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Anomalous radon emission as precursor of earthquake

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ABSTRACT

Recent years have seen an ever increasing interest in studying the usefulness of radon measurements in earth sciences. Radon emissions that are enhanced by forthcoming geophysical events as earthquakes or volcanic activity have been observed all over the world. The abnormal radon exhalation from the interior of earth, as a precursory phenomenon related to earthquakes and as an indicator of underlying geological faults, is an important field of investigation. For this purpose a number of active and passive methods for getting radon signals have been developed. Several models have been proposed as an explanation of the experimental field data. This paper gives a brief review of the progress made in the field of radon measurements in earth sciences specially in predicting earthquakes. Radon anomalies that have been observed in soil gas as well as groundwater or spring prior to earthquakes have been reviewed in this paper. The models proposed in relating precursor time, epicentral distance, magnitude of earthquake have also been discussed.

Contents

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1. Introduction

Radon is an important terrestrial gas whose presence and concentration are easy to detect. Measurements of radon concentration within the earth's crust have long been made on the hope of detecting distant sources or to know the processes of gas release. The study relating to radon emanation from the earth's surface was also involved to point out uranium deposits, as tracer of moving air and groundwater masses (King, 1980). Subsequently, a great application of radon monitoring was immersed as a positive tool for prediction of an earthquake, when Okabe studied the correlation between radon content variation and local seismicity in Japan (Okabe, 1956). The real time radon monitoring has become an extensively studied area in order to give premonitory signs prior to an earthquake. The strain changes occurring within the earth's surface during an earthquake is expected to enhance the radon concentration in soil gas. The impressive development in the study of the earth's crust permits to estimate on probabilities for earthquake risks. The study involves the prediction of precursor time, distance from epicenter, magnitude of incoming earthquake and other parameters.

However, radon concentration levels are strongly affected by geological and geophysical conditions, as well as atmospheric influences such as rainfall and barometric pressure. As temperature, rainfall, barometric pressure, all are integrated parts of season, radon concentration thus changes seasonally and this seasonal variation of radon concentration is also an important area that is to be studied along with.

2. Relation between radon and earthquake

Radon, being an inert and water-soluble gas produced in uranium decay series, has been used as an in situ stress transducer prior to an earthquake. The total uranium content of the earth's crust is about 3–4 ppm, which is significant in terms of total mass and its radiological contribution to the atmosphere. As an intermediate decay product of uranium series, radon is ubiquitous in nature.

Among the three known radon isotopes, ^{222}Rn has the longest half-life (3.82 days) and is of most geophysical interest. Radon gas generated in rocks remains partly in the solid matrix, but some moves to pore fluids and migrates away through interconnected pores, aquifers by the method of diffusion and fluid flow. In 1926, V.I. Spitsyn studied in detail about the release of ^{222}Rn from natural minerals (Spitsyn, 1926). The recoil energy of about 100 keV enables ^{222}Rn to travel through hundreds of crystalline lattice sites.

In a geothermal area seismic changes results in changes in rock pressures and fluid convective flows. Prior to an earthquake, the build-up of stress causes the change in strain field also. The displacement of rock mass under that tectonic stress opens up various pathways and a new surface becomes exposed when it cracks open. The stress–strain developed within earth's crust before an earthquake leads to changes in gas transportation and rise of volatiles from the deep earth to the surface (Thomas, 1988; Fleischer, 1997). As a result, unusual quantities of radon come out of the pores and fractures of the rocks on surface. Thus due to the seismic activity, changes in underground fluid flow may account for anomalous changes in concentration of radon and its progeny (Steinitz et al., 2003).

According to Grammakov (1936) and Clements (1974) a small change in velocity of gas into or out of the ground causes a significant change in radon concentration at shallow soil depth as changes in gas flow disturb the strong radon concentration gradient that exists between the soil and the atmosphere. A slight compression of pore volume causes gas to flow out of the soil resulting to an increase in radon level. Similarly, when pore volume increases, gas flows into the soil from the atmosphere. Thus, an increased radon concentration occurs in the region of compression and radon concentration decreases in the region of dilation. As small changes in gas flow velocity causes significant change in radon concentration, soil radon monitoring is thus an important way to detect the changes in compression or dilation associated with an earthquake event.

Radon might also be dissolved in pore fluids and migrate into the groundwater-bearing layer. Before a seismic event, when regional stress increases, dilation of rock masses causes an increase in surface area of rocks due to cracking or an increase of flow rate of pore fluids. Both of these methods enhance the radon from its original enclosures into the groundwater or spring water.

According to the Dilatancy–Diffusion model proposed by Martinelli (1991), considering the medium as porous cracked saturated rocks, when a tectonic stress develops the cracks extend and appear near the pores with the opening of favourably oriented cracks. As a result, the pore pressure decreases in the total preparation zone and water from surrounding medium diffuses into the zone. At the end of the diffusion period the main rupture occurs due to the appearance of pore pressure and increase in cracks. According to the Crack–Avalanche model (Lay et al., 1998), as tectonic stress increases a cracked focal zone is formed and with time the shape and size of the zone change. Comparing these two models it can be concluded that at a certain period, a region of several cracks is formed. The earthquake is always associated with deformations and as a result short and long term precursory phenomena like anomaly in radon concentration occur. The variation of radon concentration has been monitored in soil gas as well as ground water.

R.L. Fleischer showed that entry of water causes release of radon that was previously stored in soil or rock (Fleischer, 1983). In principle, the gas flux along the fault area and through microfractures influences the transport of radon from its origin to the surface (Facchini et al., 1993). But it must also be considered that radon anomaly is not only controlled by earthquake, it also changes due to meteorological parameters like soil moisture, rainfall, temperature, atmospheric pressure, etc. These were studied by several authors (Stranden et al., 1984; Luetzelschwab et al., 1989; Asher-Bolinder et al., 1993). Thus it is necessary to measure changes of radon prior to an earthquake reducing the effect of meteorological parameters. A schematic cross section of the radon out flux mechanism in the Tashkent groundwater basin is shown in Fig. 1.

The anomalies associated with an earthquake may disappear after the quake for the following reasons:

- Stress relaxation associated with earthquake
- Healing of fault zone
- Exhaustion of gas supply

2.1. Variation in background radon

Due to atmospheric changes the concentration of different terrestrial gases including radon changes significantly and shows anomalous fluctuations in the concentration.

In winter, the radon concentration values appeared to be higher than in other seasons, as dilution of radon rich soil gas with atmospheric air is reduced by high moisture content in soil (Kovach, 1944, 1945). The daily variation has been observed by King (1985). Increasing moisture content in soil increases the fraction of radon produced in rocks and accordingly increases the radon concentration in soil gas which migrates through the pore fluids (Tanner, 1964; Fleischer, 1983; Neilson et al., 1984). The near surface porosity may reduce due to heavy rainfall and snowfall and that inhibits the exhalation of radon into the atmosphere (Megumi and Mamuro, 1973; Klusman, 1981).

The barometric pressure has also the effect on change in radon concentration as increase in barometric pressure reduces the radon concentration and vice versa (Kovach, 1945; Hatuda, 1953; Tanner, 1959; Kraner et al., 1964; Clements and Wilkening, 1974; Kristiansson and Malmquist, 1982; Schery et al., 1982).

Several groups have studied the changes of radon concentration due to high speed winds which might be accounted due to the upward flow of soil gas as a result of Bernoulli's effect (Pearson et al., 1966; Guedalia et al., 1970; Woodcock and Freidman, 1979). Birchard and Libby found the significant seasonal variation due to different meteorological factors (Birchard and Libby, 1980).

It was suggested by Mavlyanov and his group that the release of radon could be promoted by ultrasonic vibrations in deep zones (Mavlyanovet et al., 1972).

2.2. Radon signal: local or distant

Transport velocity of radon (^{222}Rn) in the earth is quite low ($\leq 10^{-3}$ cm/s) and half-life is 3.82 days. Thus radon is lost by radioactive decay long before even 1 km is traversed (Fleischer, 1981). The build-up stress prior to a seismic event can alter the radon concentration at a position where such premonitory changes can be measured (Fleischer and Mogro-Campero, 1978). The anomalous radon signals observed during earthquake are not originated in the focal zones. Rather it is observed locally either due to local release or due to local flow moves radon from nearby regions of higher or lower radon concentrations generally within a few meters of the observation point.

By 'distant' source it is meant that the source is too far from the site of observation to have delivered radon solely by diffusion. In geological settings, all of the signals will include and normally dominate by local signals from radon and thoron decay chains in the soil or rock in or above which the detector and its air space are emplaced. Occasionally, readings are significantly different from the local values that allow distant signals to be recognized (Fleischer and Mogro-Campero, 1978). The detection of distant signal of original strength 'c_0' depends on its residual strength 'c_d' relative to the local strength 'c_1' at the observation point after moving a distance 'z'. The factors that are strongly related to this are velocity of transport 'v', diffusion constant 'D', decay constant 'λ'.

The one dimensional flow of arriving concentration (Grammakov, 1936) is given by

$$c_d = c_0 \exp\{-z[((v^2/4D^2) + \lambda/D)^{1/2} - v/2D]\}$$

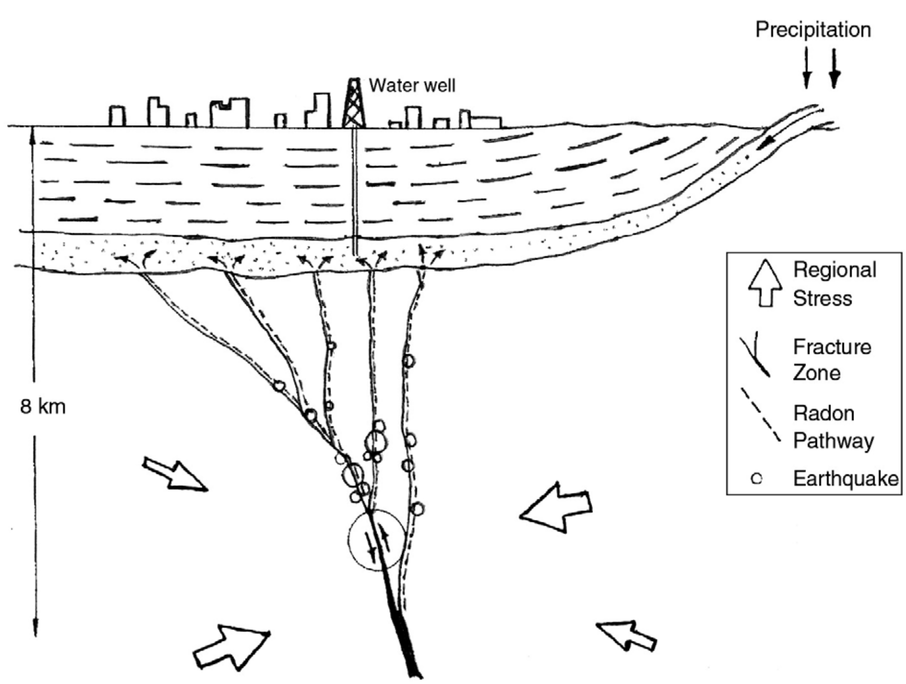

Fig. 1. Schematic cross section of the radon out flux mechanism in the Tashkent groundwater basin (Ulomov and Mavashev, 1971).

The more distant the source, the stronger it should be and the more rapid the flow toward the observation point should be in order to measure the anomaly.

3. Radon anomaly studies and earthquake prediction: a review

Radon anomaly study for prediction of earthquake has been done in soil gas as well as groundwater or spring water.

3.1. Radon studies regarding earthquake prediction in soil gas

Quite a few years before studies have been started in connection with radon emanation and seismic activity all over the world, A. B. Tanner in 1958 (Tanner, 1959) noted that the measurement of radon is very much effected by different meteorological parameters. In 1964 he cited that radon could be used as a pointer to discover uranium deposits or for prediction of earthquakes (Tanner, 1964). Quite a long back, the anomalous change in radon concentration in soil gas in fault area was investigated by Israel and Bjornsson (1967). The radon anomaly before 3–8 days of earthquakes with magnitudes of 3–3.5 was reported by Antsilevich in 1971. It was found that radon anomaly was about 20% above the background value (Antsilevich, 1971). Afterwards many important studies have been performed worldwide regarding the earthquake prediction by observing radon anomaly in soil gas. Here are detail descriptions of such studies.

3.1.1. Japan

Z. Hatuda performed a study in 1953 at an active fault zone for 2 years in Japan (Hatuda, 1953). He measured the radon concentration in soil gas and reported anomalous radon concentration change before the strong earthquake occurred at Tonankai with a magnitude of 8.0. In 1956, S. Okabe discovered that there is a positive correlation between the daily change of atmospheric radon concentration near the ground surface and local seismicity occurring in Tottori, Japan (Okabe, 1956). He also studied that soil gas is enriched in radon in the fault zone. His daily measurements showed that the near surface air manifests significant increase in radon concentration at the time of earthquakes.

Hirotaka and group observed radon anomaly before the Nagano Prefecture earthquake of $M=6.8$ on 14 September, 1984 (Hirotaka et al., 1988) and the measuring site was about 65 km away from the epicenter at the Atotsugawa fault. They observed a gradual increase in radon count before three months of the quake and a remarkable increase before 2 weeks of the shock.

Y. Honkura and A. M. Isikara reviewed some results that were done along Izmit-Sapanca and Iznik-Mekece fault zones (Honkura and Isikara, 1991). Along with the magnetic and electric potential anomaly radon anomaly in soil gas was also observed which was assumed as an effective way for detecting changes prior to fault.

3.1.2. China

In the vicinity of epicenters of earthquakes radon in soil gas was measured by Heinicke and Koch in Germany (Heinicke and Koch, 1993) and in China (Yang Yurong and Zhu Ziqiang, 1993). They studied the dependence of radon concentration on temperature, air pressure, etc. in the first case.

3.1.3. USA

In 1978, King and Slater measured soil gas radon concentration at two sites in the Calaveras fault, California, along with the observation of crustal strain. They found radon emanation to be higher during crustal compression (King and Slater, 1978).

C. Y. King performed a study in 1978 over the area of the San Andreas fault and Hayward-Calaveras fault and found episodic radon anomaly during two strong earthquakes with magnitudes of 4.3 and 4.0 (King, 1978). King extended his work along the San Andreas fault with the study of episodic radon change and relation to earthquakes (King, 1980). The radon anomaly in one case showed a peak value of 60% above the average value, in other cases it were more than a factor of 2 or 1.8 from the average value. But there were discrepancies in the relation between radon fluctuation and earthquake magnitude. The effect that were considered were extracrustal (weather, cosmic ray) and intracrustal (seismic shaking, fault slip, increase in pressure in the fault zone, etc.). The earthquake of $M=4.3$, epicentral distance 21 km was preceded by radon concentration peak before a short while. Significant radon anomaly was also observed in the San Francisco Bay area, on the Hayward Fault in 1976 and on the Calaveras Fault in 1977. A swarm of earthquakes occurred on 8 January, 1977 was preceded by radon peak at the San Andreas and Hayward Faults, but followed by radon peak at the Calaveras Fault 1977 earthquake ($M=4.0$), 15 December 1977 ($M=4.0$). During summer 1978 recognizable radon concentration increase more than a factor of two than the average value) was recorded on the San Andreas Fault when two earthquakes of $M=4.0$ and 4.2 occurred by that time. A few exceptional radon behavior was also seen—as high radon concentration during spring 1978 was not associated with any quake and again no radon anomaly was observed during the June 1977 quake event of $M=4.0$ and 4.6.

3.1.4. India

In Bhatsa dam, Maharashtra, India, major earthquakes occurred during August 1983–July 1984. In that region radon concentration was measured by B. K. Rastogi and group and they found an increase in radon concentration during March–April 1984 (Rastogi et al., 1986) when seismicity was high enough.

Precursory phenomena of radon in earthquake sequence were observed by B.K. Rastogi and other group at the Osmansagar reservoir, Hederabad, India during January–February, 1982 (Rastogi et al., 1987). A seismic event with a magnitude of 3.5 occurred on 14 January, 1982 with subsequent events also. There was an increase of radon concentration in soil gas during February due to those high seismic activities.

M. Singh with others monitored radon concentration continuously during 1984 in India that revealed considerable radon anomaly 3–10 days before of an earthquake with a magnitude of $M=3.8$ with the epicentral distance of 100–400 km (Singh et al., 1991).

The precursory nature of radon as well as helium was observed by H.S. Virk and his group in the NW Himalayas during the earthquakes that occurred on 20 October, 1991 and 29 March, 1999 (Virk et al., 2001; Virk and Walia, 2001). The Chamoli earthquake of $M=6.5$ was associated with radon anomaly which was measured at Palampur about 393 km from the epicenter. The radon anomaly started 19 days before of the quake, 9 days before the quake it was minimum and 2 days before that quake the radon concentration reached at peak value ($>2\sigma$). Using emanometry technique Walia et al. (2005a,b) carried out a radon monitoring programme at Palampur and Dalhousie in Kangra Valley, Himachal Pradesh. They found positive as well as negative pre signals of radon anomalies. Ghosh et al. (2007) have performed an experiment on measuring radon concentration in soil gas with the use of CR-39 (SSNTD) at Kolkata, India. Radon anomaly before the earthquakes that occurred during the period of November 2005 to October 2006 within the range of 1000 km from the measuring site and of $M\geq4$ was observed. Precursor signal before 7–11 days of earthquake events was monitored.

3.1.5. Spain

Radon concentration in soil gas was studied by Duenas and Fernandez (1988) at Spain. They found both pre and post anomalies along with 'no' anomaly of radon concentration related to earthquakes with magnitudes of 2–4 at a distance of 90 km from the monitoring site. Across the Amer fault, soil radon level was monitored by Font et al. (2008). Using LR115 and Clipperton II, they monitored radon level at 27 points along the fault zone.

3.1.6. Turkey

H. Friedmann and his group monitored radon in soil gas at five sites along 200 km at the North Anatolian Fault Zone, Bolu, Turkey (Friedmann et al., 1988). They observed the effect during the Biga earthquake of $M=5.7$ on 5 July, 1983 and found an increase in radon concentration.

In search of the relation between earthquakes and radon undulation M. Inceoz and others performed a study using SSNTD (CR-39) at the North and East Anatolian fault system, Turkey (Inceoz et al., 2006). They found that radon anomaly was quite significant over the fault line whereas it fell drastically going away from the fault line.

3.1.7. Alaska

Fleischer and Mogro-Campero studied the correlation between radon concentration and earthquake occurrence during the period 1981–1983 (Fleischer and Mogro-Campero, 1985). Near Sand Point, Alaska, they observed a rise of radon concentration 6 weeks prior to the quake event of $M_S=6.3$ at a distance of 180 km from the radon measuring stations.

In the Yakataga region, they found both a decrease and an increase in radon concentration during seismic events such as the earthquake of May 2, 1982 with radon minimum, June–July 1980 with radon maximum, May 1981 with termination of large increase. They calculated the RSI (relative dislocation strain intensity) value and concluded that larger quakes are observable by radon, though smaller quakes are observable only if the magnitude of quakes is close to the maximum allowed by the uncertainty. They found no significant correlation between radon and other meteorological effects such as rain fall, snow accumulation, temperature, etc.

3.1.8. Mexico

N. Segovia and others performed a long term study along the Mexican Pacific Coast near the Mesoamerican trench regarding radon concentration fluctuation in pre, co and post periods of any seismic activity (Segovia et al., 1993). SSNTD was used for this systematic study.

Segovia extended his work regarding the study of radon measurements and finding relation with earthquakes. He along with his group measured radon concentration in soil along the Guerrero coastal zone (Segovia et al., 1995a,b). Using SSNTD a survey of radon and short lived daughter concentration in soil gas was measured by N. Segovia and group near Laguna Verde, Mexico. At Acapulco stations they observed weak radon anomaly during earthquakes of $M=4.7$, 5.5 during 1990–1991, but significant radon increase during 1992–1994 earthquakes. Among the observation in different sites, higher radon concentration was found near geologic fault region (Segovia et al., 1996). On the basis of long term monitoring of soil radon, N. Segovia and his group surveyed for five years along the Pacific coast of Mexico. They explained the lack of biunivocal relation between single radon peak and quakes for the long term study done by SSNTD. The effect of earthquakes and other meteorological conditions were also explained by short term radon anomaly obtained from the continuous data (Segovia et al., 1999).

Monnin and Seidel used a radon probe near Acapulco, State of Guerrero, united state of Mexico to observe radon behavior. For an earthquake that occurred on 30 October, 1994, of $M=5.1$, they got a spike-like anomaly of radon concentration before 6 days of the shock event (Monnin and Seidel, 1998). They used Clipperton probe for Rn detection. The schematic view of the probe is seen in Fig. 2. M. Monnin and J. Seidel reported a finding on characteristics of radon in soil air during the earthquake (Monnin and Seidel, 1991). They found that near surface radon fluctuation were mainly due to deeper fluid motion which supports the Pore Collapse (PC) model creating an upward motion of pore fluids that acts as radon carrier. Considering the theoretical model they inferred that a large quantity of radon is expected to show during a short duration prior to a quake.

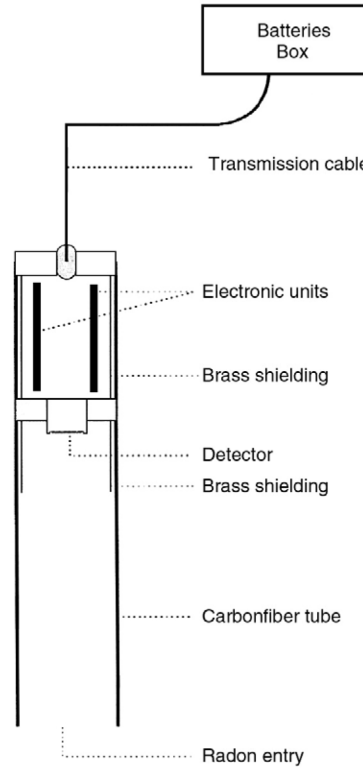

Fig. 2. Schematic view of the Clipperton probe (Monnin and Seidel, 1998).

3.1.9. Turkmenistan

Alekseev with other scientists performed a study on radon and metal contents measurements in soil as well as water in Turkmenistan (Alekseev et al., 1995). They chose the measuring site area in the Ashkhabad and Kum-Dang region. Nitrocellulose detector (SSNTD) was placed inside the 70 cm deep pit and continuous radon measurement was carried out at intervals of 5–7 days. A simultaneous increase in radon concentration was observed during the devastating earthquake that occurred on 14 March, 1983.

3.1.10. Thailand

Wattananikorn and others performed a systematic study on radon measurements in soil gas at the region that is 65 km N-NE of Chiang Mai City, Northern Thailand (Wattananikorn et al., 1998). They used SSNTD (LR-115) at the depth of 50 cm and 100 cm below the surface to detect radon changes. The data obtained during several earthquakes occurred during their observation period (40 weeks) has been tabulated in Table 1. They also studied a correlation between radon concentration at 100 cm depth and earthquakes at Thailand.

Table 1
Study on radon measurements in soil gas at the region that is 65 km N-NE of Chiang Mai City, Northern Thailand (Wattananikorn et al., 1998).

Date of EQ	Magnitude of EQ	Epicentral distance (km)	Serial no. of week on which EQ occurred	Serial no. of week when radon anomaly occurred
11 November, 1996	6.2	293	6th	3rd–8th
22 December, 1996	5.5	159	12th	8th–15th
3 March, 1997	2.5	11	22nd	19th–24th
	2.6	16		24th–30th
20 April, 1997	2	73	29th	30th–36th
	3	70		
6 June, 1997	4	134	36th	30th–36th

A new method based on Adaptive Linear Neuron was developed by A. Negarestani and group for estimating radon concentration in soil (Negarestani et al., 2003). They performed a study at Thailand and they were able to differentiate the variation in radon concentration caused by environmental parameters and that caused by earthquake.

3.1.11. Russia

The variation of radon as precursor signal of earthquake was studied by Tsvetkova in the Caucasus (Tsvetkova et al., 2001). Measurement of radon was analysed by Tsvetkova and group in east Europe under the ground (Tsvetkova et al., 2005). An extensive work using SSNTD along the Northern Caucasus was carried out by Nevinsky and Tsvetkova (2005). An average earthquake on 28 September, 2002 was pre-assigned by radon concentration variation from 25 to 28 September, 2002.

3.1.12. Slovenia

B. Zmazek with his coworkers performed a study on measurement of radon activity in soil gas with temperature and pressure variation at the Krsko basin, Slovenia. They found change in the correlation coefficient between radon and barometric pressure before an earthquake at one place (Zmazek et al., 2002). B. Zmazek and other workers used regression methods to predict radon concentration in soil gas on the basis of different environmental parameters and also seismic activity at the same place (Zmazek et al., 2003). They found radon concentration with a correlation of 0.8 when it was influenced by environmental parameters and much lower correlation with seismic activity. The decrease appeared before 1–7 days of earthquakes with magnitudes of 0.8–3.3.

The anomalies in soil gas caused by earthquake were studied extensively by Zmazek et al. (2005). The detail result is in Table 3.

3.1.13. Poland

In the geologic fault region of Krakow, Poland, the concentration of radon in soil gas and other radioisotopes (radium, thorium, potassium) was measured by Swakon et al. (2004) using ALPHA GUARD, diffusion chamber with CR-39 and gamma ray spectrometry. High values of radon and thoron in soil gas compared to previous value were found at that fault region.

3.1.14. Antarctica

Radon in Antartica was studied extensively by Ilic et al. (2005). During a yearly investigation they monitored an earthquake that occurred on 4 August, 2003 of $M=7.5$, in the Scotia Sea at a distance of 1176 km from the measuring site Academician Vernadsky station. Using a model (Ilic et al., 2005) they made a prediction that an earthquake would happen on 30 October, 2003 of $M=4.0$ and that was proved later.

3.1.15. Italy

A study on radon measurements in soil in seismic area of NE Italy was conducted by Garavaglia et al. (1998). The test site was in the cave in Villanova, which was one of the most seismically active regions of the Alps. Radon concentration variation was measured during the local seismicity occurred within December 1996–March 1997 of $M=2.5$–4.2. Along with the effect of seismic events, radon anomaly was also observed with pressure and temperature variation. Radon measurement in the SE and NE flank of Mt. Etna was carried out by Delfa et al. (2007). They found radon anomaly associated with seismic as well as volcanic activity.

3.1.16. France

The anomalous behavior of radon during earthquake was studied by Klein et al. (1991)in France.

3.1.17. Greece

Richon et al. (2007) performed an experiment to observe radon in soil gas in the Gulf of Corinth region. Using Barasol probe they studied radon concentration in relation to seismic activity.

3.1.18. Croatia

Radon concentration in soil gas was measured by Planinic et al. (2000) at Croatia in 1998 using SNTD (LR-115), result shown in Table 2. Barometric pressure, precipitation, air temperature, etc. were also observed by them.

3.1.19. Egypt

Along the fault line of the Qena-Safaga fault, Egypt, Moussa and Arabi observed soil radon concentration during 2001–2002 (Moussa and El Arabi, 2003). They found the radon peak nearly 5–10 times greater than the background on the fault trace when they performed a study on radon concentration variation with distance along the fault. With the use of ALPHA GUARD they observed high radon peak on different dates in active fault zone.

3.1.20. Taiwan

Considering 125 data points for radon analysis across the Shan-Chiao fault, N Taiwan, Walia and group found variation in radon concentration along the fault (Walia et al., 2005a,b). Along an active fault zone of SW Taiwan, an automatic soil gas monitoring station was set up by Yang et al. (2005). During the measurement period of March 2003 to June 2004, anomalous high concentration of about 200 kBq/m^3 was found whereas background count was only15 kBq/m^3 for radon. The details of earthquake occurrences are shown in Table 3. In general, the earthquakes were preceded by radon anomaly peak before 1–20 days, though some exceptions were there. Thus the shock events were correlated with precursory signal of radon. Continuous soil radon monitoring was carried out by Chyi et al. (2005). Drastic change in radon concentration was observed before the onset of quakes at fault zone of Taiwan. In Southern Taiwan, anomaly in radon along with that in helium in soil gas was observed by Fu et al. (2008). They used the radon detector (RTM 2100, SARAD) for detection of radon concentration. A correlation was found between anomalous precursor peak and earthquake events.

3.1.21. UK

During the period of June to December, 2002, the University College Northampton Radon Research Group made an investigation with a RAD-7 detector (Crockett et al., 2006). An earthquake occurred at Dudley on 22 September, 2002. Two spikes were observed on the 21st and 22 of September 2002, preceded by two smaller spikes on the 20th and 21 of September 2002 and a negative correlation was there during late October to Mid November. The English Channel earthquake during August 2002 was also observed.

3.2. Radon studies regarding earthquake prediction in ground water and hot spring

3.2.1. Japan

To see the possible effect of earthquake related changes in groundwater studies have been performed quite a few years back by Shiratoi (1927) in hot springs and by Imamura (1947) in Japan. Radon monitoring in groundwater was performed extensively at about 1000 sites in mainland China after the Xingtai earthquake of $M=7.2$ in 1966.

5 days before the Izu-Oshima-Kinkai earthquake of $M=7.0$ on 14 January, 1978, a spike-like radon anomaly was recorded by Wakita

Table 2
Radon concentration in soil gas was measured by Planinic et al. (2000).

Date of EQ	Magnitude of EQ	Epicentral distance (km)	Radon anomaly occurred before	Earthquake effectiveness parameter
25 June, 1998	2.8	70	1 month	8.2×10^{-10}
27 November, 1998	2.7	200	1 month	2.6×10^{-12}

Table 3
Radon monitoring as a precursor of earthquake—a comparative study (** work done with SSNTD).

Date of EQ	M_s	Distance between site and epicenter(km)	Radon anomaly occurred	Reference
6 Mar, 1984: Japan	7.9	1000	*Before*	Tectonophysics
			7 days: anomaly observed (gr water)	180 (2–4),1990, 237
6 Feb, 1987	6.7, 6.4	130	*Before*	
			3 days: anomaly observed (gr water)	
**14 Mar, 1983: Turkmenistan	5.7		Increase of concentration during EQ	Rad Meas., 25 (1–4), 1995, 637
**1991–1993, Acapulco, Mexico	4.7	100	*Before*	Rad Meas., 25(1–4), 1995, 547
	5.5		10 days: peak	
9000 EQ swarms: Izu peninsula, Japan	≤3	30	*Before*	Appl. Geochem.13,1998 89
11–13 Sept, 1995	≤3		3 days: start increase	
18–19 Sept, 1995	4.8		17 Sept: increasing by 50%	
29 Sept–1 Oct, 1995			Oct: high	
			After	
			Nov: returned to normal	
22 Dec, 1996:	2.5,3.2	40,31		Phys. Chem. Earth, 23 (9–10),
Rome	2.5	25		1998,949
23 Dec, 1996	3.0,3.2	23,23		
18 Jan, 1997	4.2	210		
27 Jan, 1997	2.9	40		
15 Feb, 1997	2.9	35		
17 Mar, 1997				
** 11 Nov, 1996: Thailand	6.2	293	*Before*	Rad Meas., 29, 1998, 593
			14 days: peak	
22 Dec, 1996	5.5	159	14 days: peak	
3 Mar,1997	2.5,2.6	11,16	7 days: peak	
			On date: abrupt downturn	
20 Apr, 1997	2,3	73,70	45 days, 7 days: peak	
			On date: abrupt downturn	
6 June, 1997	4	134	*After* 7 days: downturn	
**25 Jun, 1998: Modrica, Croatia	2.8	70	*Before*	Fizika B, 9 (2), 2000, 75
			30 days: large increase,,	
27 Jun, 1998	2.7	200		
**16 Dec 1997: Caucasus		150	*Before*	Rad Meas., 33, 2001, 1
			10 days: burst	
16 May, 1998: Turkey			9 days: hour burst	
29 Mar, 1999: Chamoli, India	6.5	393	*Before*	Rad Meas., 34 2001, 379
			19 days: highs/lows	
			9 days: min value	
			2 days: peak value	
18 Nov, 1998: Arax basin, Armenia	4.2	Dvin Site: 65–135 km	*During*	Surface Geo- Science, 334,
23 Nov, 1998	4.7	(centre of basin, near Arax-Vedi fault)	3 months: drastic and abrupt decrease	2002, 179
27 Nov, 1998	3.3			
08 Dec, 1998	4.0			
21 Dec, 1998	3.7			
	3.5			
14 Feb, 1999		Metsamor-Dvin -20		
		Aroutch-Dvin-30	*During*	
		(north of basin, on each side of Arax fault,	1 month: increases considerably	
		inside tectonic microbloc)		
25 EQ: N–W Himalaya, India	9 EQ:	17–128		Rad Meas., 36,2003, 393
1992–1999	2.1–2.9			
	9 EQ:	31–187		
	3.0–3.8			
	6 EQ:	44–166		
	4.0–4.8			
	1 EQ:	393		
	6.8			
25 Jan, 1999: Quindio, Columbia	6.2		*Before*: Increase starts	Proc ICGG7, 2003, 6
			On date: sharp drop	
Barranco station	2.1	≤6	*Before*: Increase	
**31 Jan, 1999: Sakhalin,	5.4	700	*Before*	Rad Meas., 40, 2005, 98
			12 days: peak	
Caucasus	3.0	50	*Before*	
20 Apr, 1999			1–2 days: peak	
			On date: abrupt downturn	
Pyatigorsk	5.4	300	*Before*	
31 Jan, 1999:			3 days: peak	
			After: Decrease	
Abrau:	5.8,4.4	regional	*Before*	
12 Apr, 2002	4.8		Increase/ splashes	
17 Apr, 2002				
**28 Sept, 2002, AbrauDurso, Caucasus	avg		*Before*	Rad Meas., 39, 2005, 115
			3 days: increase start	
			On date: max	
			After	
			Returned to previous value	

(continued on next page)

Table 3 (*continued*)

Date of EQ	M_s	Distance between site and epicenter(km)	Radon anomaly occurred	Reference
**Aug. 2003: Vernadsky station, Antartica	7.5	1176	No observable variation *before, during or after* EQ	Rad Meas., 40, 2005, 415
1 Jan., 2003–31 Jul, 2004: Taiwan	11 EQ: ≥4.5	≤60	*Before* 1–20 days: anomalous peak	Rad Meas., 40, 2005, 496
488 EQ: among those 30 EQ were meaningful w.r.t measuring site	14 EQ: ≥5.0	60–120		
	5 EQ: ≥5.5	≥20	80% EQ have relevant precursor,	
Date of EQ	M_s	Epicentral distance/Dobrovolsky radius	Radon anomaly occurred	Reference
		R_E/R_D=	Before	
Krsko I, Slovenia				Applied Geochemistry 20, 2005,1106
13 Apr, 1999	0.8	1.4	2 days	
22 May, 1999	0.7	1.6	3 days	
06 Oct., 1999	2.1	2.0	17 days	
14 Apr, 2000	1.8	1.6	–	
16 Apr, 2000	3.2	0.5	–	
17Apr, 2000	2.2	1.2	33 days	
28 Sept., 2000	3.0	0.4		
24 Aug, 2000	1.8	1.0		
31 Aug, 2000	1.9	2.0	5 days	
13 Oct, 2000	1.1	1.4		
29 Oct., 2000	2.7	1.5		
31 Oct., 2000	1.3	1.0	1 day	
06 Nov.,2000	1.0	2.0		
29 Nov., 2000	1.6	0.8	22 days	
19 Feb., 2001	1.4	0.4	10 days	
4 Jun, 2001	2.7	2.0	33 days	
25 Sept., 2001	1.9	1.4		
Kremen, Slovenia				
28 Jul, 2000	3.0	0.4	3 days	
19 Feb, 2001	1.4	0.4		
4 Jun, 2001	2.7	2.0		
25 Sept, 2001	1.9	1.4		
Grmada, Slovenia				
28 Jul, 2000	3.0	0.4	18 days	
24 Aug, 2000	1.8	1.0	7 days	
31 Aug, 2000	1.9	2.0		
19 Feb., 2001	1.4	0.4		
04 Jun, 2001	2.7	2.0	4 days	
25 Sept. 2001	1.9	1.4		

et al. (1980), at a 350 m deep artesian well at 25 km away from the epicenter.

An extensive study was performed by Igarashi et al. (1995) regarding radon anomaly observation in ground water. They started radon monitoring in well water during 1993–1994. The observation well was 17 m deep and 30 km away from the site where a devastating earthquake of $M=7.2$ occurred on 17 January, 1995. The radon concentration was stable at 20 KBq/m^3 during the end of 1993 and started to increase gradually from October 1994 reaching the value 60 KBq/m^3. Then there was a sudden increase on 7 January, 1995, 10 days before the earthquake and again a sudden decrease on 10 January, 1995, 7 days before the earthquake. The sudden increase might be due to the formation of microcracks in the aquifer system and the decrease might be due to sealing of the cracks.

A radon monitoring system was installed in the Yugano hot spring, Izu peninsula, Japan in May 1995 and anomalous behavior of radon was observed by Nishizawa et al. (1998). They observed radon anomaly with the use of alpha-ray detector PD which is a specially designed PIN photodiode. A swarm of quakes (around 9000 quakes) occurred there from 11 September 1995, increased highly on 29 September, decreased after 6 October and ceased on 23 October 1995. Some quakes were of $M<3$ and depth >8 km, and some were of $M>4$ and depth <2–3 km. the radon concentration was seen to be increased 3 days before the onset of quake swarm on 8 September 1995. The formation of microcracks caused by compressional stress prior to an earthquake was considered as the possible reason for that. There were ups and downs in radon concentration afterwards also.

Ondoh carried out an extensive study on investigation of radon anomaly in groundwater (Ondoh, 2009). He investigated the nature of radon anomaly occurred during three large earthquakes of $M>6.5$.

3.2.2. Tashkent

Some pioneering works have been performed in USSR during 1966–1971. In 1968, Ulomov and Mavashev (1968, 1971) observed anomaly in radon concentration in hot mineral water from aquifer (1300–2400 m deep) in a Tashkent artesian basin, USSR before the Tashkent earthquake of $M=5.3$ in 1966 and some other shocks of $M=3.0$–4.0. The wells were such chosen that they were situated on seismically active zone and at a depth interval of 0–7 km. The epicentral distance was within 5 km and most of the anomalies were prominent precursor signals. Since 1974 extensive works have been done regarding radon concentration in groundwater or springs by Sultankhodzhayev et al. (1980).

In a review Asimov et al. (1979) correlated the radon concentration change in the Tashkent, Dushanbe, Alma-Ata, Andizhan area with regional seismicity (Asimov et al., 1979). Prominent precursor signals were observed before the Markansu (1974), Gazli (1976), Alma-Ata (1978) earthquakes, though some other quakes did not have any distinct precursor signal. The magnitude, epicentral distance (km) were as $M=7.3$, 530 km; $M=7.3$, 470 km; $M=7.1$, 65 km respectively. The duration of radon anomaly was 100, 4 and 50 days respectively.

Pulinets et al. (1997) measured radon concentration in the well near Tashkent, where an earthquake occurred on 13 December, 1980.

Radon concentration increased with maximum sharp few days before the quake and then again a sharp fall on the day of shock.

3.2.3. Slovenia

In Slovenia, measurement of radon concentration in water samples during earthquake was done by Zmazek et al. (2000). The earthquake in the middle of March 1982 was followed by an increase in radon concentration, but some smaller earthquakes in the middle of June 1982 were preceded by a decrease of radon concentration. In most of the cases earthquake incidence was preceded by a peak in radon concentration. But some exceptional evidence of radon anomaly which were not correlated with any earthquake was also seen.

3.2.4. China

In China, quite a few studies have been carried out by eminent scientists. Raleigh et al. (1977) and Teng (1980) observed the radon anomaly at Liaoyang where increasing radon emission was seen several hours before and peaked a day later the Haicheng earthquake of $M = 7.3$ in 1975. The radon counting system used by Teng is shown in Fig. 3. Wang (1978) and Jiang and Deng (1980) observed radon data characterized by small amplitudes and a lack of distinctive increase in activity as earthquake approached. At Kuanchuang and Ankochuang the long term anomaly were reported which lasted for 970 and 1370 days respectively.

The group of Hydro-Chemistry conducted an extensive controlled study for radon monitoring in groundwater at China (1975, 1977). They observed radon anomaly in six different springs and one artesian well. They performed a study in a laboratory by sample rocks—natural and radium-doped both. By a small pump the radon containing air was forced to pass through a scintillation counter. They observed an increase in radon emission with stress loading and rupture of rocks. A device for radon measurement used by Tasaka and Sasaki (1992) is shown in Fig. 4.

The response to the devastating Chi-Chi earthquake of $M = 7.6$ that occurred on 21 September, 1999 at China, was observed by Huang et al. (2004). Radon concentration in around 52 wells was measured in 5 different tectonic areas. In area 1, which was less than 550 km away from the epicenter, the changes were observed 5 days before, that is pre-seismic changes. In areas 2 and 3, away 1100–1280 km and 800–1160 km respectively from the hypocenter co-seismic change were noticed. In area 4, 1750–2060 km distant from the hypocenter some co and pre-seismic changes were observed. In area 5, with hypo-central distance 1810–2120 km, there were co-seismic changes.

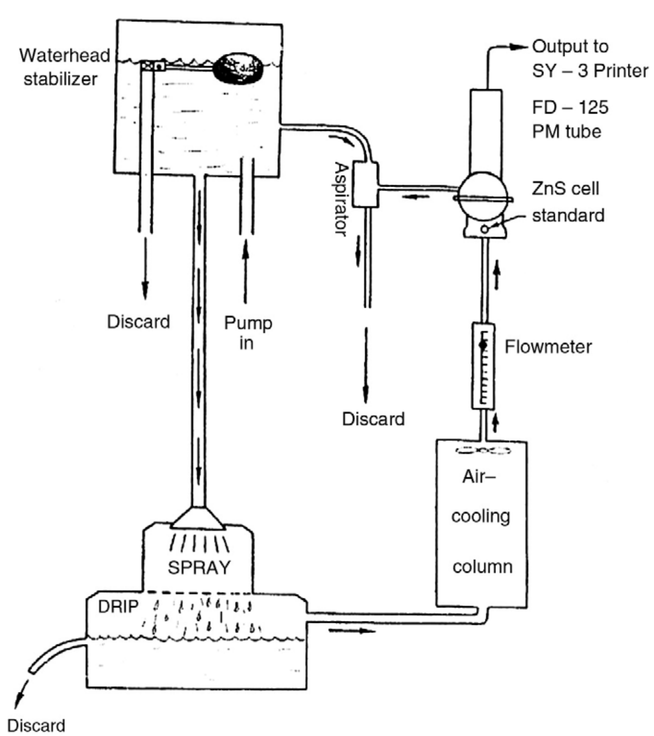

Fig. 3. A schematic diagram of the continuous radon counting system used in China (Teng, 1980).

3.2.5. Taiwan

Weekly radon measurement at a CO_2 rich cold spring, a hot spring and a geothermal well of 275 m and 30 m depth was done in northern Taiwan during 1980–1983 (Liu et al., 1985). Six anomalies were recorded which were followed by earthquakes with magnitudes of 4.6 and above within 4–51 days at 14–45 km from epicentral distance. They observed much more radon concentration in gas bubble in water samples than the expected value. The observation made by them and also by Teng (1981) and Craig (1980) revealed the possibility of radon anomaly due to episodic strain change in Southern California before the Imperial Valley earthquake of $M = 6.6$ on 15 October, 1979 and 290 km away from the measuring site. Before the earthquake of $M = 6.8$ occurred at Chengkung, eastern Taiwan on 10 December, 2003, an anomalous decrease in radon concentration in groundwater was observed by Kuo et al. (2006). Using a liquid scintillation counter, they observed a decrease of radon concentration before 45 days of the quake reaching minimum value (12.2 Bq/l, background: 28.9 Bq/l) before 20 days of the quake and increase again.

3.2.6. India

A significant radon monitoring study was done by Das and group at the Agnikunda thermal spring, Bakreswar during 2004–2005 (Das et al., 2006). The electronic radon monitor SARAD DOSEman was used to determine the radon and progeny concentration. Before the devastating tsunami that occurred in Indonesia ($M = 9.1$) on the 26th December of 2004 and also the seismic events during January–February 2005 in Sumatra, they observed distinct radon anomaly peak of $>2\sigma$.

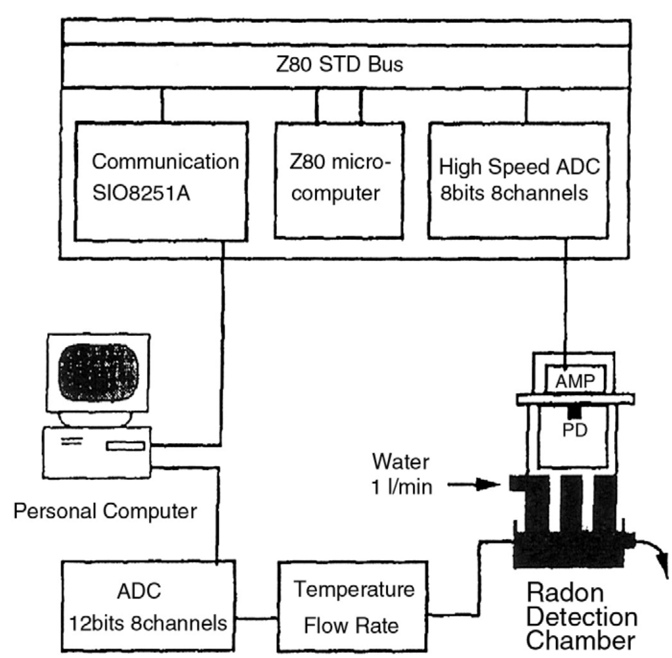

Fig. 4. Radon monitoring system developed by Tasaka and Sasaki (1992).

3.2.7. Iceland

Radon content in water samples of 9 geothermal wells was measured periodically in Iceland by Hauksson and Goddard (1981). It was found that there is a 65% probability of radon anomaly before 17–37 days of an earthquake of $M=2.0$–4.3. A radon monitoring programme in geothermal water from drill holes was conducted by a group of scientists at South Iceland (Einarsson et al., 2005, 2008). Radon time series was observed during seismic activities that occurred during June 2000 with magnitudes of 6.5 and 5+. They started the programme in 1999 with the use of liquid scintillation technique. Pre-seismic decrease as well as an increase in radon concentration was observed with co-seismic and post-seismic changes also.

3.2.8. USA

In the United State Teng et al. (1981) measured radon concentration in 14 water wells and spring water samples along the San Andreas Fault. They observed several hundred percent greater anomalies than background before earthquake. A 1 day to few weeks before precursor signal was also recorded at a hot spring, a 30 m deep well in the fault gouge zone and a cold spring in granite within 60 km of the Big Bear earthquake of $M=4.8$ on 30 June, 1979.

Craig et al. (1980) did their monthly measurements at 16 thermal springs and wells during 1974 and they concluded the anomalies to admixing of gas-rich water from deep source with shallow water within the spring.

Regarding groundwater radon data Shapiro and others recorded tectonic as well as non-tectonic effects on radon concentration at several static boreholes (25–80 m deep) and two wells (78 m and 180 m deep) in southern California (Shapiro et al., 1980, 1981). They used automated and telemetered beta particle counting devices.

3.2.9. Italy

The radon concentration in well water was monitored in central Italy during 1978–1980 by Allegri et al. (1983). They observed an anomalous increase of about 25% and 170% above background, before the Irpinia earthquake of $M=6.5$ on 23 November, 1980, 250 km away from the site.

3.2.10. Austria

Friedmann (1985a) started radon monitoring in groundwater of 5 springs in Austria using ionization chamber in 1977. They recorded an anomalous increase of a factor of 3 for 8 months, before 3 months of Montenegro earthquake, Yugoslavia, of $M=6.9$ in April, 1979, about 650 km away from the site. Some other precursor anomaly was also noticed before earthquakes of $M=4$. He pointed out that the initial rate of increase of radon anomaly tended to be smaller for larger epicentral distance and proposed a model to explain his observation (Friedmann, 1985b).

Anomalous radon increase from 5 to 18 counts/s was reported for 10 days at thermal spring that showed tidal response before 4 days of the Gazli earthquake of $M=7.3$ in May 1976, about 400 km away (Sultankhodzhayev et al., 1976). Some smaller radon anomalies were also observed by them at a distance of 720 km from the epicenter.

Some radon anomaly observed by Teng et al. (1981) is shown in Table 4.

Table 4
Radon anomaly observed by Teng et al. (1981).

Region	Date of EQ	Magnitude of EQ	Distance between epicenter and station (km)	Precursor time
Malibu	1 Jan, 1979	5.0	54	Before EQ
Kettleman Hill	4 Aug, 1985	5.6	300	2 weeks before
Bernardino	1 Oct, 1985	5.0	<90	6 weeks before
Santa Barbara	13 Aug, 1978	5.6		No significant anomaly
Coalinga	2 May, 1983	6.5		No significant anomaly

In 1978, King and Wakita (1981) started radon monitoring at an artesian well in San Juan Bautista near San Andreas fault and they observed about 25% decrease in radon concentration for 7 months, before 4 months of the Coyote Lake earthquake of $M=5.7$ on 6 Aug, 1979 at a distance of 30 km from the Calaveras fault. They also noticed a decrease in the radon concentration value before 10 days of an earthquake of $M=4.8$ on the San Andreas fault.

3.2.11. Turkey

An experiment on radon level measurement in well water was conducted by Yalim et al. (2007) at the Aksehir fault zone, Afyonkarahisar. They observed the radon level at the fault region where several high magnitude seismic activities have occurred, though they did not infer about correlation between seismic activity and radon concentration. Similar study was also carried by Baykara and Dogru (2006). In search of correlation between earthquake and radon concentration in thermal water, study was conducted by Erees et al. (2006, 2007). At two thermal spring at Denizli basin site they observed significant radon anomaly before earthquake events of $M=3.8$–4.8.

4. Experimental method

4.1. Device used in early stage of study—SSNTD

As SSNTD is the device used widely from very earlier days to predict earthquakes, the measurements made by this device are being discussed here. In 1974, Birchard and Libby (1980) monitored radon tri-weekly along San Jacinto fault using SSNTD. The same method was used by Fleischer and group in 1975 to perform integrated radon mapping (Fleischer et al., 1975) and also was used by Gingrich (1975).

This method was also applied by King (1978, 1980) in 1975 in central California. The monitoring system used by King is shown in Fig. 5. He monitored soil gas radon activity at 60 different sites along the San Andreas fault and Hayward-Calaveras fault and found episodic radon anomaly during two strong earthquakes of magnitudes 4.3 and 4.0. During summer 1978 recognizable radon concentration increase more than factor of two than the average value, was recorded on the San Andreas Fault when two earthquakes of $M=4.0$ and 4.2 that occurred by that time.

In the United States, the track-etch method was first introduced by Steele and group in the year of 1977 (Steele, 1981, 1985; Steele et al., 1982). He studied the radon activity in soil gas near the New Madrid seismic zone.

The use of membrane in this technique was introduced by them during this observation as the study by Ward et al. (1977) and introduced the desiccant inside the cup as was by Likes et al. (1979). Mogro-Campero and group performed a study at the Blue Mountain Lake region with the use of SSNTD and track-etch method (Mogro-Campero et al., 1980). From the 3 year long study starting from November 1975 to September 1978, they revealed change in radon concentration during earthquakes at the Racquette Lake region and at Newcomb. Fleischer and Mogro-Campero observed significant radon concentration changes during 1982–1983 (Fleischer and Mogro-Campero, 1985). At the Blue Mountain Lake (BML) site, they observed premonitory radon changes somewhere it was decreasing, somewhere increasing. Near Sand Point, Alaska, they observed rise of radon concentration 6 weeks prior to the quake event of $M_S=6.3$. In the Yakataga region, they found both a decrease and an increase in radon concentration during seismic events.

SSNTD was used by Savvides and group to measure radon exhalation from the ground at Greece (Savvides et al., 1985). They

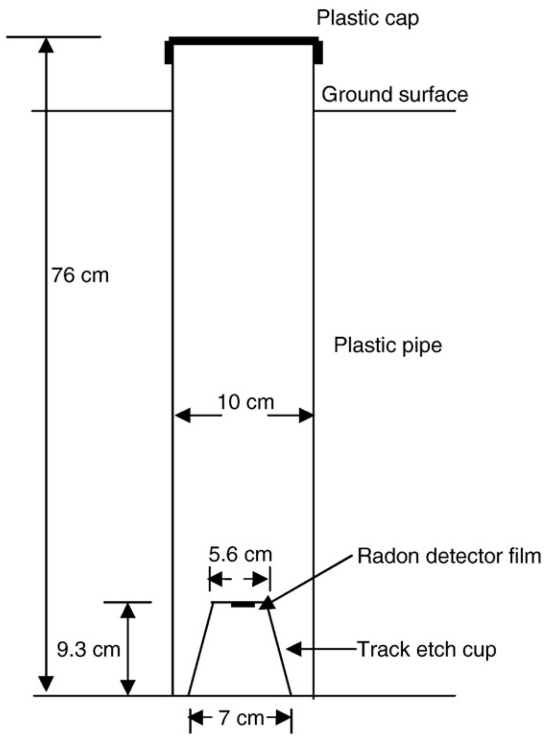

Fig. 5. Radon monitoring system with SSNTD (King, 1980).

used a CA 80-15 detector as a probe. Woith and group performed a study after a German–Turkish project started at the North of Anatolian fault zone, Turkey since 1984 (Woith et al., 1988). Regarding earthquake prediction, studies on radon concentration using SSNTD were done by several researchers in later times as in India (Virk, 1991; Singh et al., 1993), Pakistan (Qureshi et al., 1991; Khan, 1991), Algeria (Cherouati et al., 1991), Turkey (Kleis et al., 1992), etc. Radon in soil gas was measured by Heinicke and Koch (1993) in the vicinity of epicenters of earthquakes in Germany.

Segovia and others performed a long term study regarding radon concentration fluctuation in pre, co and post periods of any seismic activity along the Mexican Pacific Coast near the Mesoamerican trench (Segovia et al., 1993) and also along the Guerrero coastal zone (Segovia et al., 1995). Among the observation in different sites, higher radon concentration was found near geologic fault region (Segovia et al., 1996). The effect of earthquakes and other meteorological conditions were also explained by short term radon anomaly obtained from the continuous data (Segovia et al., 1999). Alekseev with other scientists performed a study on radon and metal contents measurements in soil as well as water in Turkmenistan (Alekseev et al., 1995). They chose the measuring site area in the Ashkhabad and Kum-Dang regions. A simultaneous increase in radon concentration was observed during the devastating earthquake that occurred on 14 March, 1983.

Radon concentration in soil gas was measured by Planinic et al. (2000) in Croatia in 1998. The device used by him is shown in Fig. 6. The variation of radon as precursor signal of earthquake was studied by Tsvetkova in the Caucasus, Russia (Tsvetkova et al., 2001, 2005). Radon in Antarctica was studied extensively by Ilic et al. (2005). They made a prediction that an earthquake would happen on 30 October, 2003 of $M=4.0$ and that was proved later.

A work using SSNTD along the Northern Caucasus was carried out by Nevinsky and Tsvetkova (2005). M. Inceoz and others performed a study at the North and East Anatolian fault system, Turkey (Inceoz et al., 2006). They found that radon anomaly was quite significant over the fault line whereas it fell drastically going away from the fault line.

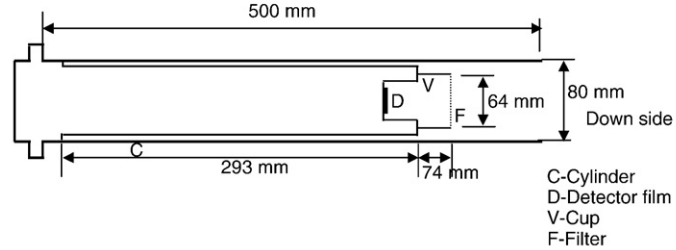

Fig. 6. Radon emanation detector (Planinic et al., 2000).

4.2. Modern devices

The devices that have been used in later periods are mainly electronic devices. These are discussed in previous sections: such as ALPHA GUARD (Moussa and El Arabi, 2003; Swakon et al., 2004) BARASOL (Richon et al., 2007) (Fig. 7), Scintillation Counter (China 1975, 1977; Einarsson et al., 2005, 2008); Kuo et al., 2006, collector chamber (Erees et al., 2007) (Fig. 8), Radon Detector (SARAD) (Das et al., 2006; Fu et al., 2008), RAD-7 detector (Crockett et al., 2006) are important among them.

5. Radon anomaly and earthquake: some models

Considering the earth as an infinite isotropic solid with circular dislocation loop of radius 'R' and slip vector 'b', the relation between strain distance 'x' and 'R' was proposed by Nabarro (1951) as

$$\text{Shear strain } \gamma = bR^2/x^3$$

Some modification was done on this Dislocation Model further by Stacey (1969). Observing the relation of radon concentration with diffusion constant of radon, Junge (1963) showed

$$C = \frac{a}{\lambda}\left[1-e^{-\left(\frac{\lambda}{D}\right)^{1/2}.x}\right]$$

where 'a' is rate of release of radon in pore space, 'D' is the diffusion coefficient of radon in the medium.

Regarding the flow of fluid in the major stress area some models have been proposed by several researchers (Schroeder et al., 1965; Giardini et al., 1976; Mogro-Campero, 1978; Mogro-Campero and Fleischer, 1979).

Rikitake (1976) proposed a model showing the relations between anomaly and earthquake parameters like precursor time T, magnitude of earthquake M, distance from epicenter R. According to his model,

$$\log T = 0.76M - 1.83$$

King proposed a model in which he treated the soil as a homogeneous porous half space having uniform radon production rate (King, 1978). Using Fick's law and Darcy's law regarding molecular diffusion in the soil he showed the steady state concentration as function of depth as

$$C = \frac{\Phi}{\lambda}\left\{1-\exp\left[\gamma\left(\frac{\varepsilon\lambda}{D}\right)^{1/2} z\right]\right\}$$

where $\gamma = \frac{v}{2(\varepsilon\lambda D)^{1/2}} + \left(\frac{v^2}{4\varepsilon\lambda D}+1\right)^{1/2}$ Φ = radon production rate, λ = its decay constant, ε = soil porosity, D = molecular diffusion coefficient of radon in the soil, v = apparent soil gas flow velocity.

A small upward or downward flow of gas (~3×10^{-4} cm/s) changes the subsurface radon concentration at shallow depths. At the same time larger upward gas velocity does not associate with larger increase in radon concentration.

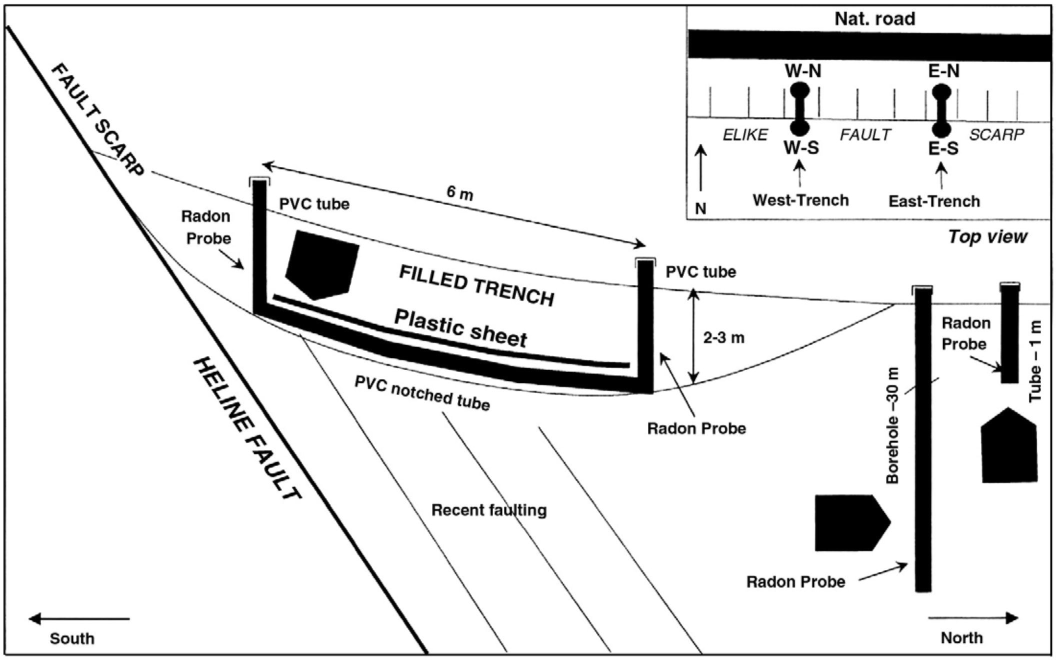

Fig. 7. Radon probe in soil (Richon et al., 2007).

A model on empirical earthquake prediction was given by Talwani (1979) as

$$M_L = \log D - 0.07$$

Where M_L = magnitude of shock, D = duration of precursory period (days).

He applied the model successfully for the event of shock $M_L = 2.3$ on 23 February, 1977 which was associated with radon anomaly.

In 1979, Guha gave a model relating precursor time (T) and magnitude of shock (M) (Guha, 1979) as

$$\log T = A + BM \ (A, B \text{ are statistically determined coefficients})$$

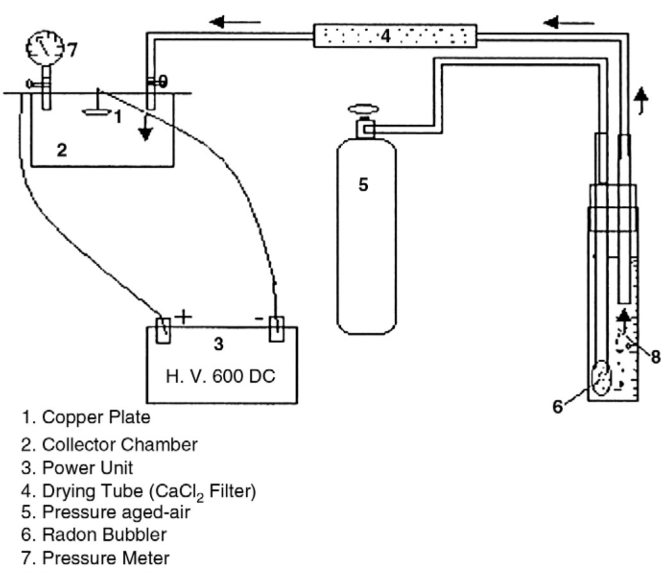

Fig. 8. Radon measuring system (Erees et al., 2007).

He studied the effect of major earthquakes occurred during 1963–1975 in Koyna, India.

Sultankhodzhayev et al. (1980) suggested the model as

$$\log \mathrm{RT} = 0.63M \pm 0.15$$

Taking recourse to the strain field models, Virk proposed a modified model (Virk, 1996) as

$$\left.\begin{array}{ll} D = 10^{0.32M} & (10 < D < 50) \\ D = 10^{0.43M} & (50 < D < 100) \\ D = 10^{0.56M} & (100 < D < 500) \\ D = 10^{0.63M} & (500 < D < 1250) \end{array}\right\}$$

He gave an empirical relation between radon anomaly (A), epicentral distance (D), earthquake magnitude (M) considering 142 case studies in the N–W Himalayas, India, as

Parameters	Correlation coefficient (R)
$M-D$	0.54
$M-A$	0.13
$D-A$	−0.10
$M-\log(AD)$	0.33

In connection with dislocation model R.L. Fleischer and group (Fleischer, 1981) found the relation for the signals that controls the amount of ^{222}Rn recorded as

$$\Delta\gamma t / T = \frac{10^{2.44M}}{x^3} f\left(\frac{R}{b}\right) / 1000, \ \text{for } M \le 3$$

$$\Delta\gamma = \frac{10^{1.44M}}{x^3} f\left(\frac{R}{b}\right), \ \text{for } M \ge 3$$

$\Delta\gamma$ = strain change, M = magnitude of strain.

They found the relation between 'x' and 'M' as

$$\left.\begin{array}{l} x_m = 10^{0.813M} / 16.6 \text{ for } M \le 3 \\ x_m = 10^{0.48M} / 16.6 \text{ for } M \ge 3 \end{array}\right\}$$

The derivation of a relation between the earthquake magnitude and distance from the dislocation given by Fleischer and Mogro-Campero (1985) was that the strain is proportional to

$$\gamma_{RSI} = 10^{1.44M_S} / x^3$$

M_S = magnitude of S-wave, x = distance in km from the dislocation, RSI = relative dislocation strain intensity.

They also gave a relation between timing of radon change with magnitude of quake as

$$t(\text{days}) = 10^{M} / 143$$

Rikitake extended his work on finding relation between earthquake magnitude, epicentral distance, precursor time, etc. He found that precursors found by geodetic and geomagnetic observations reflect a crustal strain of the order of 10^{-7}–10^{-6}, that obtained by resistivity variometer represents strain of the order of 10^{-9}–10^{-8} and that by other disciplines corresponds to strain of the order of 10^{-8}–10^{-7} (Rikitake, 1987).

A model was proposed by Ramola and group for establishing a relation between radon anomalies and earthquake magnitude (Ramola et al., 1988). They used the diffusion equation of Ghosh (Ghosh and Seikh, 1976), Junge (1963) and empirical relations of Dobrovolsky (Dobrovolsky et al., 1979; Hauksson and Goddard, 1981) to get their relation as (symbols having their usual meaning)

$$M = 2\log(\lambda \Delta R / KT) - 15.26$$

The logarithmic dependence of precursor time (T) on earthquake magnitude (m) was correlated as (Ilic et al., 2005)

$$\log T_{long} = \left\{\begin{array}{c} 0.79m - 1.88 \\ 0.685m - 1.57 \\ 0.80m - 1.92 \\ 0.76m - 1.83 \end{array}\right\}$$

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