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Radon as a Earthquake Precursor: A Review

Ashish Tomer

Abstract

The first measurements of radon as a seismic precursor are dated back to 1927, but the first recording, which is reported in many publications, and that encouraged research on seismic precursors, was detected before the Tashkent earthquake of 1966. This paper is a review of the radon measurements performed all over the world, trying to distinguish between discrete and continuous measurements, and between measurements in soil, water or air. The role that the "precursor radon" had in the forecast of strong earthquakes in the past has been examined. In this paper some of the radon anomalies cases are discussed.

Introduction

Earthquake predictions are based mainly on the observation of precursory phenomena. However, the physical mechanism of earthquakes and precursors is at present poorly understood, because the factors and conditions governing them are so complicated. Methods of prediction based merely on precursory phenomena are therefore purely empirical and involve many practical difficulties.

A seismic precursor is a phenomenon which takes place sufficiently prior to the occurrence of an earthquake. These precursors are of various kind, such as ground deformation, changes in sea-level, in tilt and strain and in earth tidal strain, foreshocks, anomalous seismicity, change in b-value, in microsismicity, in earthquake source mechanism, hypocentral migration, crustal movements, changes in seismic wave velocities, in the geomagnetic field, in telluric currents, in resistivity, in radon content, in groundwater level, in oil flow, and so on. These phenomena provide the basis for prediction of the three main parameters of an earthquake: place and time of occurrence and magnitude of the seismic event.

The most important problem with all these precursors is to distinguish signals from noise. A single precursor may not be helpful the prediction program strategy must involve an integral approach including several precursors.

Moreover, in order to evaluate precursory phenomena properly and to be able to use them confidently for predictive purposes, one has to understand the physical processes that give rise to them. Physical models of precursory phenomena are classified in two broad categories: those based on fault constitutive relations, which predict fault slip behavior but no change in properties in material surrounding the fault, and those based on bulk rock constitutive relations, which predict physical property changes in a volume surrounding the fault. Nucleation and lithospheric loading models are the most prominent of the first type and the dilatancy model is of the second type.

During the past two decades efforts have been made to measure anomalous emanations of geo-gases in earthquake-prone regions of the world, in particular helium, radon, hydrogen, carbon dioxide. Among them radon has been the most preferred as earthquake precursor, because it is easily detectable.

Radon is found in nature in three different isotopes: 222Rn, member of 238U series, with an half life of 3.8 days, 220Rn (also called thoron), member of 232Th series, with an half life of 54.5 s and 219Rn, member of 235U series, with an half life of 3.92 s.

Owing to his longer half-life, the most important of them is 222Rn, produced by 226Ra decaying. After his production in soil or rocks, 222Rn can leave the ground crust either by molecular diffusion or by convection and enters the atmosphere where his behavior and distribution are mainly governed by meteorological processes.

The radon decay products are radioactive isotopes of Po, Bi, Pb and Tl and they are easily attached to aerosol particles present in air. In table 1 are shown the principal decay characteristics of 222Rn and 220Rn, including properties of their respective parent radionuclides and their short-lived decay products.

The release of radon from natural minerals has been known since 1920's [1] but its monitoring has more recently been used as a possible tool for earthquake prediction, because the distribution of soil-gas radon concentration is closely related to the geological structure, fracture, nature of rocks and distribution of sources. Therefore, surveying of radon concentration can prospect fracture trace, earthquake forecast, environment monitoring, etc.

Table 1: Principal decay Characteristics of 222Rn and 220Rn

Radionuclide	**Half-life**	**Radiation**	**E_{α}(MeV)**	**E_{γ}(MeV)**
^{226}Ra	1600 y	α	4.78(94.3%) 4.69(5.7%)	0.186(83.3%)
^{222}Rn	3.824d	α	5.49(100%)	
^{218}Po	3.05m	α	6.00(100%)	
^{214}Pb	26.8m	β, γ		0.295 (19%) 0.352 (36%)
^{214}Bi	19.7m	β, γ		0.609 (47%) 1.120 (15%) 1,760 (16%)
^{241}Po	164μs	α	7.69(100%)	
^{224}Ra	3.66 d	α	5.45(6%) 5.68(94%)	0.241(3.9%)
^{220}Rn	55 s	α	6.29 (100%)	
^{216}Po	0.15 s	α	6.78 (100%)	
^{212}Pb	10.64 h	β, γ		0.239(47%) 0.300 (3.2)
^{212}Bi	1.01 h	α, β, γ	6.05(25%) 6.09(10%)	0.727(11.8%) 1.620 (2.8)
^{212}Po	298 ns	α	8.78(100%)	
^{208}Tl	3.05 m	β, γ		0.511 (23%) 0.583 (86%) 0.860 (12%) 2.614(100%)

Radon as a Precursor

Radon is a natural gas, produced in soil, by the radioactive decay of the radium element, produced in turn by uranium. Radioactive decay is a natural, spontaneous process in which an atom of one element decays or breaks down to form another element by losing atomic particles. Radon itself is radioactive because it also decays losing an alpha particle and forming the element polonium. The half-life of radon is 3.8 days.

Because radon is a gas, it has much greater mobility than uranium and radium, which are fixed in the solid matter of rocks and soils. Radon can leave the rocks and soils more easily by escaping into fractures and openings in rocks and into the pore spaces between grains of soil. It can travel a great distance before it decays and gathers, in high concentrations, also inside a building. Radon travels by diffusion (but in this case it moves slowly) or by convection through gas carrier (as methane, carbon dioxide and nitrogen). Radon is formed in the rocks as a result of the decay of radium-226; high concentrations of radon gas in the soil and subsoil are found, but only where this item can be expelled from the crystal lattice of minerals that contain it [2]. In particular, in the decay of radium-226, an alpha-particle is emitted and the newly formed radon atom recoils in the opposite direction. The position of the atom of radon in the granule and the direction of recoil atom itself can determine whether or not the leakage of radon from the crystal lattice of the mineral that generated it. Under these conditions, three different situations may occur: the radon atom remains in the granule, the atom of radon enters a adjacent granule, the radon atom is ejected from the crystal lattice and is subsequently removed from the gases from soil or water. Only in the third case, the radon is actually free to move through the soil, to reach the surface, and finally spreading into the atmosphere; its mobility will be linked to the permeability of the soil and to the degree of fracturing of rocks.

Radon moves more rapidly through permeable soils, such as coarse sand and gravel, than through impermeable soils, such as clays. Radon is moderately soluble in water. Its solubility depends on the temperature of the water: colder the water, greater is the solubility of radon. A measure of the solubility of gas in water is given by the solubility coefficient, defined as the ratio between the concentration of radon in water and in air. At 20°C the coefficient of solubility is about 0.25, which means that the radon is preferentially distributed in the air rather than in water [3, 4].

The connection between the anomalies of chemical and physical parameters and seismic events has been explained, in the past, by the dilatancy model [5] opening of cracks before an earthquake, increases the diffusion of pore fluid and, together with the modified strength and pore pressure, causes variations in the chemical-physical characteristics of the rocks. The increase of the radon concentration, particularly in compact rocks, happens when the cracks start to form in the rocks of the involved area in the impendent earthquake. During the last stage of the dilatancy model, the radon emission can be stable or decrease before the earthquake. The width of the zone involved by the stress loading is proportional to the magnitude and to the depth of the impending earthquakes. The pressure variations, caused by the stress loading, lead changes of the rocks characteristics constituting the "precursor phenomena". The pattern dilatancy does not seem to justify the observation of precursory phenomena even at great distances from the epicentral area of the earthquake that will occur. Actually, the problem lies in the definition of the area to investigate. The preparation of a strong earthquake, or simply a substantial crustal deformation, involves, in general, a very wide area (even hundreds of kilometres). In the monitoring sites of the precursors, even very far from the future epicentral area, some local conditions can be alterated, described by the theory of dilatancy, which allow the occurrence of precursory phenomena. The first objection to the use of radon as an earthquake precursor was that the radon decay time did not allow radon to travel great distances within the Earth. But, in reality, the stress propagation, moving in the soil, creates a lot of "local" radon anomalies, even a hundred miles away.

Considerations on Radon Anomalies

Anomalies have been detected in the signals obtained by passive track detectors, by passive detectors recording in continuous and by active detectors, used for measures both in soil and in water. When radon concentrations are measured in continuous mode for a long time and with a time resolution of at least one hour, it is possible to classify the observed radon anomalies according to different trends. Mainly they show two different shapes. The first type, called type A [6], shows a rather slow change of the radon concentration and can continue even over years. The other type (type B), involves anomalies which appear much faster and can be followed by a slow increase or a rather constant radon concentration, or be characterised as a short peak (duration: hours to days) in the radon concentration. These peaks can be either positive or negative and are often followed by an earthquake within about ten days.

The problems related to the identification of anomalies are: a) the definition of the anomaly; b) the identification of the maximum distance between the epicentre of an earthquake and the site where the anomaly of radon is observed; c) the identification of the time between the radon anomaly and the occurrence of an earthquake of a given magnitude (time precursor); d) the importance of the tectonic structure.

The first definition of anomaly was done in a subjective manner, based exclusively on the percentage increase from the background value. The method of the 2 sigma was later introduced: any radon variation that can be considered "significant anomaly" must differ from the mean +/-2 standard deviations[7]. A correlation between radon emission and barometric pressure should be analyzed before the identification of possible radon anomalies. Other methods are the machine-learning methods, applied to exclude the anomalies generated by meteorological parameters. Particularly, the applications of artificial neural network of regressions and of tree models have proven to be useful means of extracting radon anomalies caused by seismic events [8].

In a summary of 1999, [9] analysed 15 cases of geochemical precursors reported in the scientific literature. Anomalies appear at distances sometime much greater than typical source dimensions, and occur in the field of strain higher than 10-9, most of them being in the field of strain higher than 10-8. Taking into account the very high heterogeneity of such a set of data, they suggest that amplitudes of gas anomalies are independent from both magnitudes and epicentral distances of related earthquakes, suggesting local conditions to control amplitudes. On the contrary, precursor time and duration of anomalies seem to increase both with magnitudes and epicentral distances. Similar conclusions were obtained by analysing data recorded continuously at the Friuli site of Cazzaso [4].

Several groups investigated the maximum distances between the epicentre of an earthquake and the site of the observed radon anomaly. Many empirical relationships or relationships based on theoretical considerations on the diffusion of radon, were obtained. Widely used is that of [10]:

$$M \geq 2.4 \log10 D - 0.43 \qquad (1)$$

Where M is the minimum magnitude required to obtain a radon anomaly at distance D (km).

The application of this relation, allows making a selection of the used catalogue events, and can give information on the area affected by the deformation process that precedes an earthquake of a given magnitude, defining the distance at which we can detect an anomaly attributable to a given earthquake.

For the determination of the time precursor, one of the first empirical relationships, was that of [11]:

$$\log t = 0.76 M - 1.83 \quad (2)$$

Where t is the time precursor, and M the magnitude of the impending earthquake

Higher fluid flows are expected in reverse-fault area than in normal faults during interseismic regimes [12]. Accordingly, soil gas prospecting might be more effective in detecting fractures in the compressional regime.

Radon Anomalies and Earthquakes: Some Cases

Several radon investigations have been carried out all over the world. Measurements of this gas both in soil and in groundwater have shown that spatial and temporal variations can provide information about geodynamical events.

In the following we report some examples of studies among the numerous ones performed around the world with the purpose to relate abnormal radon emission to seismic events. The pioneering work on radon investigation in ground soil was performed at an active fault zone for two years [13]. Radon concentration in soil gas was measured and anomalous radon concentrations were reported before the strong earthquake (M=8) of Tonankai (December 1944, Japan).

Some years later [14] evidenced the importance of the influence of the meteorological parameters on radon measurements and in 1964 he suggested that radon could be used as tracer to discover uranium deposits or to predict earthquakes [15].

The first evidence of radon in groundwater as precursor of earthquakes was observed in Tashkent [16]. The author observed that the radon concentration in a spring near Tashkent increased constantly before the M=5.2 earthquake on April 15, 1966. Afterward many studies have been performed about radon anomalies and earthquakes. In the following some examples are reported on ground radon monitoring in the most seismic regions in the world.

Japan

As already cited, studies performed by [13], at an active fault zone evidenced anomalous radon concentration before the strong earthquake (M=8) of Tonankai. Radon anomalies were recorded before the Nagano Prefecture earthquake (M= 6.8) on September 14, 1984[17]. The authors observed a gradual increase in radon counts three months before the quake and a remarkable increase two weeks before the shock.

For about twenty years an extensive network of groundwater radon monitoring has been operated mainly by the University of Tokyo and the Geological Survey of Japan for the purpose of earthquake prediction in eastern Japan. In figure 1. a significant example of radon anomaly is reported [18]. The authors performed radon concentration analysis in a well 17 m deep from November 1993 to March 1995 and observed stable radon concentration of 20 Bq/l at the end of 1993. The radon concentration started to increase gradually from October 1994 reaching 60 Bq/l on November 1994, three times that in the same period one year before. Furthermore, a sudden increase of radon concentration, recorded on 7 January was followed by a sudden decrease on 10 January, 7 days before an earthquake of magnitude 7.2. After the earthquake, the radon concentration returned to the pre-October 1994 levels. The main result of this example is that it is possible to observe strange behavior before an anomaly. This, for instance, as in this case, must be preceded by a continuous increasing in the background level till its manifestation. Naturally it depends on the geodynamical evolution of the area.

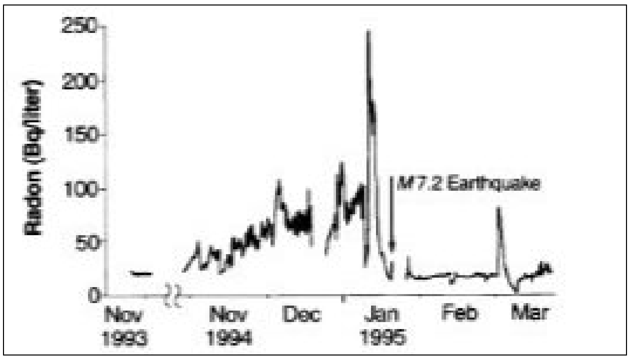

Figure 1: Radon concentration data at the well in the southern part of Nishinomiya city, Japan From[18]

India

In Bhatsadam, Maharashtra, India, major earthquakes occurred during August 1983 - July 1984. In that region radon concentration was measured by [19]. They found an increase in radon concentration during March–April 1984 when seismicity was high enough. Precursory phenomena of radon in earthquake sequence were observed by[19] and by other groups at the Osmansagar reservoir, Hederabad, India during January– February, 1982 [19]. An earthquake with a magnitude of 3.5 occurred on January 14, 1982 with subsequent seismic events. There was an increase of radon concentration in soil gas during February due to those high seismic activities.

[20] performed a daily radon monitoring in soil-gas in Amritsar from 1984 to 1987. They recorded radon anomalies before different earthquakes: June 1988 (M=6.8); April, 26, 1986 (M=5.7); July 1986 (M=3.8); Kangra earthquake March 1987 (M=7) and May 1987 (M= 5).

[21] carried out daily measurements of radon in soil-gas and groundwater at Palampur since 1989 and radon anomaly was recorded simultaneously in both soil- gas and groundwater. Weekly integrated data also showed abnormal radon behaviour during first week of October, 1991 at different recording stations. These recorded anomalies were correlated with an earthquake of magnitude 6.5 occurred in Uttarakashi area in October 1991.

Syria

[22] recorded groundwater radon data for two years, during 1993 and 1994 at monthly intervals, from two selected monitoring sites of the northern extension of the Dead Sea Fault System. The results showed that measured radon concentrations fluctuate around the mean value, showing some variations with peak values, about two or three times the mean value, preceding some seismic events. It is possible to consider those anomalies related to changes in crustal strain and thereby to indicate a probable relation with the local seismicity. Nevertheless, the authors conclude that this does not necessarily means that it is possible to relate univocally these radon peaks to seismic event occurrence, but rather, it may indicate the possibility of using groundwater radon variations as a useful tool.

Turkey

In soil radon gas was monitored by [23] in a network of five monitoring sites along 200 km at the North Anatolian Fault Zone, Bolu. They observed an increase in radon concentration during the strong earthquake (M=5.7) on July 5, 1983. In order to search some relation between earthquakes and radon concentration variations, more recently [24] performed a radon investigation at the North and East Anatolian fault system. They found that radon anomaly was quite significant in particular over the fault line but not away from this line.

Also the Aksehir fault zone was investigated, by [25,26], trough radon measurements in well water. Although the observed radon levels could be related to several seismic activities that at the fault region occurred with high magnitude, the authors did not infer correlation between seismic activity and radon concentration. Radon concentration in thermal water was investigated by [27, 28] at two thermal springs at the Denizli basin site and significant radon anomalies were observed before earthquakes with magnitude between 3.8 and 4.8.

Italy

In the last fifteen years systematic studies on Radon as precursor of geophysical events have been carried out on Mt. Etna since 2001 [29–35]. In particular two sites were investigated among the cropping up structural discontinuities, which lie along the NE-SW direction through the volcano. One site (Biancavilla) is in the SW flank, while the other one (Vena) is in the NE flank (circles in fig.2). Continuous monitoring was performed by using active systems with time resolution of 10 min. Capillary probes inserted into the soil at one meter depth, allowed to reduce influence from the meteorological parameters that were measured too.

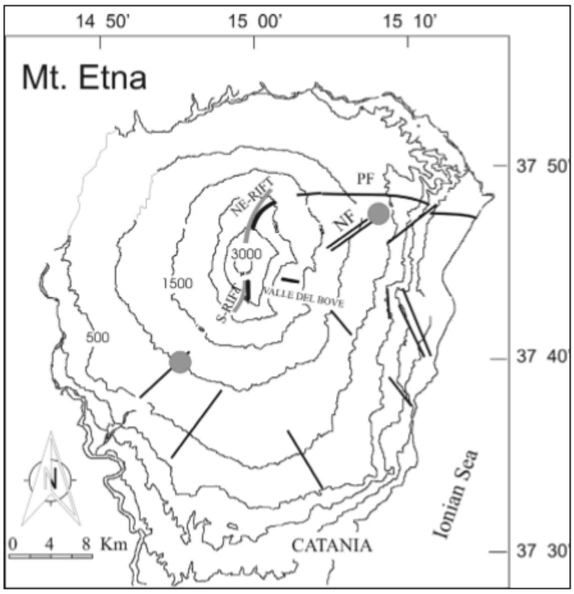

Figure 2: Mt. Etna map– Circles indicate the sites where devices for continuous in soil gas Radon monitoring was positioned

Several studies conducted in tectonic areas evidenced relation to earthquakes of magnitude bigger than 3 [16, 22, 23]. The etnean area is characterized by a big number of earthquakes, up to about thousands per day before an eruptive period [36, 37], but with low magnitude (< 3) and rarely they exceed magnitude 4. Moreover Mt. Etna has a very complex structure, due to the occurrence of both tectonic and volcanic phenomena. Major results have been obtained respect to a possible link between radon concentration and volcanic activity. Nevertheless, some relations were also observed with seismic events as reported by [26], the data are referred to the period 2001-2002. Radon concentration values started to increase the 27th of October 2002, reached the maximum the 1st of November 2002 and the minimum the 3rd of November 2002. During this period several earthquakes of magnitude higher than 3 occurred, some of them reached values up to M= 4.5 (29/10/02 time 09:02:00 epicentral area of Santa Venerina).

It was observed that, as well as the radon raises the earthquake daily rate and strain release raise, correspondently at the eruption beginning.

A radon anomaly was recorded before the November 3rd event (M= 3.5), with epicentral zone close (less than 1 km) to the Vena Station (NE station), also associated to evident soil fractures.

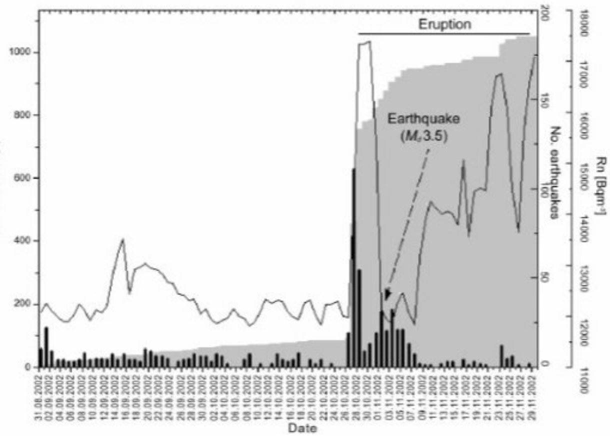

Figure 3: Radon concentration (black line), daily earthquakes rate (black column bar) and strain release (grey histogram) measured in the period between 1st September 2002 and 30th November 2002 (Vena station).[29]

More recently a systematic radon investigation was extended to fault systems, in particular the Pernicana fault, one of the more active etnean fault, was chosen as first monitoring area. In particular, two different horizontal profiles, orthogonally to the main fault plane, were investigated. The first one was located at 1400m asl, the second one at 1370m asl [38]. Each profile consisted of ten measurement points where CO2 efflux values were also measured. Concentrations of 222Rn were obtained by means of three different methodologies: passive, spot and continuous. The pattern of soil 222Rn values measured in the two profiles is clearly similar: higher values were generally recorded on the up thrown side of the fault and the lowest values occurred generally close to the main fault plane. Differently to radon, higher CO2 emissions were recorded on the fault plane. This behavior can be justified by the in-soil gas transport mechanism. In particular, along the main fault plane, advective transport of deep gases (CO2, Rn) occurs because of the high ground fracturation and permeability. Near the surface, dilution of radon by CO2 prevails, thus producing lower radon values. This kind of investigations is useful to study the dynamics of the faults and the possible earthquake mechanisms.

Conclusion

Finally it can conclude that the measurements of radon gas in soil and in ground water have been carried out all over the world and the results seem to indicate the radon as a good indicator of crustal activity such as earthquakes. However, the above cases describing the possible correlation between radon levels and earthquake activity uses such qualifying and caution words as possible, apparent, limited, could, sometimes, may be, and so on. It is clear that in some cases there are precursor changes in radon levels, but that the causal relationship or mechanism relating these to earthquake activity is not yet well understood. Thus, even if some results seem to suggest that geodynamical events could influence radon concentrations, however, because of the complexity of its transport mechanism, the correlation needs more investigations in order to clearly and firmly established it. Further contributions can be obtained from more extended continuous data recording, in particular near active faults, and from the comparison with other earthquake precursors.

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Author's details

Department of Physics, Gurukukla Kangri University Haridwar, India

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