case of central apennines, Pure Appl. Geophys., 165:75-94.

Jaacks JA (1984). Meteorological influence upon mercury, radon and helium soil gas emissions. Ph.D. Thesis, Colorado School of Mines.

King C, Walkingstick C, Basler D (1993). Radon in soil gas along active faults in central California. In: Gundersen, C. S., and R. B. Wanty (Eds.), Field studies of radon in rocks, soils and water. U.S. Geol. Sur. 77-143.

King CY, Minissale A (1994). Seasonal variability of soil-gas radon concentration in central California. Radiat. Meas. 23:683-692.

Kissin IG (1992). Results and prospects of earthquake hydrogeodynamic precursors' research. J. Earthquake Pred. 1:235-244.

Klusman RW (1993). Soil gas and related methods for natural resources exploration, John Wiley and Sons, New York, 483 p.

Kraner HW, Schroeder GL, Evans RD (1964). Measurements of the effects of atmospheric variables on radon-222 flux and soil gas concentration. In: Adams, J. A. S., and W. M. Lower (Eds.), The Natural Radiation and Environment. Univ. Chicago Press, Chicago. pp. 191-215.

Kumar A, Singh S, Mahajan S, Bajwa BS, Kalia R, Dhar S (2009). Earthquake precursory studies in Kangra valley of North West Himalayas, India, with special emphasis on radon emission. Appl. Radiat. Isot. 67:1904-1911

Lepeltier C (1969). A simplified statistical treatment of geochemical data by graphical representation. Econ. Geol. 64:538-550.

Liu KK, Yui TF, Tasi YB, Teng TL (1984/1985). Variation of radon content in groundwater and possible correlation with seismic activites in the northern Taiwan. Pure Appl. Geophys. 122:231-244.

Miklavcic, I, Radolić V, Vuković B, Poje M, Varga M, Stanić J, Planinić J (2008). Radon anomaly in soil gas as an earthquake precursor. Appl. Radiat. Isot. 66:1459-1466.

Miller JM, Ostle D (1973). Radon measurements in uranium prospecting. In: Uranium Exploration Methods (Conference Volume). Inter. Atomic Energy Agency, Vienna. pp. 237-247.

Mukherji P, Chatterjee M, Sen KG (2001). Mathematical modelling of radon emanation for earthquake prediction. In: Hunyadi, I., I. Csige, and J. Hakl (Eds.), Proc. 5th Int. Conference on Rare Gas Geochemistry, Ep Systema, Debrecen, Hungary. pp. 27-35.

Planinic, J., Radolić V, Vuković B (2004). Radon as an earthquake precursor. Nuclear Instruments and Methods Phys. Res. A, 530:568-574.

Quattrocchi FDi, Stefano G, Pizzino L, Pongetti F, Romeo G, Scarloto P, Sciacca U, Urbini G (2000). Geochemical Monitoring System II (GMS II), prototype installation at the "Aqua Difesa" well, within the Etna Region: First Data. J. Volcanol. Geotherm. Res. 101:273-306.

Singh S, Kumar A, Bajwa BS, Mahajan S, Kumar V, Dhar S ( 2010). Earthquake precursory studies in Kangra valley of North West Himalayas, India, with special emphasis on radon emission. Terr. Atmos. Ocean. Sci. 21(4):685-695.

Ulomov VI, Mavashev BZ (1967). A Precursor of a strong tectonic earthquake, Akad. Sci. USSR Earth Sci. Sect. 176:9-11.

Walia V, Su TC, Fu CC, Yang TF (2005a). Spatial variations of radon and helium concentrations in soil gas across Shan-Chaio fault, Northern Taiwan. Radiat. Meas. 40:513-516.

Walia V, Virk HS, Yang TF, Mahajan S, Walia M, Bajwa BS (2005b). Earthquake prediction studies using radon as a precursor in N-W Himalayas, India: A case study. Terr. Atmos. Ocean. Sci. 16(4):775-804.

Walia V, Yang TF, Lin SJ, Hong WL, Fu CC, Wen KL, Chen CH (2009). Continuous temporal soil-gas composition variations for earthquake precursory studies along Hsincheng and Hsinhua faults in Taiwan. Radia. Meas. 44:934-939.

Wattananikorn, K, Kanaree M, Wiboolsake S (1998.) Soil gas radon as an earthquake precursor: Some considerations on data improvement. Radiat. Meas. 29:593-598.

Yang TF, Walia V, Chyi LL, Fu CC, Chen CH, Liu TK, Song CS, Lee RY, Lee M (2005). Variations of soil radon and thoron concentrations in a fault zone and prospective earthquakes in SW Taiwan. Radiat. Meas. 40:496-502.