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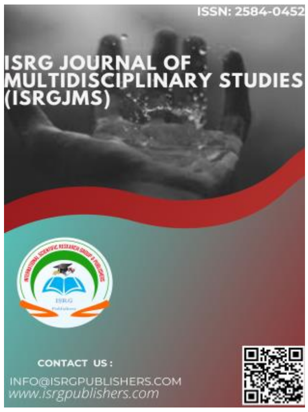


# Variation in Radon Concentration as an Earthquake Precursor

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## Abstract

*Radon (222Rn) is an element with an atomic number of 86 and a half-life of 3.82 days. It is a noble gas and exhibits behavior similar to that of an ideal gas. Radon concentrations in the soil, water, and atmosphere vary in response to crustal movement. This is because Radon is a radioactive gas that is released from cracks and cavities in the Earth's crust as it is strained before an earthquake. Radon concentrations can be abnormally high along active faults, which may be paths of least resistance for the outgassing process. In this paper, different instances of anomalies in Radon concentration as an Earthquake Precursor are discussed along with some discussion on the Radon production, measurement and transport methods.*

**Keywords:** *Radon, Earthquake Precursor, Earth's Crust, air humidity*

## 1. Introduction

Earthquakes are among the most deadly natural hazards that have affected people worldwide. Many earthquake zones coincide with areas of high population density, which have taken a toll on people's lives and property. Scientists are always eager to work on mechanisms of prediction of Earthquakes that can save millions of lives, provided the accuracy of the predictions are on the positive side. Earthquake predictions are based mainly on the observation of precursory phenomena. However, the mechanism of relating the precursors to the earthquake is an area of extensive research, because the factors and conditions governing them are complex. Methods of prediction based merely on precursory phenomena are therefore purely empirical and involve many practical difficulties.

A seismic precursor is a phenomenon that takes place sufficiently prior to the occurrence of an earthquake. These precursors are of various kinds, such as

a) ground deformation,
b) changes in sea-level, tilt and strain, earth tidal strain
c) foreshocks,
d) anomalous seismicity,
e) changes in earthquake source mechanism,
f) hypocentral migration,
g) crustal movements,
h) changes in seismic wave velocities,


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i) changes in the geomagnetic field,
j) changes in telluric currents,
k) changes in radon content,
l) changes in groundwater level,
m) changes in oil flow, and so on.

These phenomena provide the basis for prediction of the three main parameters of an earthquake: place of occurrence, time of occurrence and magnitude of the seismic event. In most of the cases, a single precursor is not considered final for the prediction, rather a combination of several precursors are considered to be at the root of a successful earthquake prediction strategy. 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.

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. In this study, the importance of studying the variation in Radon concentration as an Earthquake precursor is presented with the help of analysis of a number of case studies.

## 2. Properties of Radon

Radon is found in nature in three different isotopes:

a) $^{222}$Rn, member of $^{238}$U series, with a half-life of 3.8 days,
b) $^{220}$Rn (also called thoron), member of $^{232}$Th series, with a half-life of 54.5s
c) $^{219}$Rn, member of $^{235}$U series, with a half-life of 3.92s.

The most important of the above Radon isotopes is $^{222}$Rn, because of its longer half life. After its production in soil or rocks, $^{222}$Rn can leave the ground crust either by molecular diffusion or by convection and enters the atmosphere where its behavior and distribution are mainly governed by meteorological processes. The decay products of Radon are radioactive isotopes of Po, Bi, Pb and Tl and they are easily attached to aerosol particles present in air. The release of Radon from natural minerals has been known since 1920's (Spitsyn, 1926) 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. Thus, elevated levels of Radon gas in soil or groundwater can be a sign of an impending earthquake. As the Earth's crust is strained before an earthquake, Radon is thought to be released from cracks and cavities. The gas flux along fault areas and through micro fractures can also affect how Radon moves from its source to the surface. 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 detecting Radon signals have been developed. Several models have also been proposed as an explanation of the experimental field data.

## 3. Radon production and transport

The production of $^{222}$Rn depends on the activity concentrations of $^{226}$Ra in the earth's crust, in soil, rock and water. When radium decays in a mineral substance, the resulting Radon atoms must first emanate from the grains into the air-filled pore space. The fraction of Radon that enters the pores, commonly known as emanation fraction, consists of two components due to recoil and diffusion mechanisms. Since the diffusion coefficient of gases in solid materials is very low, it is assumed that the main portion of the emanation fraction comes from the recoil process. From the alpha decay of Radium, Radon atoms possess sufficient kinetic energy (86 keV) to move from the site where Radon is generated. The range of $^{222}$Rn is between 20 to 710 nm in common materials, 100 nm for water and 63 µm for air. (Sabol et al., 1995). The emanation fraction can be strongly influenced by water content in the material, increasing with soil moisture, up to saturation in the normal range of soil moisture content. A representative estimate of the fraction of Radon that leaves solid grains is 25%. The increase in the emanation fraction can be explained by the lower recoil range of Radon atoms in water than in air. A Radon atom entering a pore that is fully or partially filled with water has a very good chance of being stopped by the water in the pore. Generally, the presence of water increases the emanation fraction, but this trend may show a saturation effect or the effect may even later reverse as the water content becomes greater. Radon gas generated in rocks remains partly in the solid matrix, but some moves to the pore fluids and migrates away through interconnected pores and aquifers by the method of diffusion and fluid flow (Riggio and Santulin, 2015).

## 4. Radon measurements

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

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.

In general, Radon measurements can be performed in continuous, integrating or discrete mode, regarding the time duration of measurement, and by using passive devices, when Radon enters the detection system by natural diffusion, or active technique, when gas is pumped in the device, that require electric power. Some types of the most used detectors for in-soil radon measurements are the following.

a) Solid State nuclear track detectors
b) Electret detector
c) Activated charcoal
d) Thermoluminescent detector
e) Scintillation detector


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In the last years, active devices have been used for continuous measurements of in soil Radon gas. They use prevalently detectors as ionization chamber or silicon detectors. The devices have a probe placed in the soil at a certain depth, the gas Radon enters into the detection chamber or by means of a pump with a fixed flow rate or they can be placed inside the soil and the gas enters into the detection chamber via natural diffusion. This kind of measurements need power supply, not always available in active fault areas, but in the last years, the detection systems have been implemented with solar panels, overcoming the problem. These devices have more performance respect to the previous ones because they allow continuous measurements and on-line reading by means of remote data transfer and so they allow to monitor continuously the Radon temporal trend. Accordingly, the choice among the different possibilities can be guided by the particular interest in radon measurements, whether in time-dependent or in space-dependent variations of the concentrations. In particular, spot measurements (with portable detectors) of soil–gas Radon are useful for the quick recognition of high emission sites to be later monitored for Radon variations in time. Solid State Nuclear Track Detector (SSNTD) allow for the temporal monitoring of a relatively large number of sites, but cannot distinguish short-term changes due to their long integration times. Continuous monitoring probes are optimal for defining detailed changes in soil–gas Radon activities, but are expensive and can thus be used to complete the information acquired with SSNTD in a network of monitored sites (Riggio and Santulin, 2015).

## 5. Origin and mechanisms of Radon anomalies

Radon anomaly can be defined as the positive deviation that exceeds the mean Radon level by more than twice the standard deviation. Measurements of this gas both in soil and in groundwater have shown that spatial and temporal variations can provide information about geodynamical events. Radon concentration anomalies in soil gas have been observed a few weeks or months before many earthquakes. For example, soil Radon ($^{222}Rn$) has been continuously monitored at Badargadh station in the Kutch region of Gujarat to study pre-seismic anomalies before earthquakes occur. This monitoring site is close to the South Wagad Fault, which is seismically active (Sahoo etal, 2020).

### 5.1. Case-studies of Radon anomalies

Following are 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 (Hatuda, 1953). 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 Tanner (Tanner, 1959) 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 (Tanner, 1964).

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 earthquake 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.

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.

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. 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≥4 was observed. Precursor signal before 7–11 days of earthquake events was monitored.

Yong Hwa Oh and Guebuem Kim (2015) monitored $^{220}Rn$ together with $^{222}Rn$ in air of a limestone-cave in Korea for one year. Unusually large $^{220}Rn$ peaks were observed only in February 2011, preceding the 2011 M9.0 Tohoku-Oki Earthquake, Japan, while large $^{222}Rn$ peaks were observed in both February 2011 and the summer. Based on the analyses, the researchers suggest that the anomalous peaks of $^{222}Rn$ and $^{220}Rn$ activities observed in February were precursory signals related to the Tohoku-Oki Earthquake.

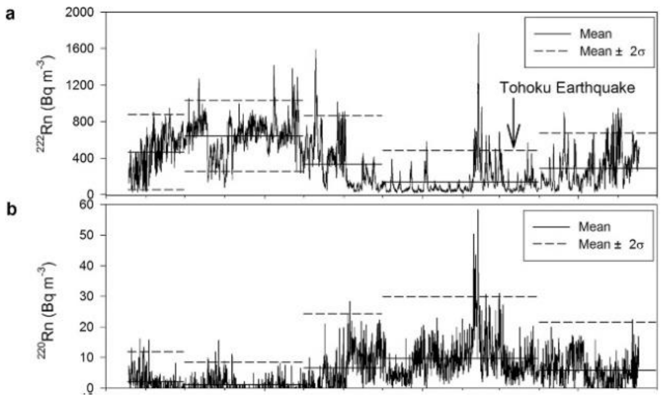


**Fig 1:** Variations in the activities of $^{222}Rn$ and $^{220}Rn$ in Seongryu Cave from May 2010 to June 2011. (a) Hourly variations in $^{222}Rn$ activity. (b) Variations in 4-hour averaged $^{220}Rn$ activity.

Ref: Hwa Oh, Y., Kim, G. A radon-thoron isotope pair as a reliable earthquake precursor. *Sci Rep* 5, 13084 (2015).

Jaishi etal (2014) carried out continuous soil-gas Radon and Thoron measurements at 15 days interval along Mat fault in Mizoram (India) between March 2012 to February 2013 using LR-115 type II detectors. Several spike like Radon and Thoron anomalies were observed preceding the earthquakes of M6.0 and M6.7.


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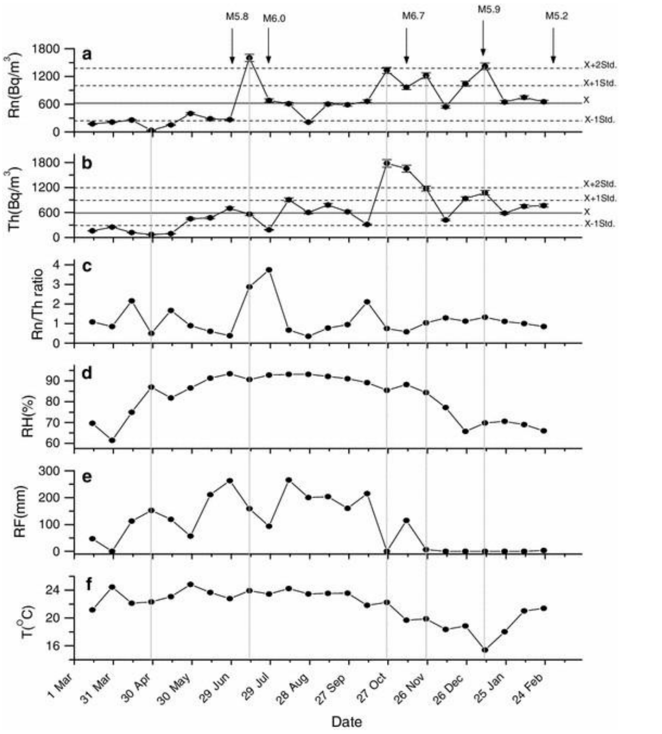


**Fig 2:** a) Radon and b) Thoron concentration variation in the soil along with the; c) Radon/ thoron ratio, d) relative humidity, e) rainfall and f) temperature.

Ref: Jaishi, H.P., Singh, S., Tiwari, R.P. et al. Temporal variation of soil radon and thoron concentrations in Mizoram (India), associated with earthquakes. *Nat Hazards* 72, 443–454 (2014).

Kim etal, (2022) studied the changes in indoor Radon concentrations, measured in a university building in Gyeongju, Republic of Korea, to find the relationship, it exists, between the indoor radon concentrations and the seismic activities in the area neighboring Gyeongju. The measurement period was from June 1, 2017, to May 31, 2019. During this period, numerous seismic activities occurred in the southeastern region of the Korean peninsula. Considering the magnitude and distances from the measurement place to epicenters, 11 earthquakes for analysis were chosen. Among these, nine earthquakes were found to have Radon anomalies before their occurrences.

### 5.2. Radon anomalies and other seismic precursors

Some group of researchers have demonstrated that the Radon gas geochemistry is a good indicator of the tectonic activity (King et al. 1993, Toutain and Baubron, 1998). There exists high correlation between the Radon variations and the air temperature (Garavaglia et al., 2000) and between the Radon variations and relative humidity (Prasad et al., 2005).

Radon emanations in the area of earthquake preparation can produce variations of the air temperature and relative humidity. Specific repeating pattern of humidity and air temperature variations was revealed as a result of analysis of the meteorological data for several tens of strong earthquakes all over the world. The main physical process responsible for the observed variations is the latent heat release due to water vapor condensation on ions produced as a result of air ionization by energetic α-particles emitted by $^{222}$Rn. The high effectiveness of this process was proved by the laboratory and field experiments; hence the specific variations of air humidity and temperature can be used as indicator of Radon variations before earthquakes.

The observed changes of relative air humidity and air temperature before strong earthquakes can be explained within the frame of the physical mechanism described in Pulinets and Boyarchuk, 2004, and Pulinets et al., 2006. The main reason of the observed variations is the air ionization produced by Radon decay. Inan (2005) demonstrates one of the prominent records of the Radon flux variation before earthquakes in Turkey. The duration of the anomalous variations is of the order of 2–3 weeks. The Radon flux reaches its peak, and at the falling edge of the observed peak the earthquake happens.

The ions produced by Radon ionization become the centers of water vapor condensation. More precisely, it is not pure condensation but so called hydration of the new formed ions. The hydration process does not need the vapor saturation as it is necessary for pure condensation. However, due to the phase state transform of the water molecules from free vapor to be attached to the ions the latent heat of evaporation is released, the same as during the pure condensation. It makes up 2370 kJ/kg under the temperature of 300 K. As a result of condensation, the air humidity drops and the temperature grows due to the latent heat of condensation release. After reaching the maximum of Radon concentration, with approaching the time of seismic shock the Radon flux diminishes, and the atmospheric conditions come to the normal state, what is accompanied by the rise of humidity and temperature drop just before the earthquake. Increased or diminished Radon concentration in comparison with undisturbed conditions produces decrease or increase of the relative air humidity, and as a consequence, the changes in the air temperature behavior. Sometimes the anomalous Radon release continues few days after earthquake (Zafrir et al., 2005), and we may expect the variations of air temperature and humidity associated with radon variations not only before the seismic shock, but also after it.

Pulinets and Dunajecka (2007) analyzed the historical meteorological data all over the Mexico around the time of one of the most destructive earthquake (Michoacan earthquake M8.1) that affected the Mexico City on September 19, 1985. Several distinct zones of specific variations of the air temperature and relative humidity were revealed that might indicate the different character of Radon variations in different parts of Mexico before the Michoacan earthquake. An interesting result on the specific variations of atmosphere parameters was obtained at Baja California region close to the border of Cocos and Rivera tectonic plates. This result demonstrates the possibility of the increased Radon variations not only in the vicinity of the earthquake source but also at the border of interacting tectonic plates. One more confirmation of the connection between the increased tectonic activity, Radon, and surface temperature are the results of satellite monitoring of the surface temperature around the time of strong earthquakes (Ouzounov and Freund, 2004; Tronin et al., 2004). The satellite infrared images demonstrate the increased temperature over the structure of active tectonic faults and its dynamics with time. Genzano etal. (2006), analyzing the Meteosat 5 satellite IR images for the time period close to the Gujarat earthquake (M7.9) on 26 of January 2001, detected the thermal anomalies not only within the area of earthquake preparation but also at the border of Eurasian and Indian tectonic plates.

## 6. Summary

Radon is emanated from the earth's crust continuously, even without earthquakes. What we observe as a precursory process – it is deviation of the radon emission intensity from undisturbed state.


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The anomalous radon activity stops immediately (within few days) after the main shock. In this paper, Radon production and transport, mechanisms of Radon emission as well as various cases of Radon emission anomaly 10-15 days before the occurrence of an earthquake are discussed. Thus it is seen that the variation in Radon concentration in and around an Earthquake prone site can be considered as a strong precursory signal.

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