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The Use of Radon as an Earthquake Precursor

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Abstract—Radon monitoring for earthquake prediction is part of an integral approach since the discovery of coherent and time anomalous radon concentrations prior to, during and after the 1966 Tashkent earthquake. In this paper some studies of groundwater and soil gas radon content in relation to earthquake activities are reviewed. Laboratory experiments and the development of groundwater and soil gas radon monitoring systems are described. In addition, radon monitoring studies conducted at the Guru Nanak Dev University Campus since 1986 are presented in detail. During these studies some anomalous changes in radon concentration were recorded before earthquakes occurred in the region. The anomalous radon increases are independent of meteorological conditions and appear to be caused by strain changes, which precede the earthquake. Anomalous changes in radon concentration before an earthquake suggest that radon monitoring can serve as an additional technique in the earthquake prediction programme in India.

INTRODUCTION

Uranium has a widespread distribution in continental rocks and radon (^{222}Rn) gas is continuously generated within the rock strata as an intermediate decay product of the ^{238}U radioactive series. It decays with a half life of 3.83 days and emits 5.48 MeV α-particles. Since the other two isotopes of radon viz. ^{220}Rn and ^{219}Rn, have comparatively short half lives, their contribution may be ignored for all practical purposes in earthquake prediction. ^{222}Rn is the only isotope with a sufficiently long life such that it can migrate a significant distance from its source.

The release of radon from natural minerals has been known since the 1920s (Spitsyn, 1926), but radon monitoring has only recently been used as a possible tool for earthquake prediction. Although monitoring radon alone has not yet been successful in predicting an earthquake correctly, in many cases it has been correlated with earthquake activity and it has been established as one of the several precursors (Fleischer and Mogro-Campero, 1981). Rather, its release depends to a large extent on the tectonic disturbance of the host minerals, whereby surface areas of microfractures and the total geometric faces of the minerals are altered. An extensive review of radon migration in the ground is given by Tanner (1964, 1980).

The analysis of radon emission and earthquake occurrence can be traced back to a study by Okabe (1956), who discovered a positive correlation between the daily variation of atmospheric radon content near the ground surface and the local seismicity at Tottori, Japan. Radon is fairly soluble in water and long-term radon measurements in the Tashkent artesian basin first suggested the usefulness of radon fluctuations in groundwater as an earthquake precursor. The first observation of significant changes in episodic radon content in deep well water prior to the Tashkent earthquake of 1966 was reported by Ulomov and Mavashev (1967). Since then, radon isotopes have been extensively monitored in many seismic areas of the world for the purpose of earthquake prediction. Anomalous radon changes in groundwater and soil gas have been reported for several earthquakes at favourably located stations at distances of several hundred kilometres from their respective epicentres (Sadvosky *et al.*, 1972; Liu and Wan, 1975; Naguchi and Wakita, 1977; King, 1978, 1980, 1984/85; Bichard and Libby, 1980; Mogro-Campero *et al.*, 1980; Shapiro *et al.*, 1980; Talwani *et al.*, 1980; Wakita *et al.*, 1980; Hauksson, 1981; Hauksson and Goddard, 1981; Steele, 1981; Teng, 1980; Teng *et al.*, 1981; Ghosh *et al.*, 1987; Singh *et al.*, 1988a; Thorsteinsson, 1973; Andrews, 1977; Dobrovolsky *et al.*, 1979). The role of radon anomalies in earthquake prediction has frequently been questioned because significant radon fluctuations may also be caused by environmental disturbances such as weather changes and groundwater pumping.

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 (Thornsteinsson, 1973; Andrews, 1977; Dobrovolsky *et al.*, 1979). Initially, the dilatancy diffusion model, and several other similar models suggested that radon anomalies were related to mechanical crack growth in the volume of dilatency, or to changes 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 on stress corrosion theory, Anderson and Grew (1977) first proposed an alternative mechanism. 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 precede any mechanical cracking in a wet environment. Subsequently, Atkinson (1979, 1980) and Wilkins (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 increased rate. An increased outgassing rate may perturb the vertical subsurface radon concentration profile (radon concentration is known to increase rapidly with depth) such that the deeper soil gas containing more radon is brought up to the detection level.

The aim of the present work has been to study the usefulness of radon monitoring for earthquake prediction. The daily and long-term integrated measurements of radon were carried out in soil and in groundwater. The values of meteorological parameters, such as air temperature, barometric pressure, wind velocity, rain-fall and relative humidity were also measured. Information on these parameters allowed recognition of changes in radon concentration not related to atmospheric effects.

MONITORING SITE

About 60 earthquakes of magnitude more than 6 have occurred in India during the past nine decades. These include the two large events of 1897 and 1950, each with magnitude of about 8.7 (Gupta *et al.*, 1979). The major seismic active region is the north-eastern zone (Kaila and Sarkar, 1978) of India (Fig. 1). The present work has been carried out in Amritsar (Fig. 2), one of the regions in the north-western seismic zone.

EXPERIMENTAL TECHNIQUES

Radon monitoring in soil

The change in near surface radon concentration is measured by using two types of detector, namely the plastic track detector and the silicon-diffused junction detector. Plastic track detectors are capable of recording average values of radon over relatively long periods, but they are insensitive to transient radon variations that last only several hours or less. In order to seek and study such variations, the silicon-diffused junction detector has been used since this can record integrated radon values over short time-periods. The detector is connected to an automated battery-operated system (Alphalogger), which can also record values of environmental parameters such as atmospheric pressure, air temperature and rain-fall. The values of other meteorological parameters, viz. wind velocity and relative humidity, were supplied by the Department of Soils at the Irrigation and Power Research Institute, Amritsar, about 5 km far from the monitoring site.

Using the plastic track detector, a radon–thoron discriminator (Fig. 3) with a LR-115 type II track recorder was used. The discriminator is kept in a auger hole 50 cm deep for one month. After retrieval, the detector films are etched in 2.5 N NaOH solution at 60°C for 2 h and scanned under an optical microscope at a magnification of 600 × for track density measurement. The measured track density is assumed to be proportional to the average radon content.

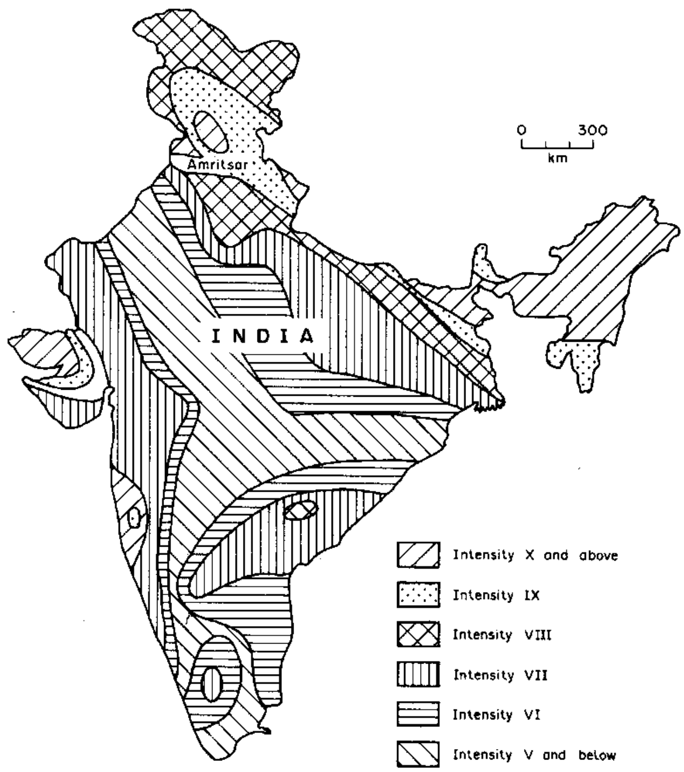

Fig. 1. Observed maximum intensity map of India (Kaila and Sarkar, 1978) based on earthquake data up to 1975.

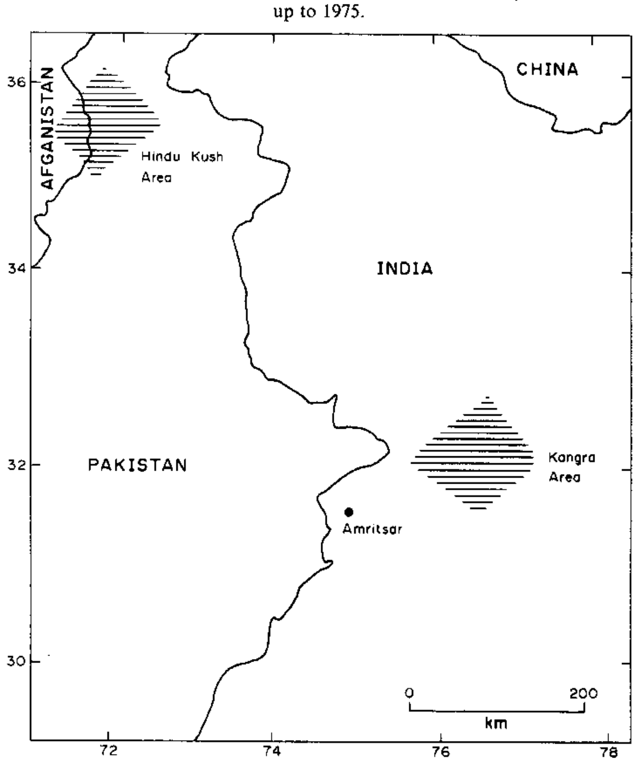

Fig. 2. Location of measurement site (dot) and epicentres of earthquakes (shaded rectangular areas).

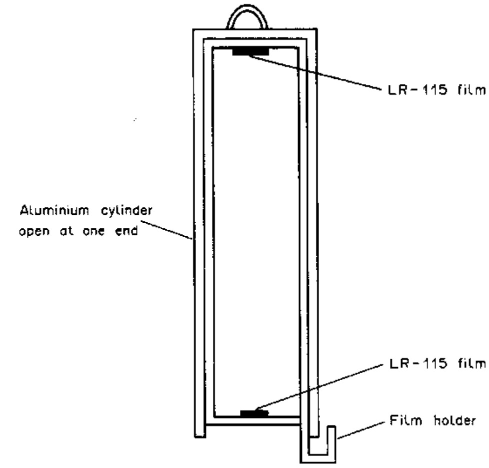

Fig. 3. Radon–thoron discriminator.

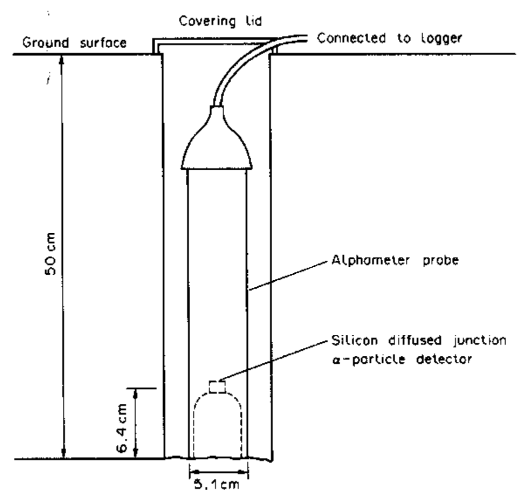

Fig. 4. Schematic diagram of silicon-diffused junction electronic detector.

In the second technique , an alphameter probe is buried in the auger hole at a depth of 50 cm (Fig. 4). The detector is separated from the soil surface at the bottom of the hole by a 6.4 cm gap in order to prevent direct α-particles from the soil reaching the detector; by this means the detector could only sense α-particles generated by radon and the α-emitting daughters. The detector is used for recording the cumulative particle counts at pre-set time intervals.

Radon monitoring in groundwater

The continuous measurement system (Fig. 5) is used for monitoring radon in groundwater. Groundwater is drawn from a well at a depth of 100 m and is allowed to flow continuously through a glass vessel of 1 L capacity and at a flow rate of 1 L/min. The glass vessel is connected in closed-circuit with the detection chamber. The radon gas is transferred from the vessel to the detection chamber by bubbling the water and sucking-off the gas by using a hand-operated rubber pump. A diffused silicon detector (Alphameter-400) is employed for continuous measurement of the radon. Data is stored until a read mode is initiated: the accumulated α-activity is then recorded daily.

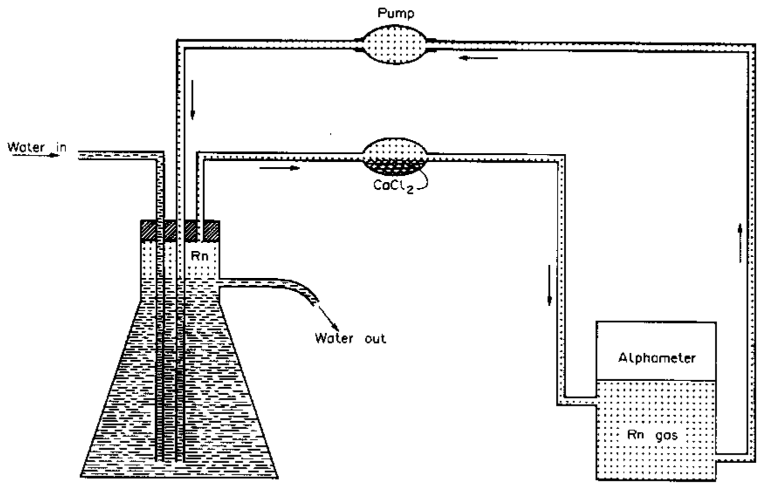

Fig. 5. Apparatus for continuous measurement of radon in water.

RESULTS AND DISCUSSION

Effect of meteorological variables on radon emission

Radon emission is very sensitive to environmental disturbances. To eliminate the effects of spurious fluctuations, meteorological variables such as air temperature, barometric pressure, wind velocity, humidity and rainfall are continuously recorded using appropriate instruments. The correlation of radon emission with meteorological factors is extremely useful for discriminating the genuine signals from spurious events.

The observed radon concentration data and the value of barometric pressure and air temperature are shown in Fig. 6. The radon data was recorded at 8.00, 13.00 and 18.00 h: on sunny days it usually showed clear diurnal variations which are about $\pm 30\%$ of the average level and generally peak in the late afternoon when the barometric pressure is at its daily minimum. Similar variations have been recorded by other authors (Tanner, 1980; King, 1984/85) and may be due to the diurnal behaviour of temperature and barometric pressure.

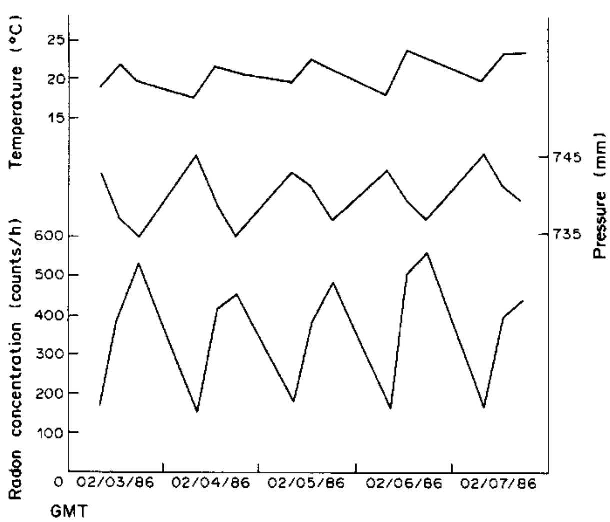

Fig. 6. Short term fluctuation in radon concentration, barometric pressure and air temperature from 3–7 February 1986.

The effects of air temperature on soil gas radon over a period of one year are shown in Fig. 7. The air temperature is found to be positively related to the radon concentration, since both radon concentration and air temperature are relatively high from April to August and low for the remaining period. This effect is believed to be the result of condensation in the soil at low temperatures which decreases with increase in air temperature, allowing more radon to escape. An increase in surface temperature not only causes soil air to expand and escape, but also tends to release the vapour species adsorbed to the surface of soil particles. However, it is worth noting that King (1978) found an inverse relationship between radon emanation and temperature in the San Andreas fault region whereas Gableman (1972) found a positive correlation between α-activity and temperature.

Figure 8 shows the observed radon concentration data and values of barometric pressure for one year. The radon concentration is found to be inversely related to the barometric pressure. It was found to increase with decrease in pressure from April to August and to decrease with increase in pressure for the remaining period. A varying barometric pressure may exert a pumping effect on the soil gas, drawing out radon-rich gas from the deeper layers during the period of decreasing pressure and forcing radon-poor atmospheric air into the ground during the period of increasing pressure (Gableman, 1972; Karner et al., 1964; Clements and Wilkening, 1974; Singh et al., 1988b).

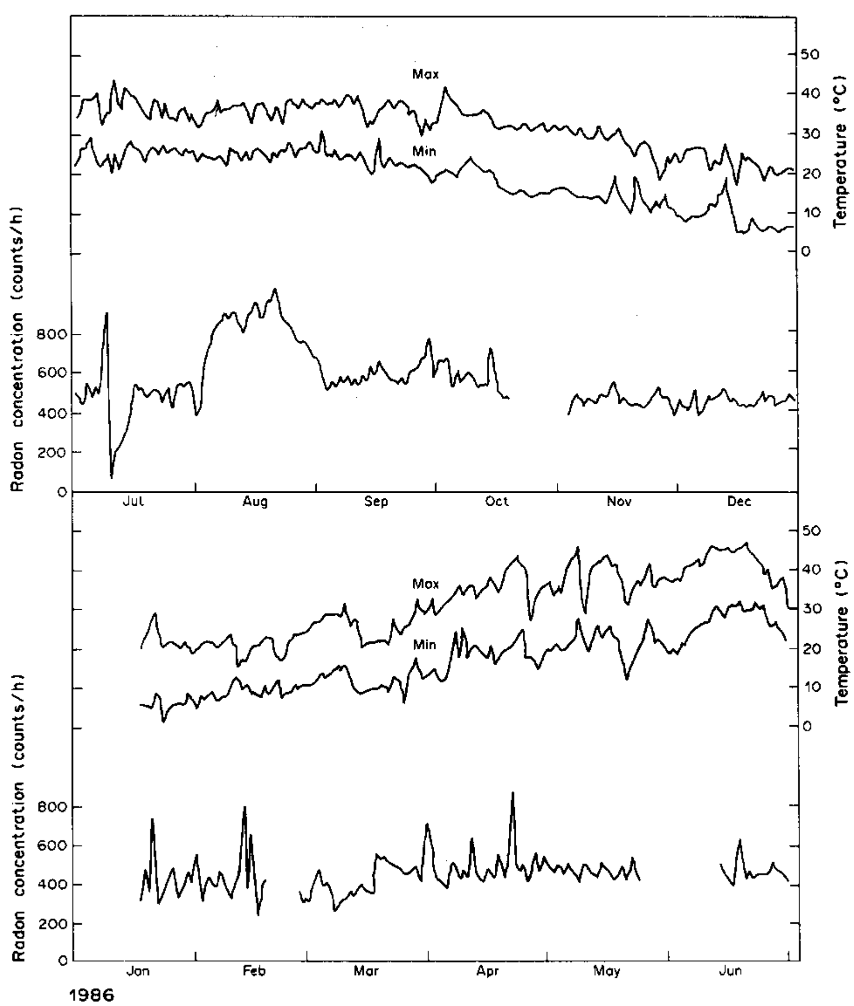

Fig. 7. Variation of radon concentration with air temperature.

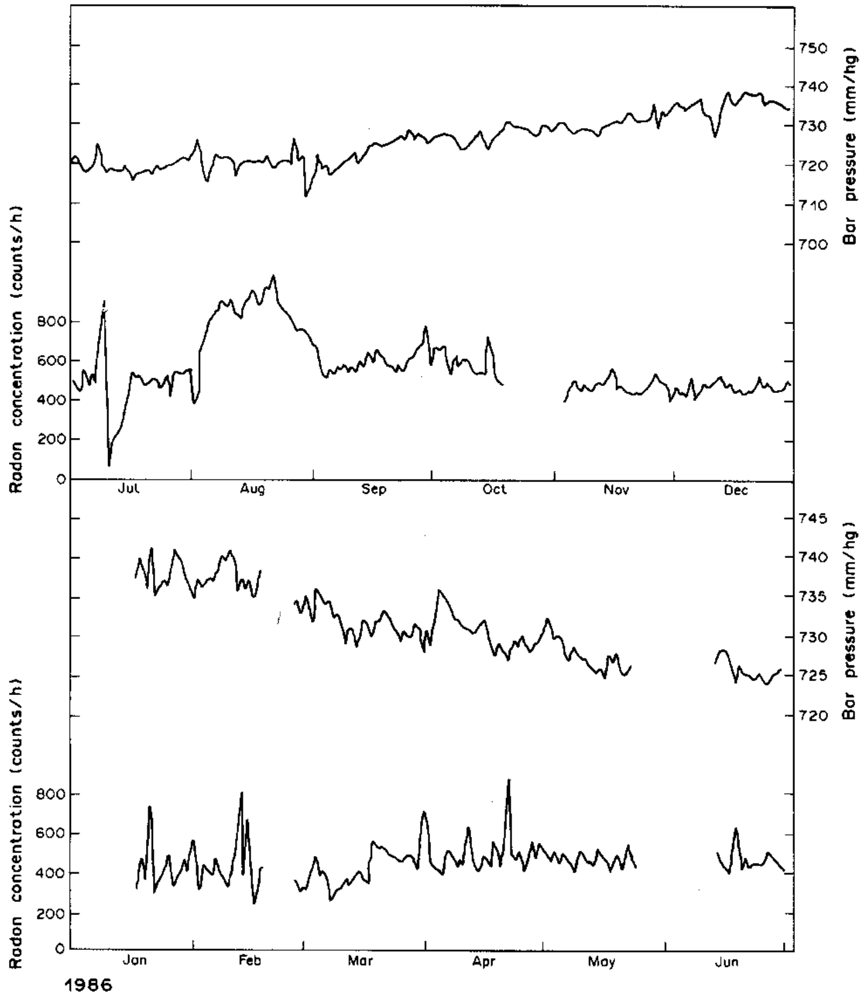

Fig. 8. Variation of radon concentration with barometric pressure.

Results for the variation in radon concentration with rain-fall and humidity are given in Fig. 9. Radon values are generally found to increase in mild rainy-days. When there is heavy rain the radon values initially fall and then increase considerably over a period of several days (e.g. the events in July and August). This increase may be due to a capping effect of a wet soil layer at the surface preventing radon from escaping into the atmosphere (Tanner, 1964; Singh *et al.*, 1988b; Ghosh and Bhalla, 1981). The decrease in soil gas radon after a heavy rain-fall may be due to the presence of high humidity and moisture in the soil which dissolves the diffusing radon and the deep percolation of rain water removes the radon by a transport mechanism.

Figure 10 shows the variation of soil gas radon with wind velocity. The radon concentration is found to be directly related to the wind velocity as it is high from April to August when the wind velocity is high and low for the remaining period. Strong winds are another possible cause for the rapid flow of soil gas in the summer season. Wind can directly force the atmosphere into the upper part of the soil and can withdraw gas from the deeper soil by the Bernoulli effect.

The correlation matrix is computed for the entire data set of radon emission and secondary influences (Table 1). The radon emission is found strongly correlated with air temperature and wind velocity and anti-correlated with barometric pressure and rain-fall. It also shows a weak inverse relation with humidity. The variation in correlation coefficients for radon emission and

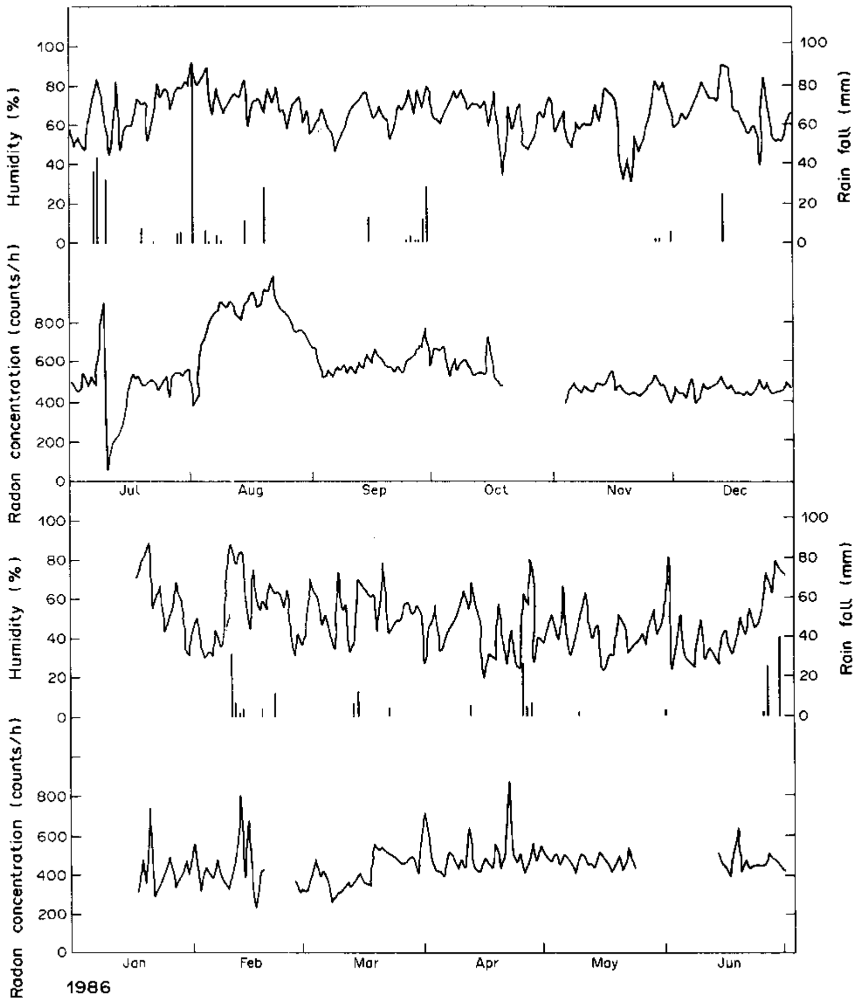

Fig. 9. Variation of radon concentration with rain-fall and humidity.

rain-fall is due to the difference in the measurements. For daily recording, the particular events of the rain-fall are correlated with the radon data. However, in other cases the total rain-fall (weekly, fortnightly and monthly) is correlated with the average radon data and thus shows a weak correlation.

Correlation of soil gas radon data with the earthquake prediction

Several impulsive radon increases with amplitudes much larger than the background level may be recorded under different weather conditions. The recorded radon concentration varies greatly with time. An impulsive radon increase was recorded on 21 April 1986 (Fig. 11) with a peak value about twice the average value. No rain-fall or unusual barometric pressure was recorded at the time but an earthquake of magnitude 5.7 on the Richter scale occurred on 26 April 1986. The epicentre of this earthquake was at a distance of about 200 km from the monitoring site in the Kangra Valley [lat 32.09°N and long 76.31°E (Fig. 2)].

Another impulsive radon increase was recorded on 9 July 1986 (Fig. 11) and this was followed by a heavy rain-fall on 10 July. This increase was followed by an earthquake of magnitude 3.8 on 17 July 1986. The epicentre of this earthquake was about 150 km from the recorder in the Kangra Valley.

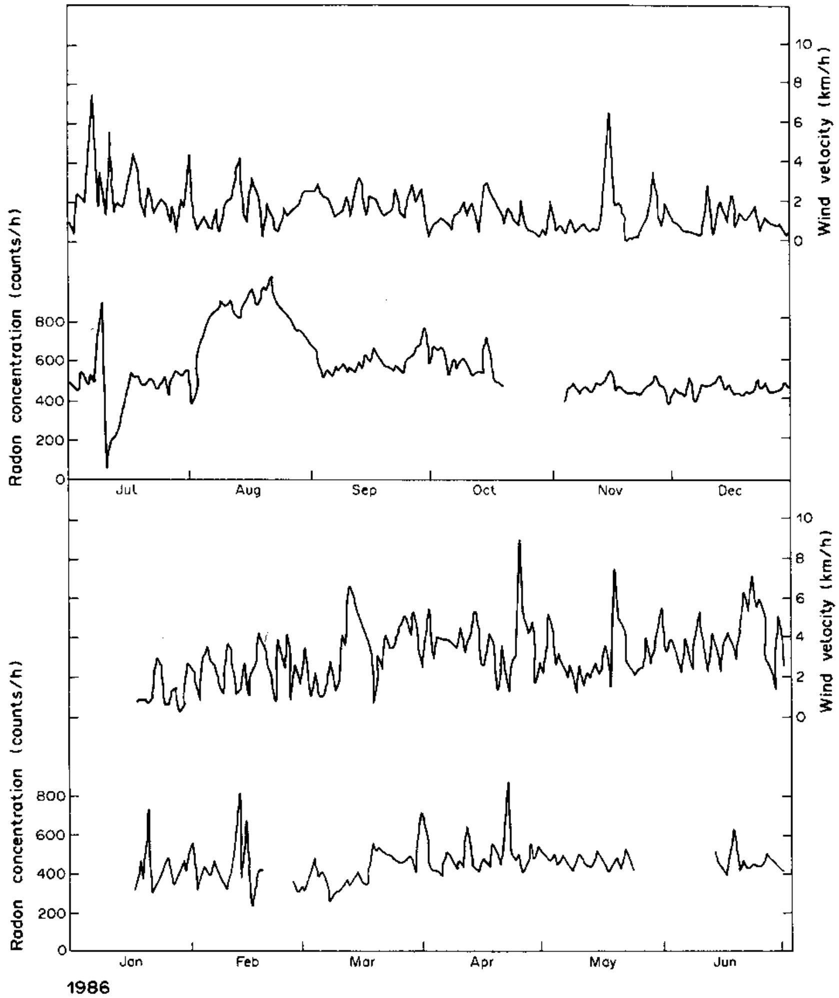

Fig. 10. Variation of radon concentration with wind velocity.

Table 1. Correlation of radon emission with meteorological variables

Variables	Alphameter				SSNTD	
	Daily	Weekly	15 days	Monthly	Weekly	Monthly
Maximum temperature	0.35	0.44	0.47	0.54	0.33	0.46
Minimum temperature	0.42	0.58	0.52	0.58	0.43	0.48
Bar pressure	−0.35	−0.47	−0.43	−0.35	−0.47	−0.40
Wind velocity	0.39	0.50	0.49	0.56	0.32	0.56
Rain-fall	−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

A third noticeable radon anomaly was recorded on 7 March 1987 (Fig. 11). This increase was followed by an earthquake of magnitude 4.3 on 17 March 1987 with epicentre again in the Kangra Valley at a distance of about 200 km from the recording site.

The fourth impulsive radon increase was recorded on 1 May 1987 (Fig. 11) followed by an earthquake of magnitude 5.0 on 5 May. The epicentre was about 400 km from the recording station in the Hindu Kush.

The monthly variation of radon concentration was also measured by using plastic track detectors

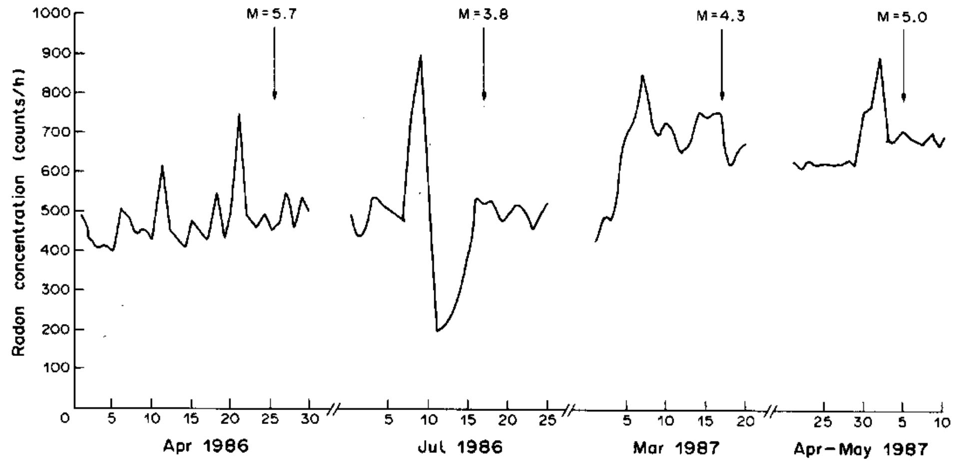

Fig. 11. Recorded daily variation of radon in soil during earthquake events.

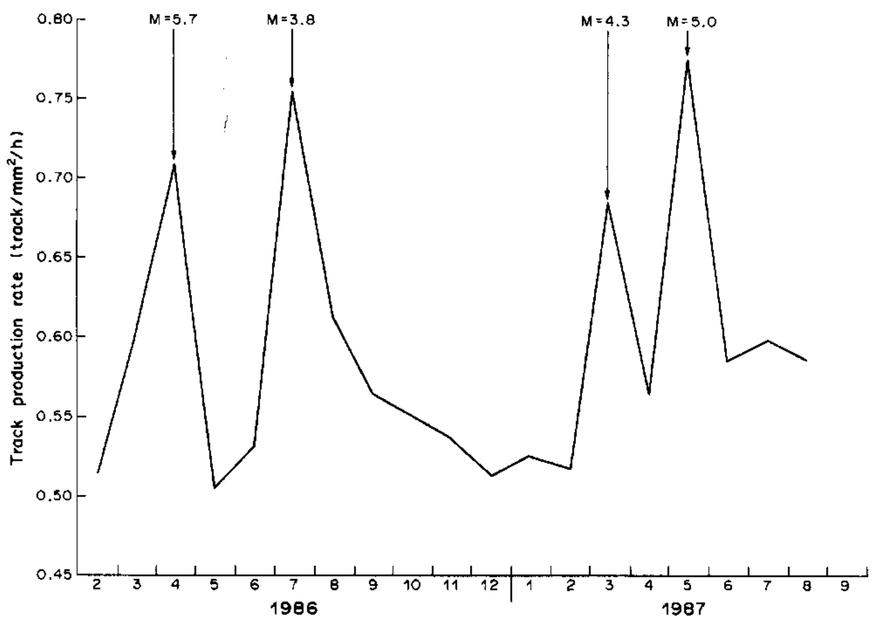

Fig. 12. Monthly variation of radon in soil with LR-115 type II plastic track detector.

(Fig. 12). By this method, it is found that the radon values were high and about two to three times the average value preceding the earthquake events.

Besides these anomalies, some other anomalies were also observed in the months of January, February, April and August (Figs 7–10). According to our interpretation the anomalies in January and February may be due to local seismicity (microearthquakes) in the Amritsar area as there were no unusual meteorological disturbances during this period. Unfortunately, a local seismic network was not available during this period and hence the anomalies may be spurious or misinterpreted. The radon anomalies in early April may be due to foreshocks before a strong earthquake which occurred on 26 April 1986. However, the high value of radon in August is due to rain-fall, as explained above. The earthquake related anomalies are clearly distinguishable from other anomalies.

The sudden increases in radon concentration suggest that these are more likely to be caused by crustal disturbances rather than by atmospheric effects. Since the distance between the monitoring site and the epicentre of earthquakes was more than 150 km, it is unlikely that any direct transport of radon from the source region to the monitoring site is responsible for the observed high values. The radon emanation began to increase rapidly a week before the earthquake, which may possibly be due to the strain build up. Crustal compression is the mechanism proposed by King (1978) as the possible cause of increased radon emanation. The anomalously high radon values may be due to an increase in crustal compression that squeezes out the soil gas into the atmosphere at an increased rate.

Correlation of groundwater radon data with earthquake prediction

Continuous monitoring of radon in groundwater was initiated in December 1987. The daily records from December 1987 to June 1988 are shown in Fig. 13. The anomalous change in radon concentration was recorded on 23 December 1987 with a peak value about three times as high as the respective average value. This increase was followed by two successive earthquakes of magnitude 4.5, each of which occurred on 24 and 26 December 1987. The epicentres of these earthquakes were at a distance of about 150 km from the monitoring site in the Kangra area (Fig. 2).

Several relatively small radon peaks were recorded during the last days of February 1988 and these were followed by an earthquake of magnitude 4.2 on 19 March 1988 with epicentre also in the Kangra Valley at a distance of 200 km from the recording site.

The third noticeable radon anomaly was recorded on 10 May 1988. This increase was followed by an earthquake of magnitude 4.8 on 16 May 1988. The epicentre was at about 400 km in the Hindu Kush (Fig. 2).

These anomalous radon changes were recorded prior to the earthquake events and thus seem to be precursory signals of these earthquakes. Beside these earthquake related anomalies, some anomalous changes in radon concentration were also recorded during the last week of May and in June 1988. These anomalies are again puzzling as no earthquake was recorded during that period: these changes may be due to microearthquakes with epicentres very close to the recording station. However, without a local seismic network it is not possible to interpret the results correctly. Our future plan is to establish a local-seismic network along with the radon study for better correlation of the results.

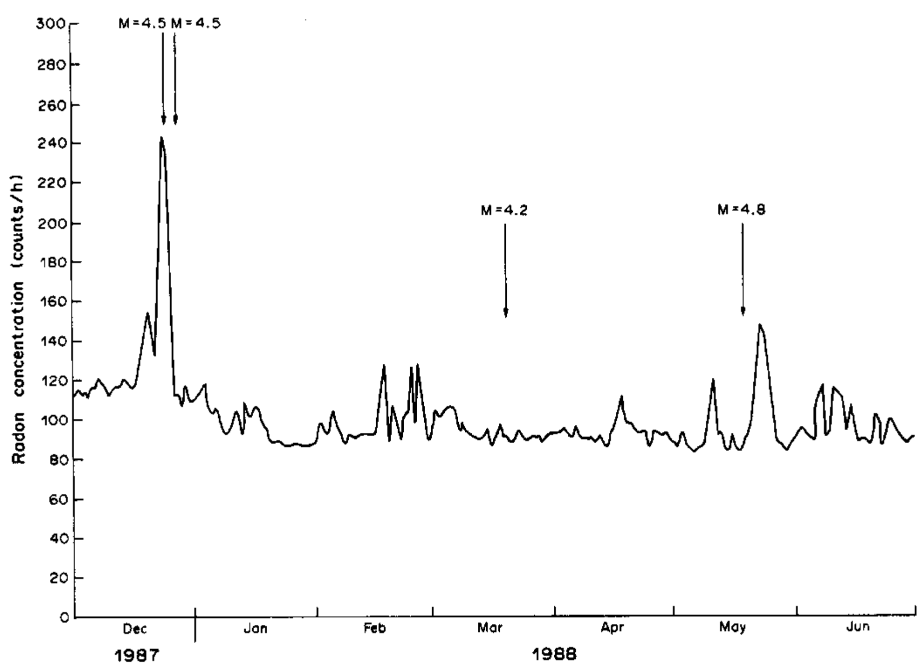

Fig. 13. Recorded daily variation of radon in groundwater.

A possible cause of precursory changes in the radon concentration in groundwater is a change in the degassing rate of radon in rocks. The formation of minute cracks and pores in rocks at the epicentral region before an earthquake may in effect result in an enhancement of the radon concentration (Wakita, 1984). Beside these effects, crustal movements, such as contraction, expansion and tilting of the ground may also cause changes in the groundwater system, with destruction and/or deformation of the artesian layer in the vicinity of the well. Mixing of groundwaters with different radon concentrations may then occur and cause the observed changes.

While a radon anomaly may be associated with an earthquake shock, the exact time when the shock will appear cannot be predicted. It is observed that an initial increase in radon concentration is followed by a fall after a few days. 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 earthquake. 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.

CONCLUSIONS

From our results so far, as well as those reported by others, we conclude that radon anomalies are sometimes associated with earthquake activity. However, radon records also show other anomalies, the meaning of which is not clear. Objective criteria are needed to distinguish instrumental artifacts from real radon anomalies that reflect changes in stress and in geological conditions. Improvement of instrumentation is required to obtain better results in the future. Radon anomalies can be correlated to earthquakes, keeping in mind the fluctuations due to rain-fall and meteorological variables. However, to be useful as a precursor in an earthquake prediction programme, the continuous monitoring of radon, both in soil–gas and in groundwater (as well as other environmental parameters) at several sites in a well-organized grid pattern is necessary.

It is also important to select monitoring sites carefully, to standardize experimental procedures and instruments in order to record long-term radon data, to perform rigorous identification of radon signals above the noise and to conduct theoretical and experimental studies of the physical basis of tectonically induced radon. Our future plan is to continue this type of work in earthquake prone areas, so that this simple technique of radon recording may be exploited as a possible tool in the earthquake prediction programme in India.

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