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Radon studies for Earthquake Prediction

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. A network of eight radon recording stations has been set up in the highly seismic zone in the Kangra and Chamba valleys of Himachal Pradesh near the Main Boundary Thrust (MBT) in the Himalaya to forecast future earthquakes using radon as a precursor. 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.

Radon anomalies from our groundwater and soil-gas data have been correlated with some of the earthquakes which occurred in the region. However, there is no one to one correspondence between radon anomalies, and earthquakes. 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.

Introduction

Earthquakes constitute one of the worst calamities on the earth. It is estimated that from the beginnings of recorded history to the present about 75 million human lives might have been lost to earthquakes. Earthquake related deaths average over 15,000 per year, and in 1990 alone more than 50,000 people have been killed in Asia. The damage to property runs into billions of dollars. Every year, on an average, about 1000 earthquakes of magnitude greater than 5 on Richter scale, several in the 6-8 magnitude and one of magnitude greater than 8 may occur, with a super-destructive earthquake occurring somewhere on earth once every three years.

The physical mechanism of earthquakes and of precursors is at present poorly understood. As a consequence, earthquake prediction is yet a distant dream and only purely empirical approach has been adopted by various groups for earthquake prediction so far. Over the past two decades a number of precursors have been identified viz., ground deformation, tilt and strain,foreshocks, anomalous changes in b-value, resistivity, seismic wave velocities, geomagnetic field, telluric currents, groundwater level, oil flow, and radon content, etc.

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. Severals groups are engaged in USA, USSR, France, China, Japan, Mexico and India to establish radon as an earthquake precursor. 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 had 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. 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; Noguchi & Wakita, 1977; King, 1978,80,84; Birchard and Libby, 1980; Mogro-Campero *et al.*, 1980; Shapiro *et al.*, 1980,81; Smith *et al.*, 1978; Talwani *et al.*, 1980; Teng, 1980; Hauksson &

Goddard, 1981; Steele, 1981; Teng *et al.*, 1981; Segovia *et al.*, 1986, 88; 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 a failure in Tangshan, where 200,000 people were killed in a devastating earthquake in 1976.

Radon Emanation and Transport

The occurrence of radon in the natural environment was known soon after its original discovery in 1900. Radon (^{222}Rn) gas is constantly generated from radium 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 McV alpha particles. There are two other isotopes of radon: thoron (^{220}Rn) and actinon (^{219}Rn), which belong to ^{232}Th, and ^{235}U decay series, respectively. They have comparatively short half lives (54.4 s and 3.9 s), and their contribution may be ignored for all practical purposes in earthquake prediction. ^{222}Rn is the only isotope with sufficiently long life such that it can migrate a significant distance from its source.

According to the theory of emanation,an isolated isotropic spherical grain of the mineral containing an uniform distribution of radium isotope is large enough to contain virtually all the recoiling radon atoms unless the grain is of less than a micron size. The recoil energy of radon atom is just 0.1 MeV and its range in a mineral grain of normal rock density will be roughly $3x10^{-6}$ cm. However, in air it can traverse about 2000 times more, i.e. $6x10^{-3}$ cm. The neutral radon atom may then diffuse and decay within the rock mass or escape from it. The fraction of the total radon atoms which escape to that which are formed is termed the emanating power of the mineral.

The radon which escapes out of the grain is therefore restricted to the outer surface of a thickness upto the recoil range. Often a recoil atom gets lodged in the microcapillary of a mineral structure. It is mostly through these capillaries filled with either an aqueous or an air medium that emanating atoms from a mineral exit. The recoil range of radon atoms in water is about 1×10^{-5} cm or about two orders of magnitude less than that in air but a few multiples of its magnitude in the mineral. As a consequence, the radon diffusion, and transport may proceed at a rate many orders of magnitude greater than in the solid rocky matrix.

Radon Anomalies and Earthquakes

Radon anomalies depend to a large extent on the tectonic disturbance of the host minerals, whereby surface areas of the microfracture are altered. According to the dilatancy mechanism for earthquake occurrence (Scholz *et al.*, 1973), when regional stress increases, dilation of rock masses could cause an increase either in the surface area of rocks due to cracking, or in the flow rate of pore fluids as they are forced out of the interstitial space. Both of these processes will enhance the transport of radon from its original enclosures into the groundwater or spring waters.

Natural water always contains radon in detectable quantities. The tremor due to an earthquake is instrumental in dislodging the suspended radon in the water and creating an anomaly. The suspended radon which gets de-emanated due to agitation tends to migrate upwards along with some other dissolved gases in the medium, and shows a higher concentration of radon in water or soil- gas at shallower depths. Since radon has a half-life of 3.83 days, which effectively means that an anomaly can spend at the most 20 days travelling from a source to a monitoring well (Hauksson & Goddard, 1981). If the travel time is longer, the anomaly will be totally attenuated since radon decays to its daughter isotopes. The flow velocity of groundwater is determined by the rock permeability and regional hydraulic gradient which in some cases can be modified by localized withdrawal of water, for example, at geothermal wells.

Radon anomalies can also occur in soil-gas prior to an earthquake when measurements are carried out in an auger hole. It must be remembered that meteorological variations and seasonal changes affect the radon emanation in the soil-gas resulting in a low signal to noise ratio as compared to the measurements carried out in deep bore wells. Radon anomalies in groundwater must be reflected in soil-gas, if radon monitoring is carried out under similar environmental conditions.

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 hydraulic experiments have been described (Thorsteinsson, 1973; Andrews, 1977; Dobrovolsky *et al.*, 1979). Initially, the dilatancy diffusion model, and its versions, suggested that radon anomalies were related to mechanical crack growth rate in the volume of dilatancy, or to change in flow rate of groundwater (Ulomov & Mavashev, 1967, 1971; Scholz *et al.*, 1973). 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, change in the earth's electrical resistivity, and change 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. Dilatancy related phenomena might not provide a recognizable short term precursor, particularly for a large earthquake. Although all precursor signals are necessarily related to the changing stresses in the earthquake zone,one might expect the short term precursors to constitute a less consistent set than long term precursors. 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 corrosion 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) 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 earthquake. One Chinese study (Liu *et al.*, 1975) suggests that radon monitors located in zones of compressional strain record anomalous increases, whereas those in dilatant 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, in close proximity to the Main Boundary Thrust (MBT) in the Himalayan foot-hills (Fig. 1).

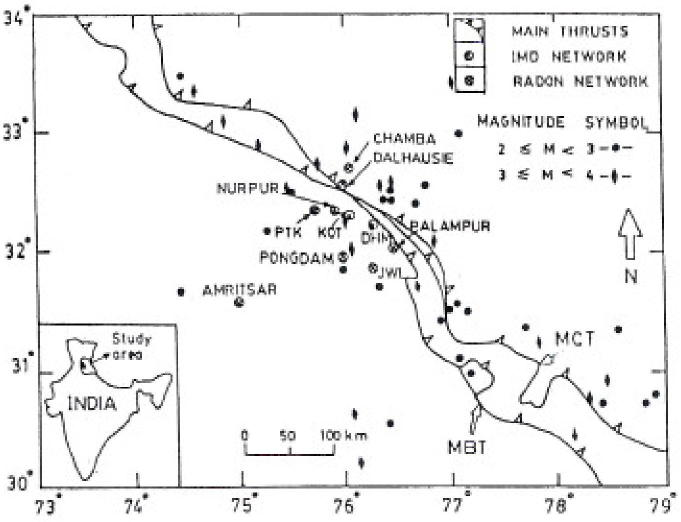

Fig. 1. Microseismic activity recorded by IMD and Radon networks in Himachal Pradesh along the Himalayan thrusts (MBT = main boundary thrust, MCT = main central thrust, PTK = Pathankot, KOT = Kotla, JWL = Jawalamukhi and DHM = Dharamshala).

The fluctuations in near surface, and groundwater radon concentration are monitored using both instantaneous, and time- integrated techniques. 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 dughters. 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 detetor using 5.4 micro-curie (200 kBq) $RaCl_2$ standard

Table 1. *Calibration constants for Radon detectors.*

Detector	Sensitivity	Equivalent Activity		Manufacturer
		pCi/ml	Bq/ml	
ZnS (Ag)	1 cpm	0.003	1.1×10^{-4}	Atomic Mineral Division, Hyderabad (India).
Silicon - difused Junction (Alphameter-400)	1 cpm	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-Pathe, Vincennes, France.

solution preferably under similar ambient conditions as prevailing at radon monitoring sites. Calibration constants are listed in table 1.

Radon Monitoring in Soil

Plastic track detectors, viz. cellulose nitrate films (LR-115 type II) manufactured by Kodak-Pathe, France and CR-39 sheets (Pershore Moulding Co., U.K.) are very sensitive for recording alpha particle tracks produced by radon. However, cellulose nitrate film has found much wider acceptability with radon groups for field trials because of its low background noise, and a precise window for alpha detection, compared with CR-39 which can record even low energy proton tracks. Plastic track detectors are capable of recording average value of radon isotopes over relatively longer periods (weeks to months) but are insensitive to transient variations that last only several hours or less. In order to monitor, and investigate such variations, the silicon- diffused junction electronic detector(a type of diode) has been used which can record integrated radon values over short time intervals (minutes to hours).

Track-Etech Method

Track-etch technique is quite appropriate for radon detection in the soil-gas because of its negligible background of spurious signals, low cost, ruggedness, and its nature as an integrating measurement. The detector assembly (Fig. 2) consists of an aluminium cylinder 25 cm in height, and 4.5 cm internal diameter with one of its ends closed. A metal strip is fitted inside the cylinder to hold the CN plastic films about 1 cm x 2 cm in size. The upper film (detector) records the alpha tracks due to radon alone whereas the lower one records the tracks due to both radon and thoron. Hence the measuring device was nick-named Radon-Thoron Discriminator (Ghosh & Soundararajan, 1984; Singh *et al.*, 1984).

Fig. 2 demonstrates the arrangement of exposing the detector films in an auger hole. An iron wire is clamped at the top of the probe for the purpose of lowering and pulling it out of the bore holes with depths varying from 60 cm to 3 m. The detector assembly rests in the vertical position near the bottom of auger hole and radon decay alpha particles impinge on the detector films leaving their radiation damage trails. CN films are collected after a week or a month, as the case may be, and etched in constant temperature bath using 2.5N NaOH solution for 2 hours. at 60°C. Alpha tracks are revealed as circular or conical spots which become etched-through holes after prolonged etching. The track spots or holes are counted using a binocular microscope under magnification of 600X. The measured track density is as-

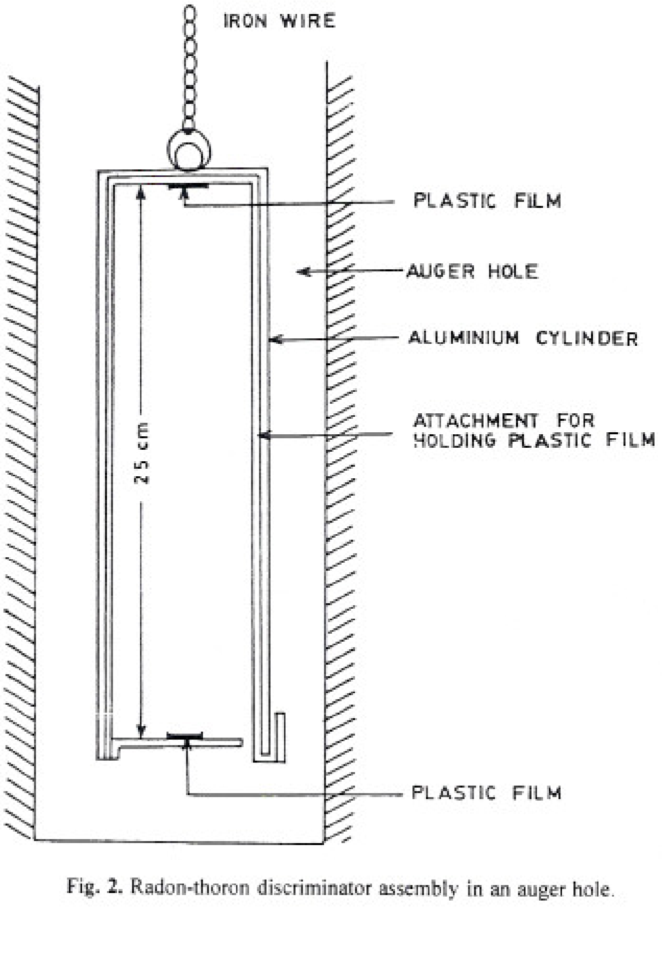

Fig. 2. Radon-thoron discriminator assembly in an auger hole.

sumed to be proportional to the average radon content in soil-gas.

Radon Emanometry

Radon emanometer (type RMS-10), manufactured by ECIL, Hyderabad and patented by Atomic Minerals Division (D.A.E.), is used to measure the instantaneous radon concentration in the soil-gas. The apparatus consists of an alpha counting scintillation assembly with inverted bell-shaped alpha detector, a hand-operated rubber pump and a soil-gas probe. The probe is a metallic tube about 4 cm diameter with perforations at the lower end, and a rubber capping at the top to seal it pneumatically in an auger hole. It has inlet, and outlet tubes for the circulation of the soil-gas. The hand-operated rubber pump is used to circulate the soil-gas into the scintillation chamber. The alpha particles emanating from the radon impact the ZnS(Ag) scintillator creating an energy pulse in the form of light quantas which are recorded by scintillation assembly consisting of a PMT and a scaler unit. This close- circuit technique (Fig. 3) was developed by Ghosh and Bhalla (1966) in India, and is considered to be one of the standard methods for radon estimation in soil-gas, and groundwater.

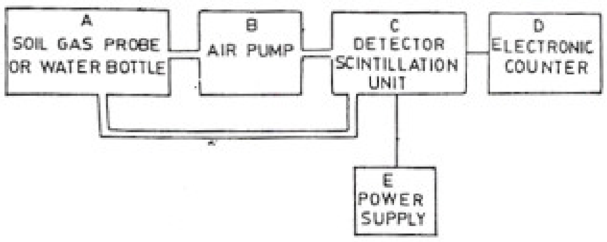

Fig. 3. Block diagram of close-circuit technique for daily radon measurement in soil-gas and groundwater.

Alpha-Logger System

Alpha-logger (Alpha Nuclear Company, Toronto, Canada) is a portable, battery-powered, microprocessor based data acquisition, and control system. The unit is designed to acquire, and record the radon data from upto twelve alphameter- 400 probes, and seven auxiliary probes for meteorological data. The instrument detects, and integrates instantaneous radon fluctuations over relatively short intervals of time, and upon command of automatic logger system, transmits its data over upto 1 km of cable for recording.

Alphameter-400 (Fig.4) is designed to measure near surface radon gas fluctuations. It consists of a silicon-diffused junction for detection of alpha particles, and gives sufficient counts over 24 hours exposure in most of the soils (Gaucher, 1976; Warren, 1977). The detector unit is placed inside a covered auger hole about 60 cm in depth. The detector is separated from the soil surface at the bottom of hole by a 6.4 cm gap and the air in the gap shields the detector from the impact of direct alpha particles generated in the soil. The detector thus records the alpha particles emanated by radon isotopes, and their alpha-emitting daughters. To reduce the operational cost, alphameter is placed in the auger hole for a full day, and the accumulated alpha activity is read the next day when the read mode is initiated with the external battery.

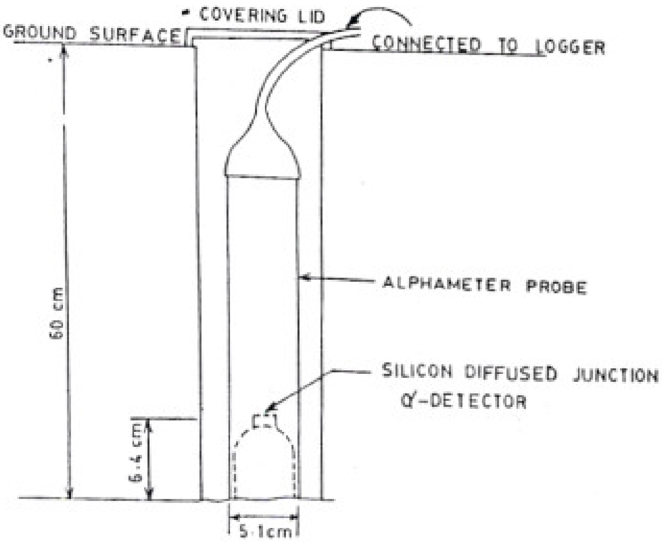

Fig. 4. Alphameter-400 probe in an auger hole.

Recently, alpha-logger 611 system has been developed as a modified version of the original model, which can record radon alpha counts in 15 minute increments over a period of 40 days non-stop. The recorded data is retrieved with the aid of a laptop IBM compatible PC by manually entering the appropriate commands. In most of the soils the alpha count rate is quite low, thus counting statistics for the 15 minute interval is usually poor. The software supplied with the system provides the facility to sum up any number of 15 minute counting intervals.

Radon Monitoring in Ground-Water

Discrete Measurement

The apparatus used for the discrete measurement of radon in groundwater is shown in Figure. 3. 200 ml of water sample is taken in radon tight reagent bottle of one litre capacity connected in a close-circuit with a ZnS coated detection chamber through a hand-operated rubber pump, and the glass bulb containing $CaCl_2$ to absorb the moisture. The air is circulated in close-circuit for a period of 10 minutes till the radon, and the resulting alpha activity is recorded. The

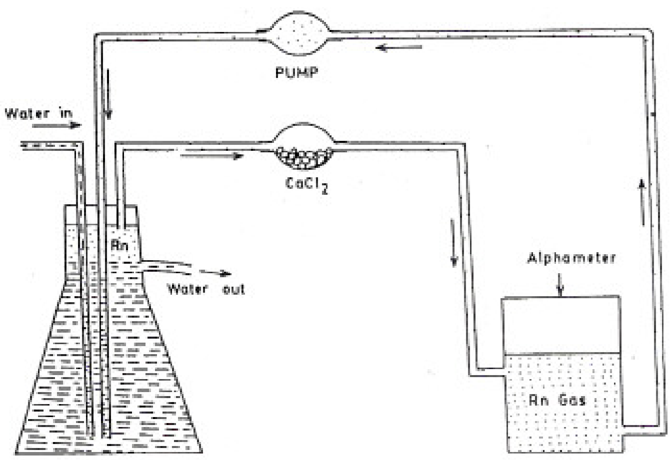

Fig. 5. Continuous radon monitoring system for groundwater.

measurements were taken daily in the ground water from same location.

Continuous Measurement

The continuous measurement system (Fig.5) is used for monitoring radon in groundwater. Groundwater is drawn from a deep bore well at a depth of 100 m, and is allowed to flow continuously through a glass vessel of 1 L capacity at a flow rate of 1 L/min. The glass vessel is connected in a close-circuit with a detector 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-junction silicon detector (Alphameter-400) is employed for the continuous measurement of radon. Data is stored until a read mode is initiated. The accumulated alpha activity is then recorded daily.

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 absorbed to the surface of 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 decease 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 & 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.

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 impuslive 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 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 Bq/L, 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 Bq/L.

Table 2. *Correlation of radon emission with meteorological variables.*

Variables	Alphameter				SSNTD	
	Daily	Weekly	15 days	Monthly	Weekly	Monthly
Max. Temperature (°C)	0.35	0.47	0.47	0.54	0.33	0.46
Min. Temperature (°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. Presure (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

The first observable radon anomaly (Fig. 6a) 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 the groundwater radon anomalies were followed by an earthquake of magnitude 2.8 which occurred on August 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. 6a & b), 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 the North-West Himalayas (Table 3). Weekly radon data recorded by Track-Etch technique is also plotted (Fig. 7a & b). 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.

Microseismicity Data froln Palampur and Dalhausie

Under Himalayan Coordinated Seismicity programme of Department of Science and Technology (DST), New Delhi, we extended our range of activity, and set up six radon recording stations along the MBT in Kangra and Chamba valleys of Himachal Pradesh in 1992. Radon emanometry data in soil-gas and groundwater has been recorded at both Palampur, and Dalhousie stations. Alpha-logger data is being collected continuously at several stations as shown in figure 1. Palampur station started functioning in April 1992 while at Dalhausie, it became operational in July 1992.

There has been no major seismic event in the study area during the time window April 1992 to September 1993. However, the area is showing enhanced microseismicity as recorded by seismic network being operated by IMD. For example, Pong Dam station recorded 16 seismic events with magnitude between 2-4, and with epicentres lying within a range of 100 km. The total number of events recorded in the grid (30-34°N, 73-79°E) having magnitudes in the range of 2-4 is reported to be more than 50 in the given interval. Most of these seismic events have epicentres along the MBT trend line (Fig. 1). It is interesting to note that radon emanometry data recorded at Palampur (Fig. 8), and Dalhausie (Fig. 9) shows anomalies corresponding to nearly 50% of these events. A correlation of radon anomalies with microseismic events is given in table 4.

Radon data comparison of two stations reveals some interesting features of this study. While at Palampur radon emanation is more pronounced in groundwater compared with soil-gas, the Dalhausie station shows the reciprocal trend. This may be due to the different geological conditions of the region. Moreover, meteorological conditions do not affect radon emanation in groundwater appreciably while these variations affect the soil-gas radon significantly.

Concluding Remarks

From our soil-gas, and groundwater radon monitoring results (Virk, 1986, 1990; Virk, & Singh, 1992, 1993, 1994; Singh et al., 1988; Ramola et al., 1990; Virk and Baljinder Singh, 1991) of over ten 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. To be useful as a precursor,continuous monitoring of radon both in soil-gas, and in groundwater, along with other environmental factors, at several monitoring sites along the MBT in a grid pattern, is necessary.

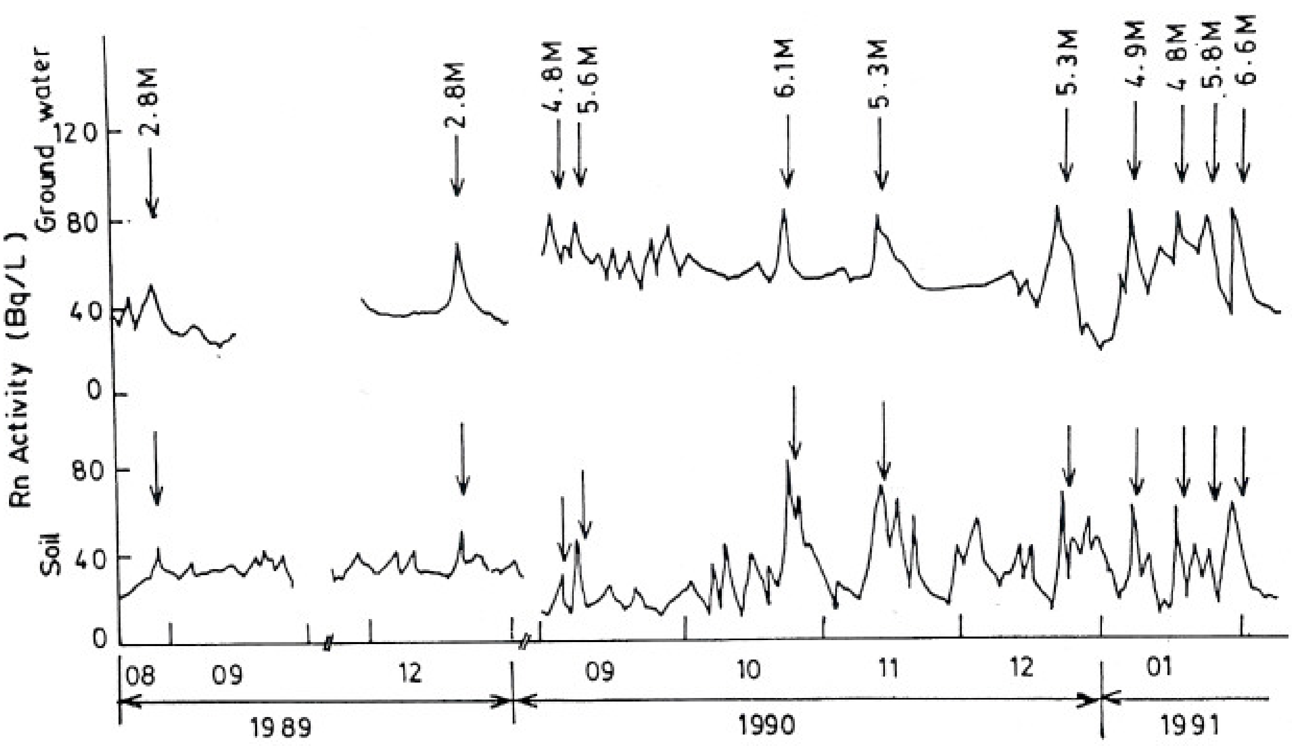

Fig. 6a. Radon activity in soil-gas and groundwater at Palampur (from Aug. 1989 to Jan. 1991).

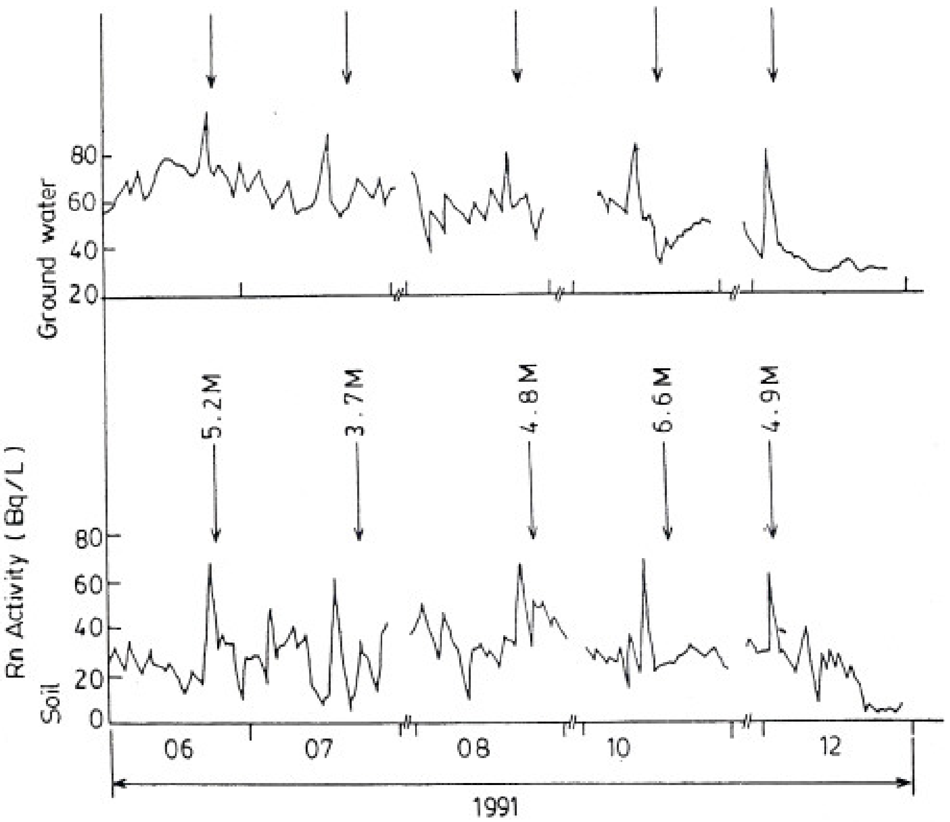

Fig. 6b. Radon activity in soil-gas and groundwater at Palamput (from June to December 1991).

Table 3. *Radon emanometry data from Palampur (Aug. 1989 to Dec. 1991).*

Occurrence of Rn anomaly	Latitude (λ)	Longitude (∅)	Depth (km)	Magnitude (M)	Correlatable 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	30.51°N	72.12°E	33	5.3	Nov.16, 1990
Dec.23, 1990	33.30°N	75.65°E	30	5.3	Dec.24, 1990
Jan. 08, 1991	33.61°N	76.01°E	15	4.7	Jan.10, 1991
Jan. 18, 1991	37.08°N	77.53°E	33	4.8	Jan.20, 1991
Jan. 24, 1991	37.08°N	70.69°E	32	4.9	Jan.26, 1991
Jan. 30, 1991	36.30°N	70.20°E	15	6.6	Feb.01, 1991
Jun. 22, 1991	32.32°N	76.69°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

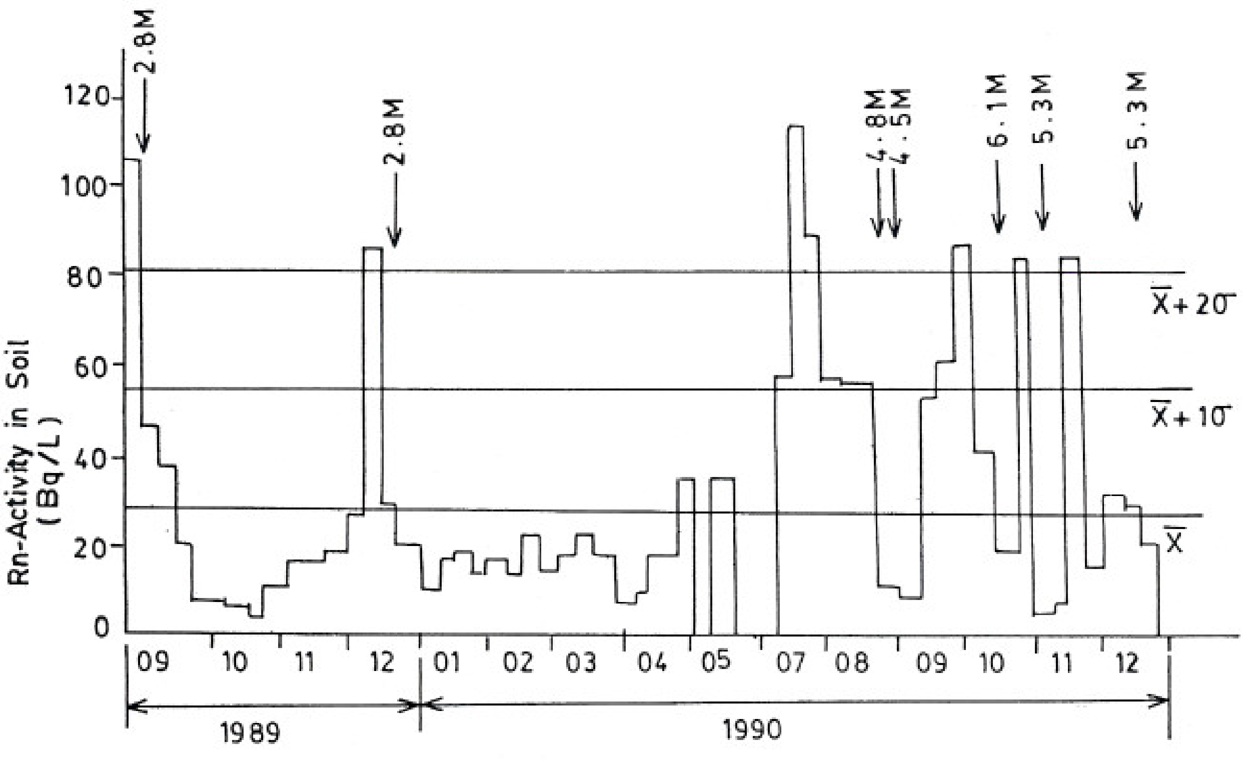

Fig. 7a. Weekly radon activity at Palampur (from Sept. 1989 to Dec. 1990) using track-etch technique.

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 earthquake precursor even though peak radon concentrations are widely different in both the media. Another plus point of our study is that radon anomalies are recorded using three different monitoring techniques.

Recording station at Amritsar is not sensitive to seismic events of magnitude 3.5 or lower occurring in Kangra valley, Himachal Pradesh. Since Palampur, and Dalhausie stations are located on the main boundary thrust (MBT) of the Himalaya, they are even sensitive to microseismic events of magnitude 2 which occurred within a range of 50 km of radon monitoring station. However, seismic events of magnitude 5 or more can be correlated with radon anomalies even when they occur at 500 km or still farther away from recording station.

The source of the anomalous radon lies in the immediate vicinity of the detector, and this may result from a net upward shift of the surface radon profile influenced by some large scale mechanism, viz., crustal compression originating at greater depths. Igarashi and Wakita (1990) have established magnitude-distance relationship for the strain step of the order of 10^{-8} for both pre-seismic and post-seismic radon anomalies, suggesting that the observed anomalies are caused by small changes in the local stress field (Dobrovolsky *et al.*, 1979; Fleischer, 1981).

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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Table 4. *Correlation of Radon anomalies recorded at Palampur and Dalhousie with microseismic activity in Himachal Pradesh.*

Date of Radon Anomaly	% change above mean	Magnitude (M)	Latitude (°N)	Longitude (°E)	Date of Earthquake
(a) Radon Emanometry Data at Palampur.					
April 14, 1992	195*	2.2	31.36	77.67	April 11, 1992
May 23, 1992	165*	2.7	31.51	77.17	May 26, 1992
July 21, 1992	-83	3.6	31.25	77.82	July 21, 1992
April 30, 1993	152	1.9	30.67	78.44	May 1, 1993
July 25, 1993	99*	3.1	30.23	76.13	July 30, 1993
Aug 11, 1993	152*	3.7	30.73	78.79	Aug 15, 1993
Aug 28, 1993	252*	2.5	32.54	76.76	Aug 28, 1993
Sept 17, 1993	247	3.0	32.84	73.24	Sept 9, 1993
Sept 28, 1993.	273	3.2	33.43	74.59	Sept 28, 1993
(b) Radon Emanometry data at Dalhousie					
July 7, 1992	250	2.4	31.08	77.06	July 14, 1992
July 9, 1992	250	3.6	31.25	77.82	July 21, 1992
Oct 23, 1992	109	3.1	31.73	76.68	Oct 24, 1992
	117*				
Jan 3, 1993	153	4.4	30.02	73.48	Jan 12, 1993
	183				
Jan 23, 1993	205	3.8	32.73	75.75	Jan 24, 1993
Jan 28, 1993	93	2.7	31.37	76.90	Jan 29, 1993
Mar 17, 1993	93	3.5	32.04	76.06	mar 22, 1993
	128*				
Mar 20, 1993	161*	2.8	32.41	76.35	Mar 23, 1993
Mar 30, 1993	94	3.0	32.52	75.43	Mar 31, 1993
June 17, 1993	109	3.2	32.86	76.02	June 24, 1993
June 18, 1993	140*				
July 9, 1993	138	3.5	33.14	76.14	July 12, 1993
Aug 5, 1993	242	3.7	30.73	78.79	Aug 15, 1993
	227*				

* Anomaly in water

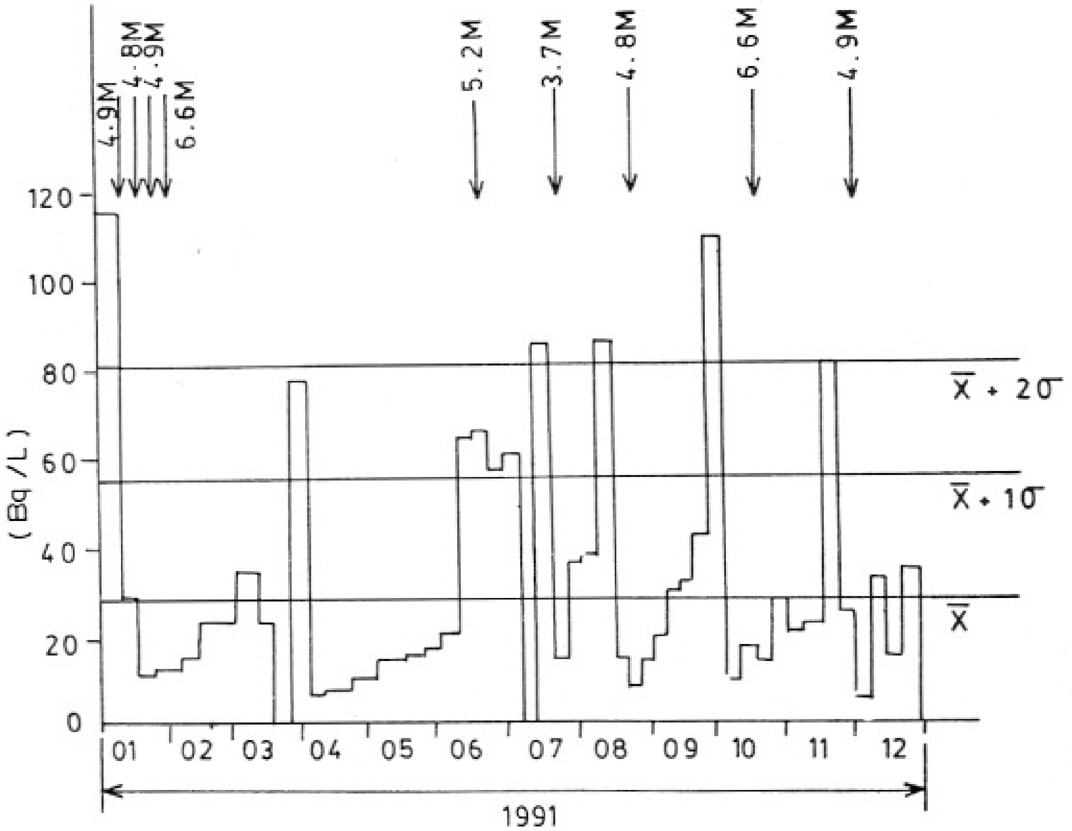

Fig. 7b. Weekly radon activity at Palampur (From Jan. to Dec. 1991) using track-etch technique.

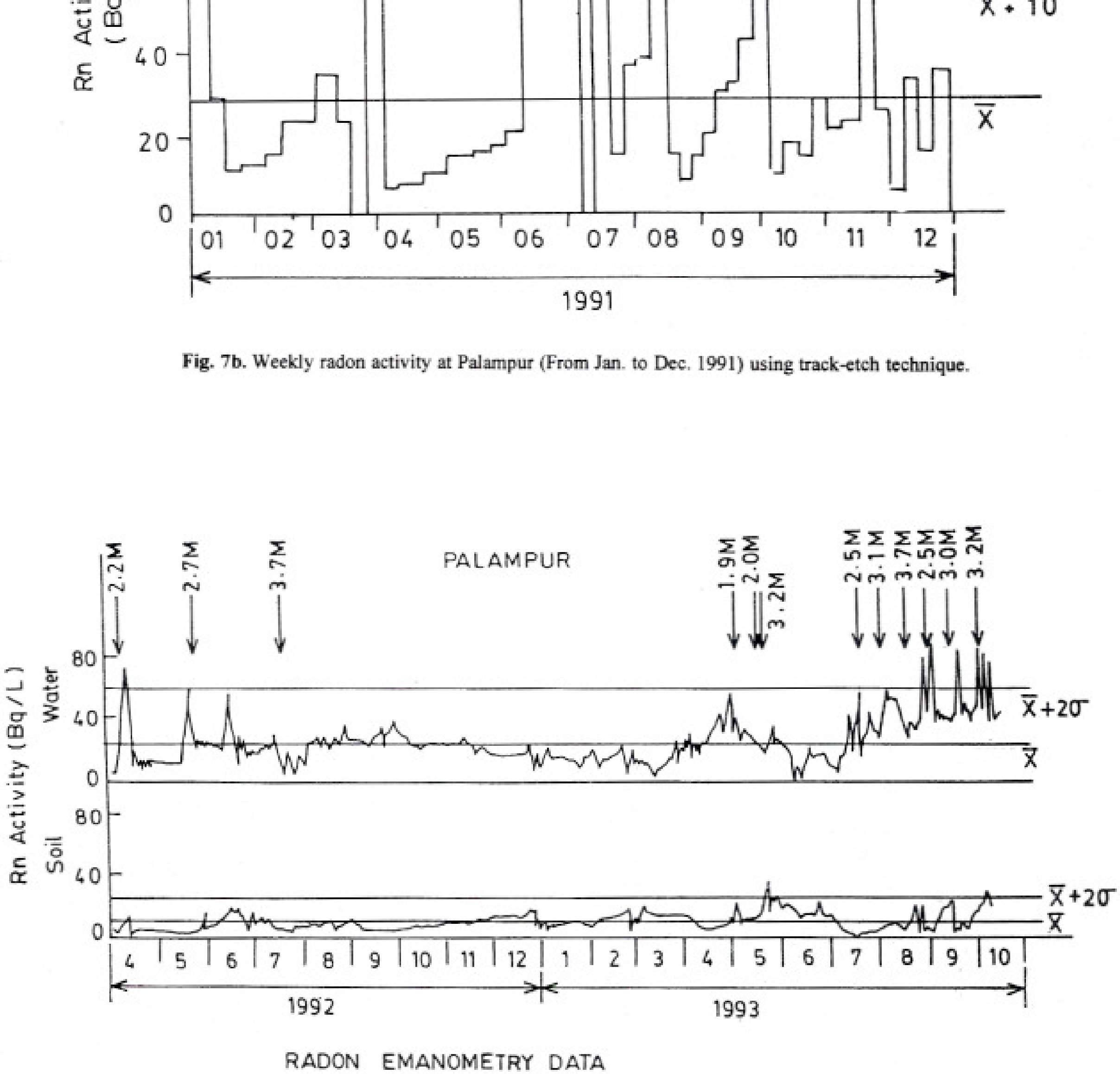

Fig. 8. Time-series radon emanometry Data in soil-gas and groundwater at Palampur (from April 1992 to Sept. 1993)

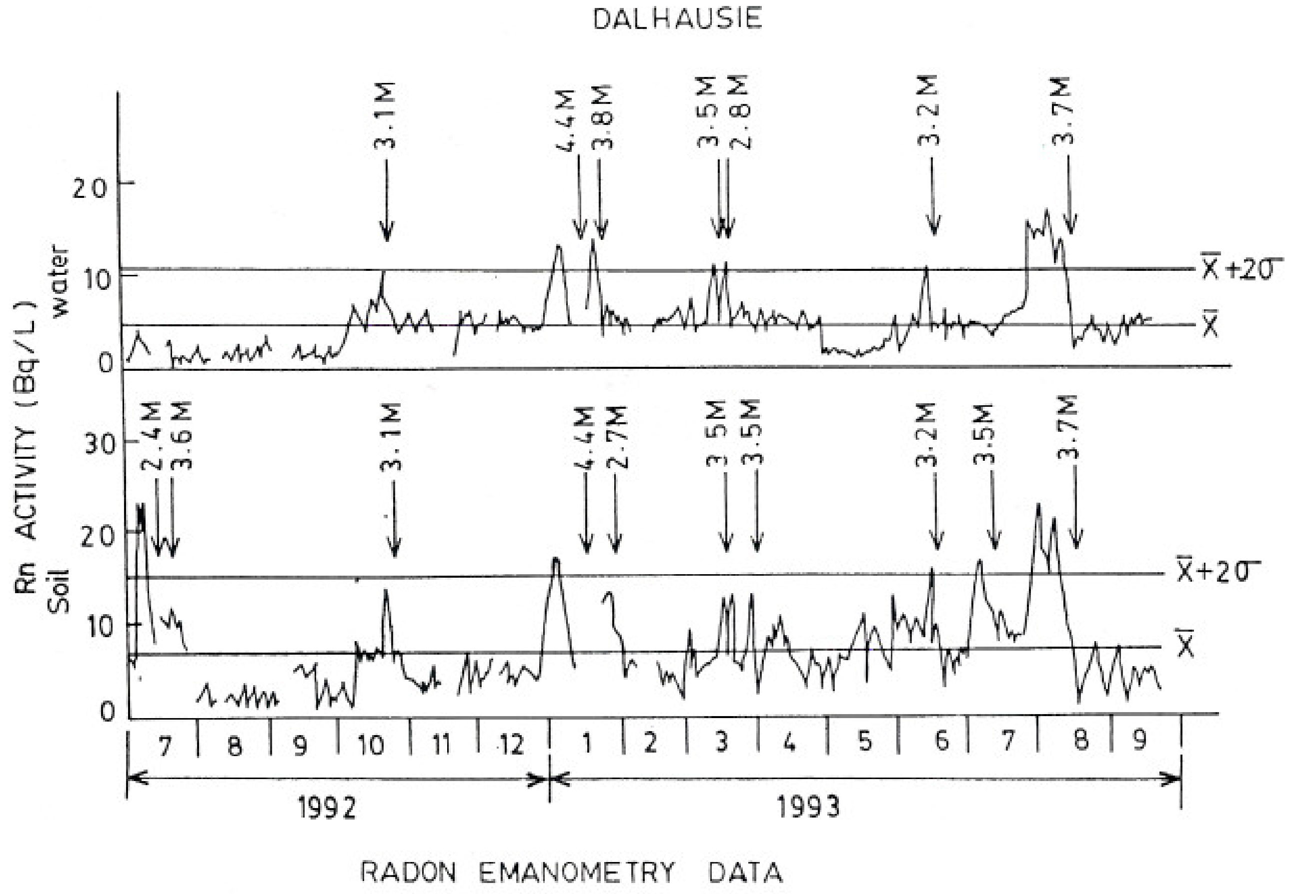

Fig. 9. Time series radon emanometery data in soil-gas and groundwater at Dalhousie (from July 1992 to Oct. 1993).

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