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RADON AND EARTHQUAKE PREDICTION IN INDIA: PRESENT STATUS

H. S. Virk

Department of Physics, Guru Nanak Dev University, Amritsar 143005, India

ABSTRACT

Radon is present in trace amounts almost everywhere on the earth, being distributed in the soil, groundwater and in the lower atmosphere. Continuous and long term measurements of radon in sub-surface soil and groundwater are carried out using electronic alpha-counter, alphalogger, emanometer and plastic detector, LR-115 type II. Radon concentration level is being monitored daily at Amritsar, Punjab and other stations in Kangra valley, Himachal Pradesh India. Radon anomalies are correlatable to some of the earthquakes which occurred in the region. Radon diffusion from soil and groundwater and influence of meteorological variables on radon emanation have been studied to differentiate true from false anomalies. A network of ten radon recording stations is being set up in the highly seismic zone near the Main Boundary Thrust (MBT) in the Himalayas to forecast future earthquakes using radon as a precursor. Radon is posing a deep concern to human life from health-hazard point of view; it can prove as a saviour of human life if exploited for earthquake prediction.

KEYWORDS

Radon; earthquake; alphalogger; emanometer; anomaly; prediction.

INTRODUCTION

In India about 55% of the land area falls under active seismic zones, considerable destruction was caused by the earthquakes of Kutch (1819), Shillong (1897), Kangra (1905), Bihar-Nepal (1934), Assam (1956), Koyna (1967), Bihar-Nepal (1988) and Uttarkashi (1991). Fortunately, most of these earthquakes in India occurred in sparsely populated areas. With a growing population, damage to life and property is likely to increase, unless success in earthquake prediction is achieved in the near future. A single earthquake in a densely populated region may claim upto a million lives and incur an economic loss up to 100 billion dollars

Radon is the only radioactive noble gas and it does not chemically react with its underground environment, be it rock, gas or water. Scientists were soon tempted to exploit it for earth science studies. Possible correlations between pre-seismic radon concentration anomalies and actual seismic events were brought to the notice of the scientific community some decades ago. Although first jubilation is over, we do believe that the method is worth investigating and still promising provided a long term detailed study is carried out in order to ascertain potential premonitary signals and to eliminate artifacts. Several groups are engaged in USA, USSR, France, China, Japan, Mexico and India to establish radon as an earthquake precursor.

In India, scientists of Atomic Minerals Division, Department of Atomic Energy (Ghosh and Bhalla, 1966) were the first to measure radon concentration in soil and water for its application in geochemical exploration of uranium. The same group exploited these measurements for recording seismic events in the upper Shillong and Dawki areas in the Northeastern part of India since 1981. We also shifted from uranium exploration to earthquake prediction in 1984. The present investigations are being carried out under Himalayan Seismicity Project of Department of Science and Technology, Govt. of India.

RADON AS AN EARTHQUAKE PRECURSOR

The release of radon from natural minerals has been known since 1920's (Spitsyn, 1926) but its monitoring has more recently been used as a possible tool for earthquake prediction. Okabe (1956) exploited the new precursor and discovered a positive correlation between the daily variation of atmospheric radon content near the ground surface and the local seismicity at Tottori, Japan. The long-term radon measurement in the Tashkent artesian basin of Russia first suggested the usefulness of radon as an earthquake precursor. The first observation of significant changes in episodic radon content in deep well water prior to Tashkent earthquake of 1966 is reported by Ulomov and Mavashev (1967). Since then anomalous radon changes in groundwater and soil-gas have been reported for several earthquakes at favourably located stations as far away as several hundred kilometers from their respective epicentres (Sadvosky et al., 1972; Liu et al., 1975; Naguchi and Wakita, 1977; King, 1978, 84; Bichard and Libby, 1980; Mogro-Campero et al., 1980; Smith et al., 1978; Talwani et al., 1980; Teng, 1980; Wakita et al., 1980; Hauksson and Goddard, 1981; Steele, 1981; Teng et al., 1981; Segovia et al.,1986,88; Virk, 1986; Ghosh et al., 1987; Singh et al., 1988). Extensive radon monitoring studies have been conducted in China by a brigade (consisting of several thousand monitoring groups) responsible for mass monitoring and protection against earthquake hazards (UNESCO, 1984). The successful predictions of the Haicheng and Songpan earthquakes in China made people think that perhaps a major breakthrough in earthquake prediction was not very far ahead. However, under similar conditions and using the same methods, the success in Haicheng became failure in Tangshan, where 200,000 people were killed in a devastating earthquake in 1976.

RADON ANOMALIES AND EARTHQUAKE PREDICTION MODELS

The origin and mechanism of observed radon anomalies and their relationship to earthquakes is poorly understood, although several constraints from laboratory experiments, mathematical modelling and in-situ hydraulic experiments have been described (Andrews, 1977; Dobrovolsky et al., 1979). Initially, the dilatancy diffusion model (Scholz et al., 1973) suggested that radon anomalies were related to mechanical crack growth rate in the volume of dilatancy, or to change in flow rate of groundwater. The dilatancy model provides a framework within which a long-term precursor can be fitted in the general sense. The time scale for such divergent parameters as the ratio of seismic velocities, changes in local magnetic field strength, in the earth's electrical resistivity, and in the radon content of subsurface water can be accounted for by the dilatancy model. The drawback with this explanation is that it often requires an unreasonably large change in stress or strain far away from the subsequent epicentre. In summarizing various precursor phenomena, Scholz et al.(1973) found that the time of appearance and/or duration of a precursor are roughly proportional to the Richter magnitude of the subsequent earthquake.

Anderson and Grew (1977) first proposed an alternative mechanism based on the stress corrosion theory. This attributes the radon anomalies to slow crack growth controlled by stress correlation in a rock matrix saturated by groundwater. They argue that crack growth by stress corrosion should proceed any mechanical cracking in a wet environment. Subsequently, Atkinson (1979; 1980) confirmed experimentally that geological materials can suffer crack growth at very low strain rates in the presence of high humidity. The mechanism of stress corrosion suggests that the occurrence of radon anomalies may depend on strain rate and local conditions such as rock type, elastic moduli, the pattern of microearthquakes, the degree of saturation, temperature, stress intensity factors and hydraulic properties.

King (1978) proposed a compression mechanism for radon release. According to this mechanism the anomalous high radon concentration may be due to an increase in crustal compression before an impending earthquake that squeezes out the soil gas into the atmosphere at an increasing rate. An increased outgassing rate may perturb the vertical subsurface radon concentration profile such that the deeper soil gas containing more radon is brought up to the detection level.

It is observed that radon anomalies frequently, but not always, precede earthquakes. While a radon anomaly may be associated with an earthquake shock, the exact time when the shock will appear can not be predicted. The earthquake shock may appear while the radon is in an increasing or decreasing mode. This behaviour may be due to the position of the monitoring site with respect to the epicentre of the earthquake. One Chinese study (Liu et al., 1975) suggests that monitors located in zones of compressional strain record anomalous increases, whereas those in dilatent zones record abnormal decreases. The delay in receiving the signal at the monitoring site from the epicentre is one of the factors which determines whether the earthquake will occur while the radon is in a rising or falling trend (Ghosh et al., 1987). However, the subsequent shock may not be equally spaced so that the radon anomaly may be used only as an indication of a possible earthquake.

RADON MONITORING TECHNIQUES

For earthquake prediction using radon monitoring, both spatial and sequential measurements are probably needed. Recording stations were set up at Guru Nanak Dev University, Amritsar in 1984 and at H.P. Krishi Vishav Vidyalya, Palampur in Kangra valley of Himachal Pradesh in 1989. The radon monitoring was carried out at sites free from uranium mineralization to reduce background effects. Radon monitoring stations fall in the North-Western seismic zone of India, with Palampur located on the Main Boundary Thrust (MBT) in the Himalayan foot-hills while Amritsar is situated about 150 km away in the south-west of MBT (Fig.1).

The fluctuations in near surface and groundwater radon concentration are monitored using both instantaneous and time-integrated techniques (Virk, 1986; Virk and Singh, 1992). Track-etch, alpha-logger and emanometry techniques have been exploited for long term, short term and instantaneous radon recording, respectively. Physical principles involved in all three techniques are different but the most important common feature is the detection and recording of alpha particles emitted by radon and its daughters. It is imperative to calibrate all types of radon detectors, namely, plastic track detector (LR-115 type II), ZnS(Ag) scintillation detector and silicon-diffused junction detector using 5.4 microCurie (200 kBq) radium chloride standard solution preferably under similar ambient conditions as prevailing at radon monitoring sites. Calibration constants are listed in Table 1.

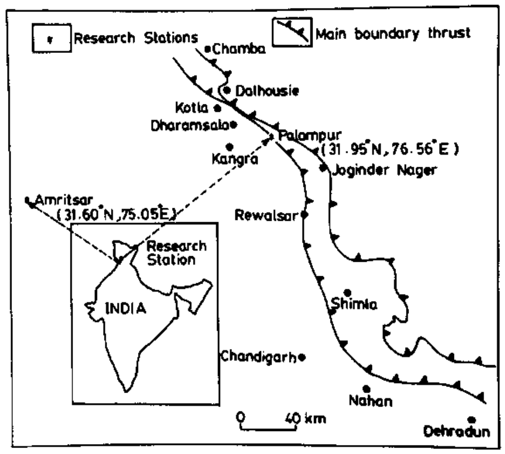

Fig. 1. Radon monitoring stations and Main Boundary Thrust of Himalayas.

Table 1. Calibration constants for Radon detectors.

Detector	Sensitivity	Equivalent Activity pCi/ml	Equivalent Activity Bq/ml	Manufacturer
ZnS(Ag)	1cpm	0.003	1.1×10^{-4}	A. M. D. Hyderabad, India.
Silicon-diffused Junction (Alphameter-400)	1cpm	0.240	0.009	Alpha Nuclear Co. Toronto, Canada.
LR-115 Type 2 (CN-Plastic film)	1 track $mm^{-2}hr^{-1}$	0.02 ± 0.02	0.074 ± 0.002	Kodak-Pathé, France.

RADON EMISSION AND METEOROLOGICAL VARIABLES

Radon emission is very sensitive to environmental disturbances and is influenced by meteorological and seasonal variations which must be understood for discriminating the genuine signal from the noise. To eliminate the effects of spurious fluctuations, meteorological variables such as air and soil temperature, barometric pressure, wind velocity, humidity and rainfall are continuously recorded using appropriate instruments.

A correlation matrix is computed for the entire data set of radon emission and meteorological variables. It is evident from Table 2 that radon emission shows a positive correlation with both temperature and wind velocity. An increase in surface temperature not only causes the soil-gas radon to expand and escape but also tends to release the vapour species adsorbed to the surface soil particles. Radon emission increases with the increase in wind velocity as it accelerates the flow of soil-gas thereby increasing the radon content.

A negative correlation is observed between the radon emission and the barometric pressure. A varying barometric pressure may exert a pumping effect on the soil-gas. An increase in atmospheric pressure tends to push the radon poor atmospheric air into the ground resulting in the fall of radon concentration while the decrease in pressure lets the radon rich soil-gas escape from the deeper layers of the ground. The radon release also shows a weak inverse relation with humidity and rainfall. High moisture content in the soil dissolves the diffusing radon and deep percolation of rain water removes the soil-gas radon by transport mechanism (Ghosh and Bhalla, 1981). However, in case of light rain or drizzle, the radon emission shows an increase. This may be due to the closure of capillary pores on the top-soil which results in the accumulation of radon below the impervious layer and is available in excess at the bottom of the auger hole.

Table 2. Correlation of radon emission with meteorological variables

Variables	Alphameter				SSNTD	
	Daily	Weekly	15 days	Monthly	Weekly	Monthly
Max. Temperature(^{o}C)	0.35	0.47	0.47	0.54	0.33	0.46
Min. Temperature(^{o}C)	0.42	0.58	0.52	0.58	0.43	0.48
Wind Velocity(Km/hr.)	0.39	0.50	0.49	0.56	0.32	0.56
Bar. Pressure(mm.)	-0.35	-0.47	-0.43	-0.35	-0.47	-0.40
Rainfall (mm.)	-0.42	-0.20	-0.20	-0.19	-0.24	-0.13
Humidity (%)	-0.05	-0.13	-0.19	-0.17	-0.11	-0.07

CORRELATION OF RADON DATA WITH SEISMIC EVENTS

There is no general definition of an anomaly for time series data of geochemical and/or geophysical observations. Hence, we must set a criterion for an anomaly appropriate to our radon monitoring. We define the radon anomaly as the positive deviation that exceeds the mean radon level by more than twice the standard deviation.

Several impulsive radon increases with amplitudes much larger than the background level may be recorded under different weather conditions. It is imperative to correct the data for the influence of meteorological variables by using the correlation matrix. The fact that an impulsive radon increase is recorded under a variety of weather conditions suggests that the radon anomaly is more likely to be caused by some crustal disturbance rather than by the atmospheric disturbance.

Radon data from Amritsar

Daily radon monitoring work in soil-gas started at Amritsar in March, 1984 using alphameter-400. In all, seven radon anomalies were recorded (Fig. 2)

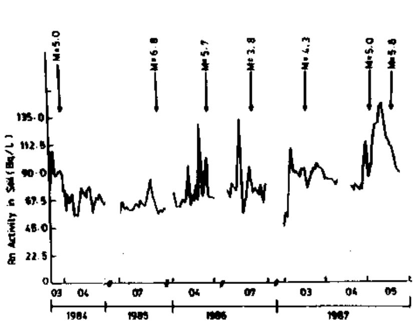

Fig. 2. Radon time-series data in soil-gas using alphameter-400.

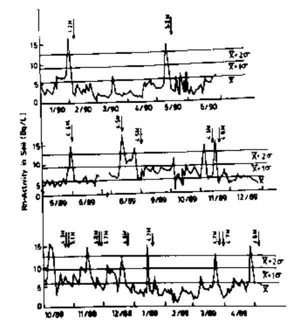

Fig. 3. Radon activity in soil gas using emanometer.

and correlated with seismic activity in Kangra and Hindukush regions (Virk, 1986). Radon monitoring work using emanometer (RMS-4501) started in October, 1988 after a gap of more than a year. Thirteen radon anomalies (Fig. 3) were recorded between October 7, 1988 to May 15, 1990. All these anomalies are correlated to earthquakes which occurred in Hindukush area 400–500 km away from the radon monitoring station at Amritsar. The focal depth of these earthquakes varies from 15 to 229 km and the magnitude varies from 4.2 to 6.4M (Table 3). These radon anomalies are related to seismic activity rather than to atmospheric disturbance because the cumulative variation in radon content due to various meteorological parameters is below the $x \pm 1\sigma$ value.

From January 1, 1991 radon monitoring was started in both soil-gas and groundwater. For soil-gas, radon emanometer and plastic detectors were employed while for groundwater, discrete measurements were taken using ZnS(Ag) scintillation assembly. The average values of radon concentration in soil-gas and groundwater for the year 1991 are 11.32 ± 0.56 and 1.55 ± 0.10 Bq/L with a standard deviation of 5.04 and 0.33, respectively. Nine radon anomalies (Fig. 4) were recorded in both soil-gas and groundwater during the span of one year. Peak values were generally higher in soil-gas as compared to those observed in groundwater. Another discernible feature of recorded data is that radon anomalies occur first in groundwater and then in soil-gas which confirms the hypothesis that fluid motions are responsible for radon transport through the crustal layers and top soil.

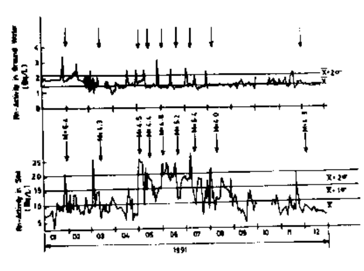

Fig. 4. Radon activity in soil-gas and groundwater at Amritsar using emanometer.

Radon anomalies are also recorded in time-integrated radon data (Fig. 5) obtained by using LR-115 plastic detectors. Almost all the anomalous peaks cross $\bar{x}+2\sigma$ level and are correlatable to seismic events that occurred in the Hindukush region during 1991 (Table 3). Meteorological variables were recorded continuously alongwith the radon data at the monitoring site (Fig. 6). The cross-correlation of radon data with meteorological parameters is helpful in eliminating spurious noise from the signal.

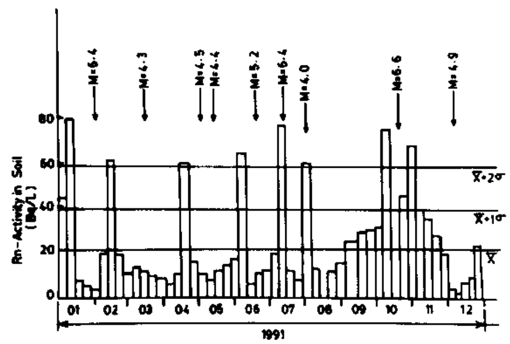

Fig. 5. Weekly radon activity in soil-gas using plastic track detector.

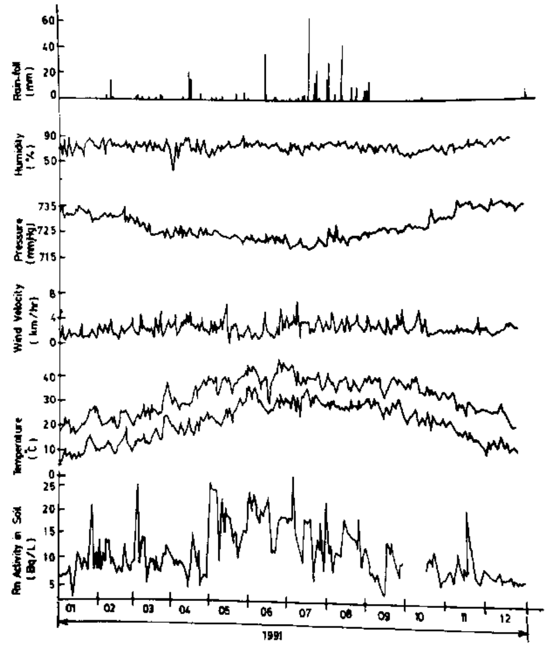

Fig. 6. Record of meteorological variables alongwith daily variation of soil-gas radon at Amritsar.

Table 3. Radon emanometry data from Amritsar.

Occurrence of Radon Anomaly	Correlatable Seismic Event latitude (λ)	Longitude (ϕ)	Depth (km)	Magnitude (M)	Occurrence of seismic event
Oct. 07, 1988	36.4°N	69.9°E	33	4.3	Oct.24, 1988
	36.5°N	70.8°E	219	5.1	Oct.26, 1988
Nov. 14, 1988	35.8°N	70.5°E	92	4.8	Nov.27, 1988
	36.5°N	70.7°E	33	4.7	Nov.28, 1988
Dec. 19, 1988	36.5°N	70.9°E	229	4.6	Dec.25, 1988
Jan. 14, 1989	36.8°N	70.7°E	133	4.2	Jan.19, 1989
Mar. 23, 1989	36.4°N	70.5°E	211	4.7	Mar.28, 1989
	36.9°N	69.5°E	33	4.7	Mar.31, 1989
Apr. 27, 1989	36.5°N	70.1°E	219	4.8	May 06, 1989
May 31, 1989	36.4°N	70.7°E	223	4.5	Jun.06, 1989
Aug. 12, 1989	36.4°N	70.3°E	222	4.5	Aug.12, 1989
Aug. 25, 1989	36.0°N	70.4°E	141	4.5	Sep.01, 1989
Nov. 06, 1989	37.1°N	70.4°E	78	4.3	Nov.12, 1989
Nov. 16, 1989	36.4°N	70.8°E	193	4.8	Nov.19, 1989
Jan. 31, 1989	29.6°N	77.2°E	15	4.2	Feb.09, 1990
May 10, 1990	36.4°N	70.4°E	113	5.9	May 15, 1990
Nov. 10, 1990	33.6°N	75.8°E	75	4.8	Nov.12, 1990
Jan. 28, 1991	36.1°N	70.5°E	15	6.4	Feb.01, 1991
Jan. 27, 1991*					
Mar. 06, 1991	34.6°N	72.5°E	33	4.3	Mar.16, 1991
Mar. 04, 1991*					
May 03, 1991	36.0°N	69.9°E	109	4.5	May 05, 1991
May 03, 1991*					
May 14, 1991	36.5°N	69.0°E	33	4.4	May 17, 1991
May 14, 1991*					
Jun. 02, 1991	36.4°N	69.6°E	33	4.8	Jun.04, 1991
May 30, 1991*					
Jun. 19, 1991	32.2°N	76.9°E	15	5.2	Jun.23, 1991
Jun. 16, 1991*					
Jul. 08, 1991	36.4°N	71.1°E	223	6.4	Jul.14, 1991
Jul. 07, 1991*					
Aug. 02, 1991	33.0°N	76.4°E	14	4.0	Aug.07, 1991
Aug. 02, 1991*					
Nov. 25, 1991	36.4°N	69.3°E	42	4.9	Dec.04, 1991
Nov. 24, 1991*					

*Radon anomaly recorded in groundwater.

Radon data at Palampur

Daily and weekly measurements of radon in soil-gas and groundwater have been recorded at Palampur since August, 1989 using radon emanometry and track-etch techniques. The mean values of radon concentration from daily and weekly monitoring in soil-gas are 27.50±2.5 and 28.48±3.0 Bq/L with standard deviation of 11.49 and 25.81, respectively. The daily measurements in groundwater using radon emanometry give an average value of 48.86±3.0 Bq/L with a standard deviation of 14.89.

The first observable radon anomaly (Fig. 7) was recorded on August 30, 1989 with radon concentration about 70 % above the mean value. This anomaly also occurred in groundwater with radon rise of 60 % above the mean. Both the soil-gas and groundwater radon anomalies were followed by an earthquake of magnitude 2.8 which occurred on Austust 31, 1989 with an epicentre in Dharamsala area about 30 km from the recording station.

In all sixteen radon peaks are observed in soil-gas and groundwater radon data (Fig. 7) and most of these peaks satisfy the criteria set for a radon anomaly after the signal is corrected for the noise. Surprisingly, all these anomalies are correlatable with seismic events that occurred in North-West Himalayas (Table 4). Weekly radon data recorded by Track-Etch technique is also plotted (Fig. 8). Radon anomalies are more pronounced but follow a different pattern due to integrating nature of the technique. However, plausible correlations can be established with the earthquakes occurring in the region in an identical manner as for daily data.

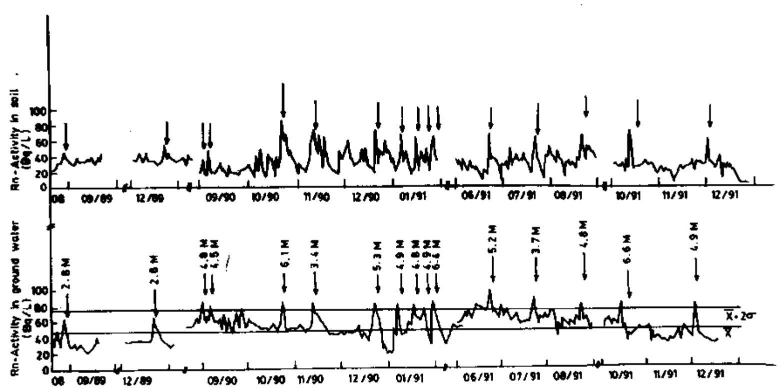

Fig. 7. Radon activity in soil-gas and groundwater at Palampur using emanometry.

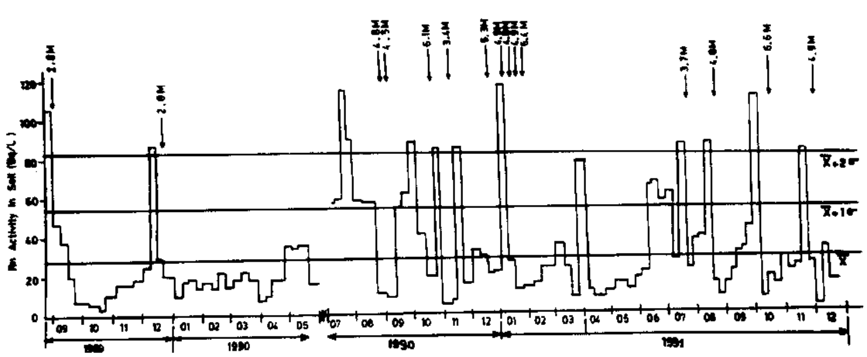

Fig. 8. Weekly radon activity in soil-gas at Palampur using track-etch technique.

Table 4. Radon emanometry data from Palampur.

Occurrence of Radon Anomaly	Correlatable Seismic Event latitude (λ)	Longitude (ϕ)	Depth (km)	Magnitude (M)	Occurrence of seismic event
Aug. 30, 1989	In Chamba area		-	2.8	Aug.31, 1989
Dec. 23, 1989	In Dharamsala area		-	2.8	Dec.24, 1989
Sep. 02, 1990	36.40°N	70.63°E	33	4.8	Sep.03, 1990
Sep. 07, 1990	37.73°N	69.70°E	33	4.5	Sep.08, 1990
Oct. 24, 1990	35.19°N	70.63°E	15	6.1	Oct.25, 1990
Nov. 14, 1990	30.49°N	79.27°E	15	3.4	Nov.17, 1990
Dec. 23, 1990	33.30°N	75.65°E	30	5.3	Dec.25, 1990
Jan. 08, 1991	33.61°N	76.01°E	15	4.9	Jan.10, 1991
Jan. 18, 1991	31.56°N	77.53°E	33	4.8	Jan.20, 1991
Jan. 24, 1991	37.08°N	71.16°E	32	4.9	Jan.26, 1991
Jan. 30, 1991	36.05°N	70.49°E	15	6.4	Feb.01, 1991
Jun. 22, 1991	32.32°N	76.68°E	33	5.2	Jun.23, 1991
Jul. 23, 1991	32.21°N	76.42°E	17	3.7	Jul.24, 1991
Aug. 22, 1991	36.36°N	68.80°E	33	4.8	Aug.23, 1991
Oct. 15, 1991	30.73°N	78.80°E	19	6.6	Oct.20, 1991
Dec. 03, 1991	36.39°N	69.30°E	42	4.9	Dec.04, 1991

CONCLUSIONS

(1) From our soil-gas and groundwater radon monitoring results (Virk, 1986, 1990; Singh et al., 1988; Ramola et al., 1990; Virk and Singh, 1991) of over seven years as well as those of other workers reported in the literature, we conclude that radon anomalies are generally associated with seismic activity. Hence radon can serve as a useful precursor for earthquake prediction in India.

(2) Most of the radon anomalies in both-soil gas and groundwater show perfect correspondence and are recorded simultaneously. This augurs well for accepting radon as an earthaquake precursor even though peak radon concentrations are widely different in both the media.

(3) Recording station at Amritsar is not sensitive to seismic events of magnitude 3.5 or lower occurring in Kangra valley. Since Palampur station is located on the main boundary thrust of the Himalayas, it is even sensitive to seismic events of magnitude lower than 3 which occurred within a range of 50 km of radon monitoring station.

(4) It is also significant to select radon monitoring sites carefully, standardise experimental procedures and instruments in order to record data, perform rigorous statistical data analysis in order to identify radon signals from the noises and conduct theoretical and experimental studies of the physical basis of tectonically induced radon anomalies in a seismic zone.

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