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Radon anomalies in soil-gas and groundwater as earthquake precursor phenomena

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ABSTRACT

Earthquake-related changes in soil-gas and groundwater radon have been detected at a sensitive observation site in the Kangra valley, Himachal Pradesh, India, using both instantaneous and time-integrated techniques. The recording station at Palampur in the Kangra valley is located near the main boundary fault of the Himalayas. Eleven earthquake-related anomalies have been recorded since August, 1989 in both the soil-gas and in the groundwater simultaneously. In order to differentiate the real signal from noise, the effect of meteorological variables (soil and air temperature, rainfall, pressure, humidity and wind velocity) on radon emanation was also studied. Most of the radon anomalies are found to be correlated with earthquakes rather than to changes in meteorological conditions.

Introduction

Radon (^{222}Rn) is produced by decay of radium (^{226}Ra) in the uranium decay series and is present in trace amounts almost everywhere on the earth, being distributed in soil, groundwater and lower levels of the atmosphere. Radon monitoring alone has not yet been successful in predicting an earthquake correctly, but in many cases it has been correlated with earthquake activity (Fleischer and Mogro-Campero, 1979; Steele, 1984/85; Wakita et al., 1989; Papastefanou et al., 1989). Anomalous radon changes in groundwater and soil-gas have since been reported for other earthquakes at favourably located stations as far away as several hundred kilometres from their respective epicentres (King, 1978, 1980; Birchard and Libby, 1980; Mogro-Campero et al., 1980; Cox et al., 1980; Teng, 1980; Jiang and Li, 1981; Teng et al., 1981; Hauksson, 1981; Liu et al., 1984/85; Ramola et al., 1990; Virk, 1990; Virk and Singh, 1992). The observed anomalous radon peaks had different amplitudes, apparently depending upon many factors such as earthquake magnitude, epicentral distance, depth and other local conditions.

Initially the dilatancy diffusion model and several other similar models suggested that the radon anomalies are related to mechanical crack growth in the volume of dilatancy or to change in flow rate of groundwater (Ulomov and Mavashev, 1971; Scholz et al., 1973). 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 a review paper of stress corrosion theory, Anderson and Grew (1977) first proposed an alternative mechanism. It attributes the radon anomalies to slow crack growth controlled by stress corrosion which should precede any mechanical cracking in a wet environment. 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, pattern of microcracks, degree of saturation, temperature, the stress intensity factor and hydroscopic properties.

The purpose of this study is to find the usefulness of radon monitoring for earthquake predic-

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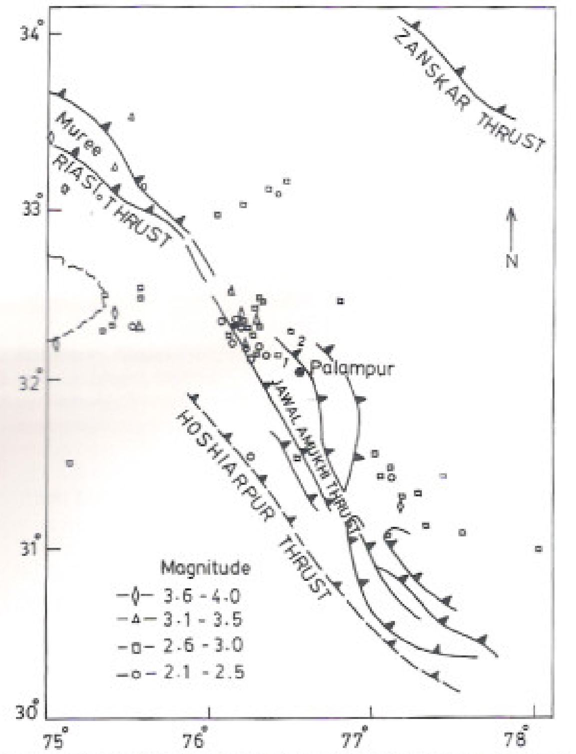

Fig. 1. Map showing the locations of the epicentres of earthquakes with magnitudes of > 2.0 that occurred from August 1989 to January 1991 in and around the Kangra valley, Himachal Pradesh, and the available tectonic features of the area.

tion. Daily and long-term measurements of radon in groundwater and soil-gas are being carried out at Palampur (32.06°N 76.51°E) in the Kangra valley, Himachal Pradesh, near the Main Boundary Fault (MBF) of the Himalayas. The area is well known for its high seismicity and an earthquake of magnitude 8.5 occurred in 1905 with the epicentre about 25 km away from Palampur. A network of seismographs has now been operated in the Kangra valley by the Indian Meteorological Department (I.M.D.) and the Wadia Institute of Himalayan Geology (W.I.H.G.), Dehradun for over a decade. The recording station and epicentres of the seismic events recorded from August 1989 to January 1991 of magnitudes $> 2.0\ M$ in the vicinity of Palampur are shown in Figure 1. Daily and long-term measurements of radon in groundwater and soil-gas have been carried out at Palampur since August 1989 using two different techniques. While radon emanometry is being exploited by daily sampling of soil-gas and groundwater, the track etch technique is used for weekly integrated measurements of radon concentration in soil-gas at a fixed site in Palampur. In order to differentiate the genuine anomalous signals from noise the meteorological parameters, namely soil and air temperature, pressure, relative humidity, wind velocity and rainfall are also monitored along with radon.

Radon monitoring techniques

The radon concentrations in soil-gas and groundwater are measured using instantaneous and time-integrated techniques. The detectors used for radon emanation are a ZnS(Ag) scintillator and plastic-track detectors.

Radon monitoring in soil-gas

For measuring radon in soil-gas, an auger hole is left covered for 24 h. An emanometer is used to measure the alpha emission from radon in the gas fraction of a sample by pumping the gas into the scintillation chamber using a close-circuit technique (Fig. 2; Ghosh and Bhalla, 1966). The alpha particles emitted from the decay of radon impact on the ZnS(Ag) scintillator, creating an energy pulse in the form of photons and these photons are recorded by a scintillation assembly consisting of PMT and scaler unit.

An integrated soil-gas radon concentration over 1-week intervals is inferred from alpha particle tracks determined by the use of a commercially manufactured nitro-cellulose plastic film (LR-115 Type II). A radon–thoron discriminator (Fig. 3; Singh et al., 1984; Ghosh and Soundararajan, 1984) containing strips of film is placed into

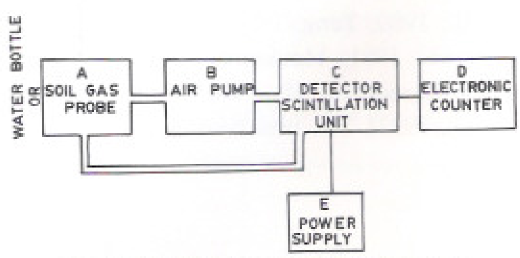

Fig. 2. Diagram of the close-circuit technique.

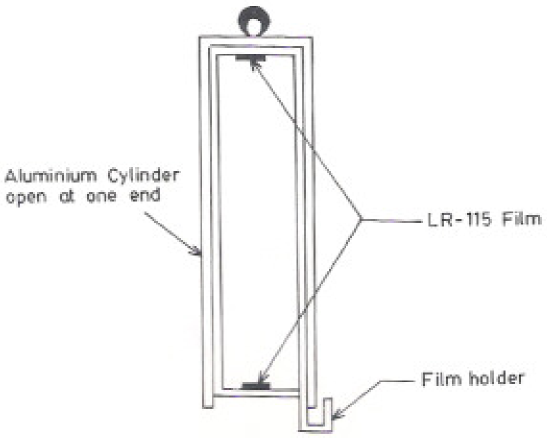

Fig. 3. Radon–thoron discriminator.

the shallow holes 60 cm in depth which are then covered for protection. The films are replaced at specified intervals and are chemically processed to enlarge the damage zone caused by alpha particle interaction. The tracks are counted within an area of 1 cm^2 for density measurements. The measured track density is assumed to be proportional to the average radon concentration of the soil-gas during the period of measurement.

Radon monitoring in groundwater

The groundwater sample is collected daily from a 'bauli' (natural spring) in a sample bottle. A close-circuit technique is used to collect the gas in the ZnS(Ag) detector cell (Ghosh and Bhalla, 1966). The air is circulated in close-circuit containing a hand-operated rubber pump, a water sample bottle, a drying chamber and a ZnS(Ag) detector cell for 10 min (Fig. 2). The counts are recorded after 4 h during which the equilibrium between radon and its daughters is established (Singh et al., 1986).

Results

Time series radon concentration data recorded in soil-gas at Palampur from August 1989 to January 1991 are shown in Figure 4 along with the fluctuations in the meteorological parameters. Weekly integrated radon data using plastic track detectors over the entire period are given in Figure 5. Daily radon emanometry data in groundwater for the same period are plotted in Figure 6.

Radon results in soil-gas

Daily and weekly measurements of radon in soil-gas have been recorded at Palampur since August 1989 using ZnS(Ag) detector and track etch methods, respectively. The average values of radon concentration from daily and weekly measurements are 27.50 ± 2.5 and 28.48 ± 3.0 Bq/l with a standard deviation of 11.49 and 25.81 Bq/l, respectively.

To distinguish the spurious anomalies from the genuine ones, a correlation matrix is established for estimation of influence of meteorological variables on radon emission. The release of soil-gas radon is directly correlated with temperature and wind velocity and it is inversely correlated with pressure, humidity and rainfall (Singh et al., 1988). The correlation coefficients are listed in Table 1. The influence of relative humidity and minimum air temperature on radon is negligible; however, other variables are strongly correlated with diurnal variation of radon emanation from soil-gas as is evident from Table 1.

An empirical criterion is here adopted to define the radon anomaly as the positive deviation that exceeds the mean radon level by more than twice the standard deviation.

The first noticeable radon peak was recorded on August 30, 1989 (Fig. 4a) with radon concentration about 70% above the mean value. The weekly soil-gas radon level was also above the mean level by more than twice the standard deviation (Fig. 5). The radon anomaly was recorded just after heavy rainfall, high humidity and above-normal pressure. The air and soil temperatures were showing a downward trend during this period. All these parameters suppress radon emission from the soil. This radon anomaly was followed by a seismic event (1) of 2.8 *M* which occurred on August 31, 1989 in the Dharamsala area (32.19°N 76.38°E), Himachal Pradesh.

The second peak in soil-gas radon was recorded on December 23, 1989 with radon concentration about 115% above the mean value (Fig. 4a). This anomaly was recorded after rainfall, high wind velocity and low air and soil temperatures. The other meteorological variables were normal during that day. In the weekly integrated data the increase in average radon concentration level started in the last week of October and attained a value above the mean level of more than twice the standard deviation in the second week of December (Fig. 5). This recorded anomaly was followed by an earthquake (2) of 2.8 *M* on December 24, 1989, which occurred in the Chamba area (32.27°E 76.42°), Himachal Pradesh.

From January to August 1990, no significant anomaly correlatable to earthquakes was recorded in soil-gas radon. However, a radon peak is observed in soil-gas using emanometry on March 18,

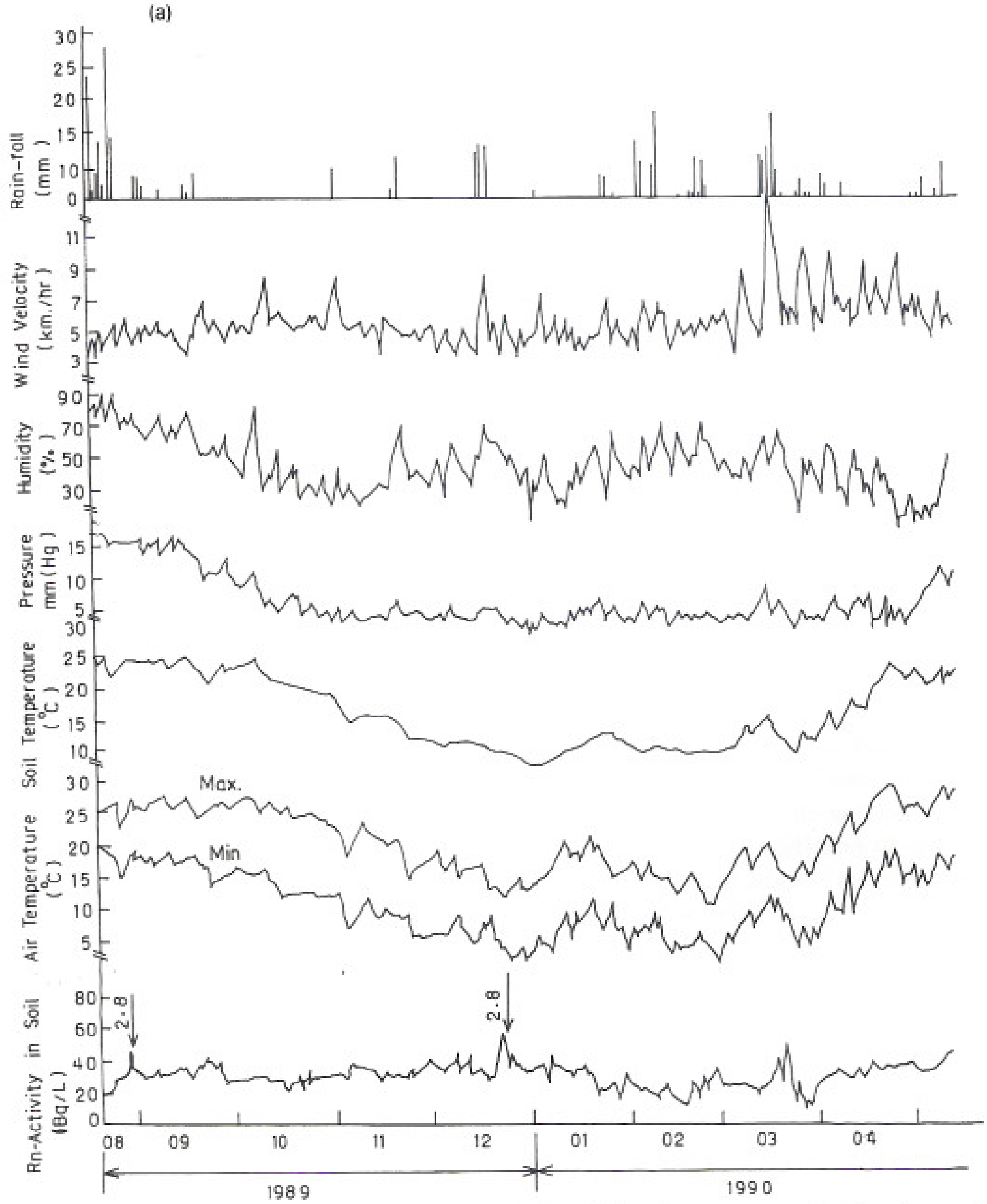

Fig. 4. Daily variation of radon activity in soil-gas with meteorological variables using emanometry: (a) from August 1989 to April 1990; (b) from May 1990 to January 1991.

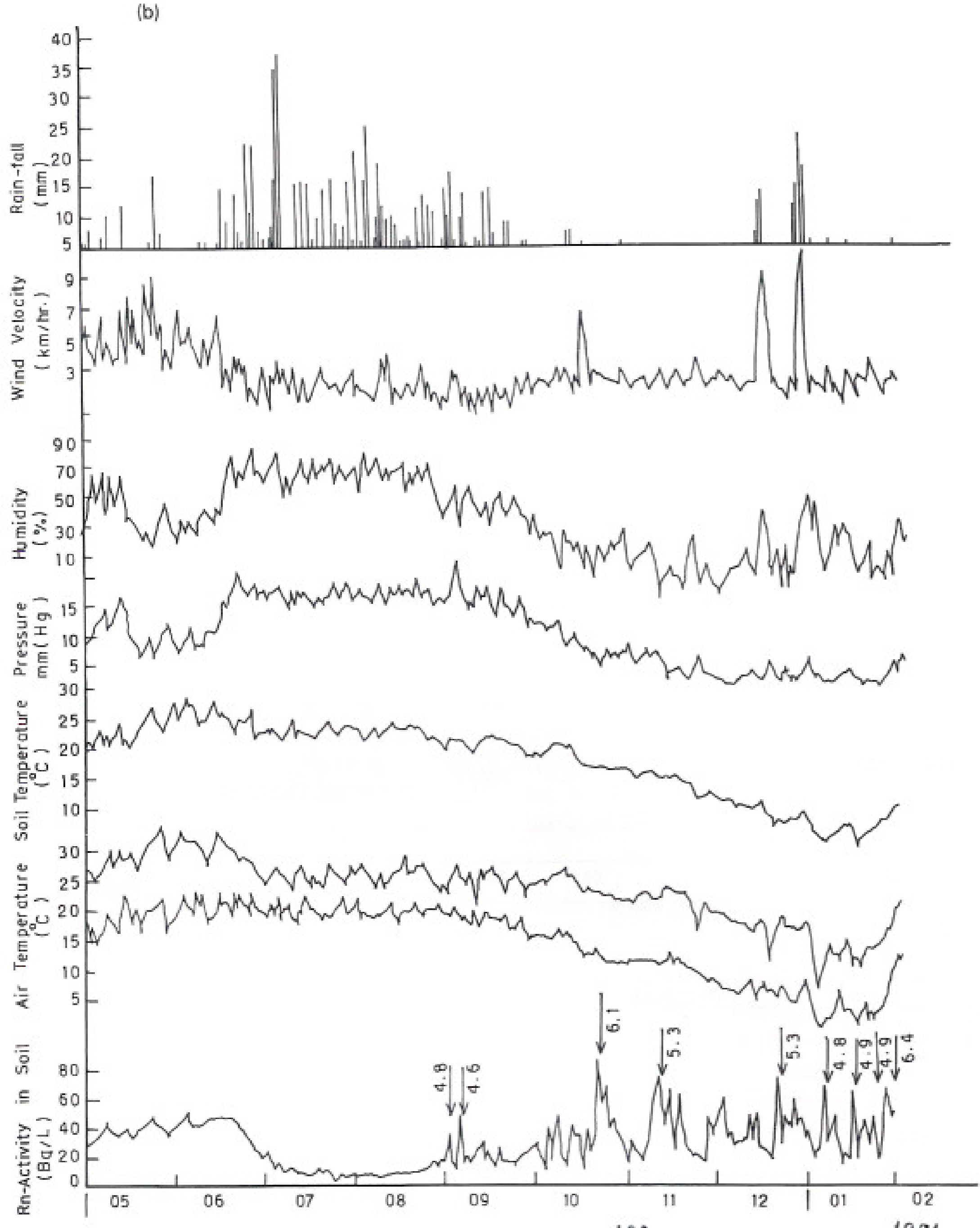

Fig. 4 (continued).

1990. This peak has no correspondence in groundwater and is also not reflected in the weekly data obtained by plastic track detectors. The recorded peak in soil-gas is interpreted as due to very high wind velocity, soil and air temperatures and low pressure during that period.

Two sharp radon peaks were recorded on September 2 and 7, 1990 (Fig. 4b). These peaks occurred during and after heavy rainfall, high humidity and rising pressure—all parameters having negative correlation coefficients for radon. During this period, wind velocity and soil and air

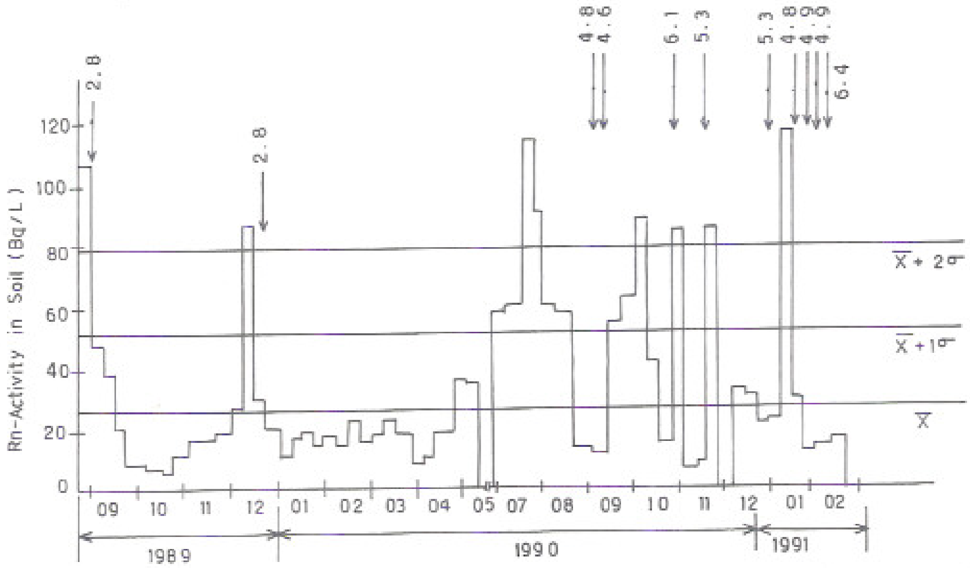

Fig. 5. Integrated (weekly) measurements of soil-gas radon using the plastic-track detector technique (from August 1989 to January 1991).

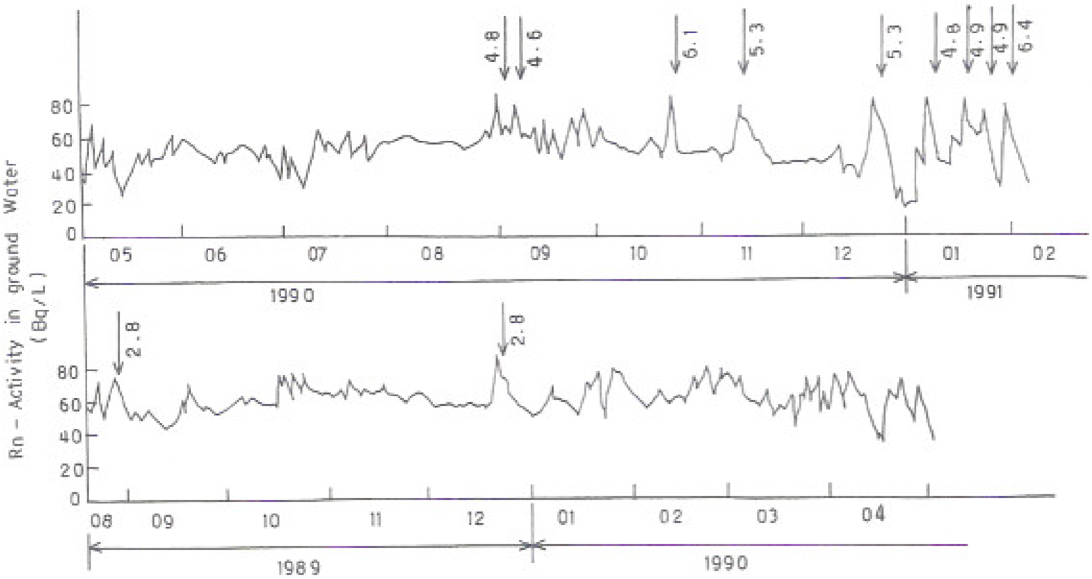

Fig. 6. Daily variation of radon concentration in groundwater (from August 1989 to January 1991) using the close-circuit technique.

TABLE 1

Correlation coefficients of radon emission with meteorological variables

Variables	Air temperature (°C)		Soil temperature (°C)	Wind-velocity	Pressure	Humidity	Rainfall
	max.	min.					
Daily	0.13	0.09	0.21	0.32	−0.18	−0.03	−0.15
Weekly	0.15	0.10	0.25	0.31	−0.21	−0.02	−0.13

temperature favoured radon emission to some extent. However, the net effect of meteorological variables is to suppress the peak (Fig. 4b). These recorded anomalies were followed by the earthquakes (3 and 4) on September 3 and 8, 1990 of 4.8 *M* and 4.6 *M* with epicentres at 36.40°N 70.63°E and 37.37°N 69.70°E in the Hindukush area, respectively.

The fifth pronounced radon anomaly was recorded on October 24, 1990 with radon concentration about 212% above the mean level (Fig. 4b). During the first week of October 1990 the weekly soil-gas radon level recorded in plastic detector samples was also above the mean level by more than twice the standard deviation (Fig. 5). This anomaly occurred when there was no rainfall, low humidity and low pressure, with other parameters showing a normal trend. This recorded anomaly was followed by the severe earthquake (5) of 6.1 *M* on October 25, 1990 in the Hindukush area (35.19°N 70.63°E) in Pakistan.

Another radon anomaly was recorded at the same site on November 14, 1990 with radon concentration about 170% above the mean level (Fig. 4b). Weekly integrated data were also showing an abnormal rise during the last week of October 1990 followed by a sudden fall in November (Fig. 5). This anomalous change in radon concentration was followed by an earthquake (6) of 5.3 *M* with its epicentre at 27.43°N 66.10°E in Pakistan. Meteorological parameters have no appreciable effect on radon emission during this period.

The seventh radon anomaly was recorded on December 23, 1990 with radon concentration about 160% above the mean level (Fig. 4b). Weekly integrated data recorded a peak about three times above the mean during the third week of November followed by a sharp fall and a levelling off of radon concentration during December 1990 (Fig. 5). An earthquake (7) of magnitude 5.3 *M* occurred on December 25 in the Himachal Pradesh area (33.30°N 75.65°E). Except for high wind velocity and low pressure which favour radon emission, other parameters had a negative correlation effect on radon, thus levelling off the meteorological influence on radon data.

Four radon anomalies were observed in January 1991, i.e. on January 8, 18, 24, and 30, with radon concentrations about 140%, 134%, 65% and 147%, respectively, above the mean radon concentration level. All these anomalies were recorded during the dry spell of the winter season (Fig. 4b). The weekly soil-gas radon level was also above the mean level by more than thrice the standard deviation in the second week of January. It decreased to the average level in the third week and much below the mean level during the fourth week of January 1991 (Fig. 5). The anomalies of January 8 and 18 were followed by earthquakes (8 and 9) of 4.8 *M* and 4.9 *M* which occurred in Himachal Pradesh (33.61°N 76.01°E and 31.56°N 77.53°E) on January 10 and 20, respectively. The remaining two anomalies are followed by the earthquakes (10 and 11) of 4.9 *M* and 6.4 *M* which occurred on January 26 and February 1, 1991 in the Hindukush area (37.08°N 71.16°E and 36.05°N 70.49°E, respectively).

It is obvious from the radon data that earthquakes follow a regular sequence soon after the radon anomalies in soil-gas are recorded by emanometer. However, the pattern is different for weekly integrated radon data recorded by using an alpha track etch technique.

Radon results in groundwater

Radon is fairly soluble in water. Because of its inertness its concentration in groundwater is usually independent of fundamental hydrological characteristics—water composition, mineralization and temperature of discharge (Cherdyntsev, 1961; Tanner, 1964); rather its fluctuation depends to a large extent on the tectonic disturbances. A daily sampling programme has been adopted in the Palampur area in the Kangra valley since August 1989. The average value of radon concentration from daily measurements is 48.86 ± 3.0 Bq/l with a standard deviation of 14.89 Bq/l. Temporal variations of radon concentration in groundwater are shown in Figure 6.

The first radon anomaly in groundwater was recorded on August 30, 1989 with a radon concentration about 60% above the mean radon level

(Fig. 6). This anomaly was followed by an earthquake (1) of 2.8 *M* on August 31, 1989 in the Dharamsala area (32.19°N 76.38°E) in Himachal Pradesh. The second radon anomaly was recorded on December 23, 1989 with a radon concentration about 70% above the mean radon level, followed by an event (2) of 2.8 *M* on December 24, 1989 in the Chamba area (32.27°N 76.42°E) in Himachal Pradesh.

Two sharp radon anomalies were recorded on September 2 and 7, 1990 with radon concentration levels about 75% and 65% above the mean radon level, respectively (Fig. 6). These anomalies were followed by the earthquakes (3 and 4) of 4.8 *M* and 4.6 *M* on September 3 and 8, 1990 with the epicentres at 36.40°N 70.63°E and 37.37°N 69.70°E, respectively.

On October 24, 1990 a fifth radon anomaly in groundwater was recorded with a radon concentration about 80% above the mean level, followed by a severe earthquake (5) of 6.1 *M* on October 25, 1990 in the Hindukush area (35.19°N 70.63°E), Pakistan.

The sixth radon anomaly in groundwater was recorded on November 14, 1990 with a radon concentration about 70% above the mean value, followed by an earthquake (6) of magnitude 5.3 *M* with its epicentre at 27.43°N 66.10°E in Pakistan.

The seventh radon anomaly in groundwater was recorded on December 23, 1990 with a radon concentration about 80% above the mean value. This anomaly was followed by an earthquake (7) of 5.3 *M* on December 25, 1990 in Himachal Pradesh (33.30°N 75.65°E).

During January 1991, radon anomalies in groundwater were recorded on January 8, 18, 24 and 30 with radon concentrations of about 75%, 75%, 70%, and 75% above the mean concentration level, respectively. The radon anomalies of January 8 and 18 were followed by earthquakes (8 and 9) of 4.8 *M* and 4.9 *M*, which occurred in Himachal Pradesh at 33.61°N 76.01°E and 31.56°N 77.53°E, respectively. The remaining two anomalies were followed by earthquakes (10 and 11) of 4.9 *M* and 6.4 *M*, respectively, which occurred in the Hindukush area at 37.08°N 71.16°E and 36.05°N 70.49°E, respectively.

Discussion

Figure 1 shows the locations of the earthquakes of magnitudes > 2.0 that occurred in and around the Kangra valley, Himachal Pradesh, along with the available tectonic features of the area. Epicentres of these earthquakes are distributed around the major thrusts across the region. Seismic events corresponding to radon anomalies are numbered. Figure 7 depicts the epicentres of all major earthquakes with magnitudes > 4.0 that occurred in the Kangra valley and the Hindukush region during the study interval. Radon signals corresponding to numbered events (1–11) qualify as anomalies and are correlatable to some of the earthquakes that occurred in the time window. To some extent, radon emanation is prone to earthquake-related processes along the faults, geological conditions in the region and meteorological variations. Radon studies (Virk and Singh, 1992) have established that while the sensitivity of a recording station depends upon the geological conditions at the site, the overall influence of meteorological variations on radon emission and transport is much less significant as compared with the criterion ($\bar{x} + 2\sigma$) fixed for identification of radon anomalies.

Scholz et al. (1973) compiled the data regarding the duration of radon precursory phenomena and their relation to earthquake magnitude. It is desirable to measure radon concentrations during short intervals of time if we want to predict $M = 1$ events. A radon anomaly corresponding to an $M = 1.3$ earthquake, with the epicentre at 18 km distance and 55 km deep, was reported by Fleischer and Mogro-Campero (1979). In our study, radon anomalies corresponding to $M = 2.8$ events are quite predominant (Fig. 5) despite the practical limitation of the track-etch technique for monitoring radon over weekly intervals. However, electronic counters with fast response are more suitable for recording microearthquakes.

From August 1989 to January 1991 eleven radon anomalies were recorded simultaneously in soil-gas and groundwater. These anomalies were followed by earthquakes. The first four anomalies are suppressed in soil-gas because of a very heavy rainfall during that period. These anomalies have normal values in groundwater. The next seven anomalies were recorded in dry weather. The variations in other meterological variables did not affect radon emanation to an appreciable extent. In addition to these earthquake-related anomalies, some other anomalies were also observed in soil-gas, but not in groundwater. The occurrence of these anomalies in soil-gas may be due to some other type of disturbance. The radon levels recorded with the track-etch method showed an anomalous increase to above the $\bar{x} + 2\sigma$ level, and then a decrease to below the normal value before the occurrence of seismic events.

The increase in radon content is connected with the amount of cracking of rock; first there is a sharp increase, and then it decreases before the earthquake due to the closure of small cracks. The observed radon patterns in soil-gas and groundwater during earthquake events are similar and may be explained with the model of the Institute of Physics of the Earth, Moscow (IPE) (Mjachkin et al., 1975).

Conclusions

The recording station at Palampur can record seismic events with magnitudes as low as 2.8 occurring within a range of 50 km distance. It can also record radon anomalies due to earthquakes with magnitudes greater than 4.0 occurring in the Hindukush area at a distance of nearly 500 km. The simultaneous recording of radon anomalies in soil-gas and groundwater is a strong indicator of the physical basis of earthquake prediction using radon monitoring. Heavy rainfall during the rise time of radon concentration in soil-gas suppresses the peak value of radon. However, the cumulative effect due to various meteorological parameters is estimated to be below $\bar{x} + 1\sigma$ value. The source of the anomalous radon concentra-

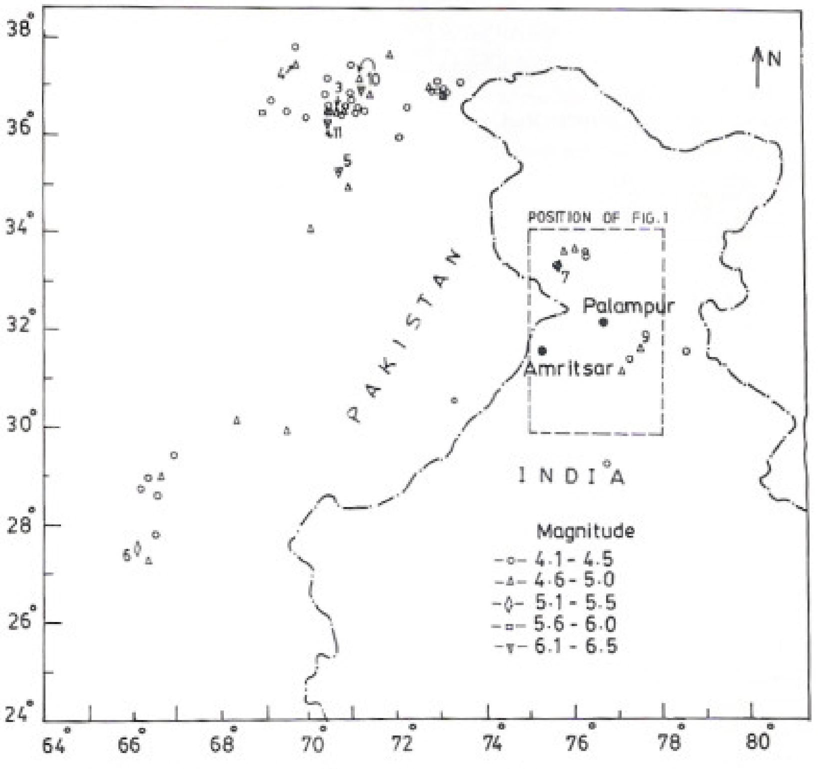

Fig. 7. Map showing the earthquakes with magnitudes of > 4.0 that occurred from August 1989 to January 1991. The epicentres of the earthquakes mentioned in the text are identified by numbers.

tion lies in the immediate vicinity of the detector and this may result from a net upward shift of the near-surface profile of radon influenced by some large-scale mechanism, viz. crustal compression originating at greater depths or convective flow within the earth.

Acknowledgements

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