Radon-222: A Potential Short-Term Earthquake Precursor

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Abstract

This paper attempts to survey and catalog published short-term pre-earthquake precursors based on radon gas emissions. A series of papers were searched to collect relevant data, such as the epicentral distance, the extent, time and duration of the radon disturbance and to analyze the precursory value of each observable. In general, enhanced radon emissions have been observed prior to earthquakes and this has been recorded all over the world. The abnormal radon exhalation from the interior of earth has been associated with earthquakes and is considered an important field of research. The proposed physical models attempt to relate the observed radon disturbances with deformations occurring in the earth’s crust prior to forthcoming earthquakes. While the models provide some physical explanations, there are many parameters that require further investigation.

Keywords: Earthquake precursors; Radon; Review

Introduction

Radon is a natural radioactive noble gas. It is generated by the decay of radium. There are thirty nine known isotopes of radon from 218Rn to 212Rn [1]. The most stable isotope is 222Rn (hereafter radon) with a half-life of 3.823 days. Four isotopes, 222Rn, 220Rn, 219Rn and 218Rn occur in trace quantities in nature as decay products of, respectively, 226Ra, 222Ra, 220Ra and 219At [1,2]. 222Rn and 218Rn are intermediate steps in the decay chain of 226U. 219Rn is an intermediate step in the decay chain of 235U and 220Rn occurs in the decay chain of 235Th [1-3]. 222Rn is also known as thoron. The half-life of thoron is 54.5 seconds [1]. Due to the short half-life, thoron disintegrates very quickly. For this reason, it is usually traced in smaller quantities compared to radon. 222Rn is also called actionin [1]. It has lesser half-life time than 222Rn and 220Rn (3.92 seconds). It is traced in earth and atmosphere in smaller quantities in respect to radon and thoron [2,3]. Most of the radioactivity in the atmosphere at sea level is due to radon [3]. Radon is released primarily from the soil [1,3,4]. Approximately 10% of the radon in soil is diluted to the atmosphere [3]. Apart from soil, radon is present in fragmented rock, building materials, underground and surface waters [3,4]. While in fluids all generated radon atoms are diluted, in porous media and fragmented rock only a percentage of radon emanates, enters the volume of the pores and dissolves into the pore’s fluid [1,4]. Once there, a macroscopic transport is possible, either by molecular diffusion advection or convection [1]. This transport is achieved through interconnected pores and water aquifers [4-6]. When the pores are saturated with water, radon is dissolved into water and is transported by it [1]. The transportation is achieved by means of fluid flow present in soil and fragmented rock [1,4,5]. Through these processes radon can travel to short, medium or long distances reaching water aquifers and air [7]. Various factors affect the whole process. The most important factors are the permeability of the soil, the temperature gradients and the pressure differences [3,7,8]. Radon is very important from radiological point of view, since it accounts for more than half of the natural exposure of the general public [2,6]. It is well known that among natural radioactivity (not man-made), the most dominant component is radon and, therefore, it is the major contributor to the effective dose equivalent.

Radon Signals and Earthquake Prediction Overview

Radon has been used as a trace gas in several studies of Earth, hydrogeology and atmosphere, because of its ability to travel to comparatively long distances from host rocks as well as the efficiency of detecting it at very low levels [9]. Significant variations of radon and progeny have been observed in geothermal fields [10], thermal spas [11], active faults [12-16], soil experiments [17], volcanic processes [18,19] and seismotectonic environments [5,7,17,20-29]. Due to its importance, radon monitoring has become a continuously growing study area in the search of premonitory signals prior to earthquakes [5]. This falls more or less, in the general area of seismology where one most elusive goals is the short-term earthquake prediction [20]. By the mid-1970s the seismological community was confident that the short-term earthquake prediction would be achieved within a short period of time [20]. One area that may hold promise in advancing the science of short-term earthquake prediction is the study of earthquake precursors [20]. In fact, the short-term predictions are typically based on observations of these types of phenomena [20]. The term earthquake precursor is used to describe a wide variety of physical phenomena that reportedly precede at least some earthquakes [20]. Under this perspective, the real time radon monitoring can be viewed as an interesting possibility for credible earthquake precursors. However, the problem of earthquake prediction still remains unsolved. All the same, positive precursors recorded prior to earthquakes indicate there is evidence that they can be used for forecasting. For example, the strain changes occurring within the earth’s surface during an earthquake enhance the radon concentration in soil gas [5,25-27] and this renders impressive development in the study of the earth’s crust which permits...
the estimate on the probabilities of earthquake risks [5]. In general, during earthquake rupture, certain precursory activity can be expected if the observation is made in the near vicinity of causative fracture [20]. The problem of the earthquake prediction however consists of the consecutive, step-by-step, narrowing of the time interval, space and magnitude ranges, where a strong earthquake should be expected [30,31]. In this sense, several investigators have attempted connections between earthquake-relating parameters (e.g. magnitude, precursory time, epicentral distance) and time-series characteristics (e.g. range, duration, number of radon anomalies) [5,20,32-36].

The prediction of earthquakes is usually distinguished in five stages. The background stage provides maps with the territorial distribution of the maximum possible magnitude and recurrence time of destructive earthquake of different magnitudes. The four subsequent stages, fuzzily divided, include the time prediction; they are as follows [31]: long-term (10^3 years); intermediate-term (1 year); short-term (10^-1 to 10^-2 years), and immediate-term (10^-3 years or less). Such division into stages is dictated by the character of the process that leads to a strong earthquake and by the needs of earthquake preparedness; the latter comprises an arsenal of safety measures for each stage of prediction [30]. According to the classification of Hayakawa and Hobara [32] the prediction of earthquakes is grouped into three categories: long-term (timescale of 10 to 100 years); intermediate-term (time-scale of 1 to 10 years); short-term. Note, that even in short-term prediction there is no one-to-one correspondence between anomalies in the observations and the earthquake events [25-27,33]. Although much more difficult than the long-term and intermediate-term predictions, the short-term prediction of earthquakes on a time-scale of hours, days or weeks, is believed to be of the highest priority for social demands in seismically active countries.

Following the classification [32] and in agreement to the aspects expressed by [30] and several other researchers [5,20], radon can be considered as a short-term earthquake precursor. Under this perspective, related research should continue and check further potential associations between radon and earthquakes [25,31-33]. Nevertheless, no universal model exists to serve as a pre-earthquake signature [34-39]. Moreover, there is no definite rule to link any kind of pre-earthquake anomaly to a specific forthcoming seismic event, either if this is intense or mild [25-27,38,39]. In addition, despite the scientific efforts, the preparation and evolution of earthquakes is not delineated yet [40]. A significant reason is that there is restricted knowledge of the fracture mechanisms of the crust [38,41-56]. This is reinforced by the fact that each earthquake is particular and happens in large-scale. Accounting that the fracture of heterogeneous materials is not sufficiently described yet, despite the tremendous up-to-date effort at laboratory, theoretical and numerical level [38], it may be understood why the description of the genesis of earthquakes is still limited [38,41-56]. According to [38] one should expect that the preparatory processes of earthquakes have various facets, which may be potentially observed before the final catastrophe at geological, geochemical, hydrological and environmental scales.

In the following, specific scientific evidence is presented regarding the possibilities of forecasting of earthquakes in terms of monitoring of radon gas emissions. The analysis is focused is on the short-term precursors of general failure since these are considered of higher prognostic value in terms of societal demands.

**Radon Gas Emission and Pre-Earthquake Activity**

In the late 1960s and early 1970s reports primarily from Russia and China indicated that concentrations of radon gas in the earth apparently changed prior to the occurrences of nearby earthquakes [34]. This stimulated a number of experiments in other parts of the world to monitor underground radon with time and to look for radon changes associated with earthquakes [20]. Table 1 presents a collection of recent important data including: (1) the earthquake details; (2) the % (6α) disturbance or detected disturbances in radon concentration; (3) the duration of the detected anomaly or the recorded anomalies; (4) the precursory time; (5) the epicentral distance (6) the related references from 1980 and after.

In general, the anomalous radon variations observed prior to earthquakes have been reported in groundwater, soil gas, atmosphere and thermal spas [5,20,21,28,57-62]. The seismological data of Table 1 are related to radon concentration data of wide fluctuations, peaks and downturns [25-27]. The earthquake-related connections of Table 1, namely the connections between the magnitude, the precursory time and the epicentral distance with the time-series characteristics, viz., the range, the duration and the number of radon anomalies vary significantly [5,20,33,34]. For example, the reported precursory times range from 3 months to some days prior to the earthquake event, whilst the epicentral distances range between 10 and 100 km. Similar ranges have been published also in [20] and [5] (please see also references therein). It is very important to note here that many precursory signals have been derived only with passive techniques [25-27] which integrate radon concentrations over long time intervals (at least 1-4 weeks), i.e., they provide coarse time-series estimations. This is a significant disadvantage for the reported estimations. On the other hand, the reported precursory signals with active techniques are limited. Note that the active techniques enable high radon recording rates (between 1/min and 1/hour) and in this manner they provide fine radon signals [5,9,16,20,25-27]. Important is that there are also other parameters that affect and alter the radon-earthquake estimations. For example, radon concentration levels are influenced by geological and geophysical conditions, the seasonal variations and atmospheric changes such as the rainfall and the barometric pressure alterations (please see e.g. [1,2,20,25-27,33,34]). For this reason the related time-series data are usually presented in parallel to the radon precursory signals [5,20,25-27]. As can be observed from Table 1, the majority of the associations between radon and earthquakes are based on events of small or intermediate magnitudes. This restricts the estimations more, since, up-to-date there seems not to exist, not only for the mild, but even for the intense earthquakes, a universal model to serve as a signature of a specific forthcoming seismic event [38-57].

Most of the disturbances of Table 1 were determined in terms of visual or simple statistical analysis. The most usual statistical criterion employed is the ±2σ one. Through this criterion, a radon disturbance is identified as such if it contains parts above the ±2σ zone. Although simple, this approach was used extensively in many papers of Table 1. Only few signals of Table 1 were analyzed through advanced techniques [25-27,57,58]. These reports are recent. They were published in the last five years, namely 2012 and after. Worth to notice is that the analysis was implemented in fine active signals recorded after significant earthquakes of near epicenters [25-27] fact which enhances the estimates of these reports further. A fact that reinforces the estimates of these reports is that the corresponding radon disturbances lasted long, i.e., between five and fifteen days. One of the advanced techniques of these reports [25-27,57,58] is the temporal Fractal Analysis based on a windowed version of the short-time wavelet transform of the density of the power spectrum in each window [25-27]. Note that the method was applied in both mono- fractals [25-27,57] and multifractals [58]. Another
| Place                  | Magnitude | Date(s)      | δα (%) or technique | Duration (days) | Precursory time (days) | ED (km) | References |
|-----------------------|-----------|--------------|---------------------|-----------------|------------------------|---------|------------|
| Single events         |           |              |                     |                 |                        |         |            |
| USA                   |           |              |                     |                 |                        |         |            |
| Kettleman Hill        | 5.6       | 8-4-85       | +                   | 100             | Not reported           | 300     | [87]       |
| Aladale, California   | 3.7       | June/1983    | +                   | 1200            | 3                      | 15      | 13         |
| P.R. China            |           |              |                     |                 |                        |         |            |
| Pohai Bay             | 7.4       | 6/18/1969    | +                   | 60              | 170                    | Not reported | 170 [70,71]|
| Ningshin              | 4.3       | 5-8-71       | +                   | 200             | 40                     | Not reported | 42 [71]   |
| Hsingtang             | 4.9       | 6-6-74       | +                   | 290             | 16                     | Not reported | 18 [71]   |
| Haicheng              | 7.3       | 4-2-75       | +                   | 38              | 270                    | Not reported | 50 [71]   |
| Haicheng              | 7.3       | 4-2-75       | +                   | 17              | 50                     | Not reported | 50 [71]   |
| Haicheng              | 7.3       | 4-2-75       | -                   | 43              | 66                     | Not reported | 140 [71]  |
| Haicheng              | 7.3       | 4-2-75       | +                   | 20              | 8                      | Not reported | 140 [71]  |
| Haicheng              | 7.3       | 4-2-75       |                       |                 |                        |         |            |
| Liaoyang              | 4.8       | Not reported | +                   | 70              | 3                      | 1       | 200 [73]  |
| Tangshan              | 7.8       | 6/27/1976    | +                   | 15              | 970                    | Not reported | 50 [71]   |
| Tangshan              | 7.8       | 6/27/1976    | +                   | 50              | 15                     | Not reported | 100 [71]  |
| Tangshan              | 7.8       | 6/27/1976    | -                   | 40              | 1370                   | Not reported | 130 [71]  |
| Tangshan              | 7.8       | 6/27/1976    | +                   | 27              | 162                    | Not reported | 130 [71]  |
| Tangshan              | 7.8       | 6/27/1976    | +                   | 200             | 12                     | Not reported | 200 [71]  |
| Chienan               | 6.0       | 3/7/1977     | +                   | 70              | 3                      | 1       | 200 [73]  |
| Sabtieh               | 5.2       | 4/8/1972     | +                   | 55              | 12                     | Not reported | 70 [73]   |
| Takung                | 5.8       | 9/27/1972    | +                   | 34              | 12                     | Not reported | 54 [73]   |
| Luhuo                 | 7.9       | 2/6/1973     | +                   | 120             | 9                      | Not reported | 200 [74]  |
| Yiliang               | 5.2       | 4/22/1973    | +                   | 41              | 14                     | Not reported | 340 [73]  |
| Songpan               | 5.2       | 5/8/1973     | +                   | 40              | 14                     | Not reported | 345 [71]  |
| Mapien                | 5.5       | 6/29/1973    | +                   | 89              | 9                      | Not reported | 200 [74]  |
| Lungfing              | 7.5       | 5/29/1976    | +                   | 20              | 510                    | Not reported | 20 [71]   |
| Lungfing              | 7.5       | 5/29/1976    | +                   | 15              | 425                    | Not reported | 190 [71]  |
| Lungfing              | 7.5       | 5/29/1976    | +                   | 8               | 160                    | Not reported | 210 [71]  |
| Lungfing              | 7.5       | 5/29/1976    | +                   | 12              | 130                    | Not reported | 215 [71]  |
| Lungfing              | 7.5       | 5/29/1976    | +                   | 7               | 75                     | Not reported | 360 [71]  |
| Lungfing              | 7.5       | 5/29/1976    | +                   | 20              | 290                    | Not reported | 420 [71]  |
| Lungfing              | 7.5       | 5/29/1976    | +                   | 200             | 12                     | Not reported | 450 [71]  |
| Songpan-Pingwu        | 7.2       | 8/16/1976    | +                   | 29              | 480                    | Not reported | 40 [71]   |
| Songpan-Pingwu        | 7.2       | 8/16/1976    | +                   | 11              | 420                    | Not reported | 100 [71]  |
| Songpan-Pingwu        | 7.2       | 8/16/1976    | +                   | 20              | 190                    | Not reported | 100 [71]  |
| Songpan-Pingwu        | 7.2       | 8/16/1976    | +                   | 70              | 1                      | Not reported | 320 [73]  |
| Songpan-Pingwu        | 7.2       | 8/16/1976    | -                   | 12              | 200                    | Not reported | 320 [71]  |
| Songpan-Pingwu        | 7.2       | 8/16/1976    | +                   | 90              | 48                     | Not reported | 340 [71]  |
| Songpan-Pingwu        | 7.2       | 8/16/1976    | -                   | 60              | 160                    | Not reported | 340 [71]  |
| Songpan-Pingwu        | 7.2       | 8/16/1976    | +                   | 55              | 160                    | Not reported | 390 [71]  |
| Songpan-Pingwu        | 7.2       | 8/16/1976    | +                   | 110             | 34                     | Not reported | 560 [71]  |
| Songpan               | 7.2       | 8/16/1976    | +                   | 100             | 1.5                    | 10       | 350 [75]  |
| Ex-USSR               |           |              |                     |                 |                        |         |            |
| Taschkent             | Ex-USSR   | 5.3          | 4/26/1966           | +               | 20                     | 400      | Not reported | 5 [71]   |
| Taschkent             | Ex-USSR   | 4.0          | 3/24/1967           | +               | 100                    | 11       | Not reported | 5 [71]   |
| Taschkent             | Ex-USSR   | 3.5          | 6/20/1967           | +               | 23                     | 3        | Not reported | 5 [71]   |
| Taschkent             | Ex-USSR   | 3.5          | 7/22/1967           | +               | 20                     | 3        | Not reported | 5 [71]   |
| Taschkent             | Ex-USSR   | 3.0          | 11/9/1967           | +               | 23                     | 8        | Not reported | 5 [71]   |
| Taschkent             | Ex-USSR   | 3.3          | 11/17/1967          | +               | 23                     | 7        | Not reported | 5 [71]   |
| Taschkent             | Ex-USSR   | 3.0          | 12/17/1967          | +               | 23                     | 4        | Not reported | 5 [71]   |
| Uzbekistan            | Ex-USSR   | 4.7          | 2/13/1973           | +               | 47                     | 5        | Not reported | 130 [71] |
| Markansu              | Ex-USSR   | 7.3          | 8/11/1974           | +               | 100                    | 100      | Not reported | 530 [71] |
| Tien Shan             | Ex-USSR   | 5.3          | 2/12/1975           | +               | 10                     | 110      | Not reported | 100 [71] |
| Location          | Region   | Magnitude | Date       | Instrument | U-238 Bq/l | U-234 Bq/l | U-232 Bq/l | Notes            |
|-------------------|----------|-----------|------------|------------|------------|------------|------------|------------------|
| Gazli             | Ex-USSR  | 7.3       | 5/17/1976  | +          | 220        | 4          | 470        | [71]             |
| Gazli             | Ex-USSR  | 7.3       | 5/17/1976  | +          | 25         | 90         | 550        | [71]             |
| Not reported      | Ex-USSR  | 7.0       | Not reported| Not reported| Not reported| Not reported| Not reported| 700 [72]         |
| Gazli             | Ex-USSR  | 7.3       | 5/17/1976  | +          | 220        | 4          | 470        | [71]             |
| Isfarin-Batnen    | Ex-USSR  | 6.6       | 1/31/1977  | −          | 30         | 60         | 190        | [71,72]          |
| Isfarin-Batnen    | Ex-USSR  | 6.6       | 1/31/1977  | −          | 20         | 125        | 200        | [71]             |
| Alma-Ata          | Ex-USSR  | 7.1       | 3/24/1978  | +          | 32         | 50         | 65         | [71]             |
| Zaalai            | Ex-USSR  | 6.7       | 11/1/1978  | −          | 30         | 470        | 270        | [71]             |
| Zaalai            | Ex-USSR  | 6.7       | 11/1/1978  | −          | 40         | 470        | 300        | [71]             |
| Zaalai            | Ex-USSR  | 6.7       | 11/1/1978  | +          | 20         | 75         | 150        | [71]             |
| Zaalai            | Ex-USSR  | 6.7       | 11/1/1978  | −          | 20         | 70         | 150        | [71]             |
| Italy             |          |           |            |            |            |            |            |                  |
| Irpinia           | Italy    | 6.5       | 11/23/1980 | +          | 25         | 150        | 150        | 220 [76]         |
| Mt Etna           | Italy    | 3.5(Md)   | 3-11-01    | Not reported| 170        | 180        | 180        | 200 [76]         |
| India             |          |           |            |            |            |            |            |                  |
| Uttarkashi        | India    | 7.0       | 10-20-91   | +          | 200        | 7          | 15         | 450 [77]         |
| Uttarkashi        | India    | 7.0       | 10-20-91   | +          | 300        | 7          | 15         | 270 [77]         |
| Uttarkashi        | India    | 7.0       | 10/20/1991 | +          | 180        | 7          | 3          | 330 [77]         |
| Maheshwaram       | India    | <1        | 4/17/2002  | +          | 100        | <1         | Not reported| 30 [78]          |
| Chamoli           | India    | 6.8       | 3/29/1999  | +          | 69.66 Bq/l| Not reported| 2          | Not reported [79]|
| Chamoli           | India    | 6.8       | 3/29/1999  | +          | 46.63 Bq/l| Not reported| 2          | Not reported [79]|
| France            |          |           |            |            |            |            |            |                  |
| Ligurian Sea      | France   | 3.9       | 1-5-86     | +          | 100        | 5          | 3          | 56 [20]          |
| Japan             |          |           |            |            |            |            |            |                  |
| Izu-Oshima        | Japan    | 6.8       | 01/14/1978 | +          | 7          | 230        | Not reported| 25 [80,20]      |
| Izu-Oshima        | Japan    | 6.8       | 01/14/1978 | −          | 8          | 7          | Not reported| 25 [80,20]      |
| Izu-Oshima-kinkai | Japan    | 7.0       | 01/14/1978 | −          | 8          | 7          | Not reported| 25 [24]         |
| Fukushima         | Japan    | 6.6       | Jan 1987   | −          | 2          | 0          | 0          | 260 [80]         |
| Fukushima         | Japan    | 6.7       | Feb 1987   | −          | 11         | 0          | 0          | 130 [80]         |
| Fukushima         | Japan    | 6.6       | Apr 1987   | −          | 9          | 0          | 0          | 110 [80]         |
| Kobe              | Japan    | 7.2       | 1/17/1995  | +          | 99         | Not reported| 60         | 20 [81]          |
| Kobe              | Japan    | 7.2       | 01/17/1995 | 2 sd above | Not reported| 2 months   | Not reported|                  |
| Kobe              | Japan    | 7.2       | 1/17/1995  | −          | 5          | Not reported| 260        | [82]             |
| Taiwan            |          |           |            |            |            |            |            |                  |
| Chengkung         | Taiwan   | 6.8       | 10-12-03   | −          | 57.8%      | Not reported| 65         | 20 [83]          |
| Antung            | Taiwan   | 5.0(Mw)   | Feb/2008   | Not reported| Not reported| Not reported| Not reported|                  |
| Chengkung         | Taiwan   | 6.8(Mw)   | 10-12-03   | Not reported| Not reported| Not reported| Not reported|                  |
| Taitung           | Taiwan   | 6.1(Mw)   | 1-4-06     | Not reported| Not reported| Not reported| Not reported|                  |
| Philippines       |          |           |            |            |            |            |            |                  |
| Mindoro           | Philippines | 7.1  | 11/14/1994 | +          | 600        | 7          | 22         | 48 [84]          |
| Uzbekistan        |          |           |            |            |            |            |            |                  |
| Tashkent          | Uzbekistan | Not reported| 12/13/1980 | Not reported| Not reported| Not reported| Not reported|                  |
| Turkmenistan      |          |           |            |            |            |            |            |                  |
| Akhhabad          | Turkmenistan | 5.7  | 3/14/1983  | Not reported| Not reported| Not reported| Not reported|                  |
| Antarctica        |          |           |            |            |            |            |            |                  |
| Scotia sea        | Antarctica | 7.5(Ms) | 4-8-03     | Not reported| Not reported| Not reported| 6          | 1176 [87]        |
| Location          | Country          | Magnitude | Date         | Method          | Duration       | Magnitude | Date         | Method          | Duration       | Ref. |
|-------------------|------------------|-----------|--------------|-----------------|----------------|------------|--------------|-----------------|----------------|------|
| Boumerdes         | Algeria          | 6.7 (ML)  | 5/21/2003    |                 |                |            |              |                 |                | [88] |
| Kato Achaia,      | Greece           | 6.5 (ML)  | 6-8-08       | Other techniques| 3-5 days       | 20         |              |                 |                | [7]  |
| Kato Achaia,      | Greece           | 6.5 (ML)  | 6-8-08       | Other techniques| 3-5 days       | 20         |              |                 |                | [26] |
| Kato Achaia,      | Greece           | 6.5 (ML)  | 6-8-08       | Other techniques| 3-5 days       | 20         |              |                 |                | [27] |
| Kato Achaia,      | Greece           | 6.5 (ML)  | 6-8-08       | Other techniques| 3-5 days       | 20         |              |                 |                | [25] |
| Mytilene, Lesvos Island | Greece           | 5.0 (ML)  |              | Other techniques| 3-5 days       | 20         |              |                 |                | [25] |

**Multiple events**

| Location          | Country          | Magnitude | Date         | Method          | Duration       | Magnitude | Date         | Method          | Duration       | Ref. |
|-------------------|------------------|-----------|--------------|-----------------|----------------|------------|--------------|-----------------|----------------|------|
| Southern          | Iceland          | 2.7       | 7/3/1978     |                 |                |            |              |                 |                | [89] |
| Iceland           | Iceland          | 3.4       | 8/28/1978    |                 |                |            |              |                 |                | [89] |
| Seismic           | Iceland          | 3.4       | 8/28/1978    |                 |                |            |              |                 |                | [89] |
| Seismic           | Iceland          | 4.3       | 11/19/1978   |                 |                |            |              |                 |                | [89] |
| Seismic           | Iceland          | 1.9       | 6/29/1979    |                 |                |            |              |                 |                | [89] |
| Seismic           | Iceland          | 2.8       | 9/5/1979     |                 |                |            |              |                 |                | [89] |
| Seismic           | Iceland          | 2.8       | 9/5/1979     |                 |                |            |              |                 |                | [89] |
| Tjörnes Facture Zone | Iceland          | 4.1       | 12/15/1979   |                 |                |            |              |                 |                | [89] |

**USA**

| Location          | Country          | Magnitude | Date         | Method          | Duration       | Magnitude | Date         | Method          | Duration       | Ref. |
|-------------------|------------------|-----------|--------------|-----------------|----------------|------------|--------------|-----------------|----------------|------|
| South California  | USA              | 2.9       | 9/24/1977    |                 |                |            |              |                 |                | [90] |
| South California  | USA              | 2.8       | 12/20/1977   |                 |                |            |              |                 |                | [90] |
| Malibu            | USA              | 4.6       | 1/1/1979     | 4 spikes        | 4 spikes       |            |              |                 |                | [90] |
| Pasadena          | USA              | 2.9       | 9/24/1977    |                 |                |            |              |                 |                | [90] |
| Pasadena          | USA              | 2.8       | 12/20/1977   |                 |                |            |              |                 |                | [90] |
| Malibu            | USA              | 4.7       | 1/1/1979     |                 |                |            |              |                 |                | [90] |
| Imperial Valley   | USA              | 6.6       | 10/15/1979   |                 |                |            |              |                 |                | [72] |
| Raquette Lake     | USA              | 3.9       |              |                 |                |            |              |                 |                | [72] |
| Blue Mountain Lake| USA              | 1.5       |              |                 |                |            |              |                 |                | [72] |
| Pearblossom       | USA              | 3.5       | 11/22/1976   |                 |                |            |              |                 |                | [71] |
| Jocasse           | USA              | 2.3       | 2/23/1977    |                 |                |            |              |                 |                | [71] |
| Malibu            | USA              | 4.7       | 1/1/1979     |                 |                |            |              |                 |                | [71] |
| Big Bear          | USA              | 5         | 6/28/1979    |                 |                |            |              |                 |                | [71] |
| Big Bear          | USA              | 5         | 6/28/1979    |                 |                |            |              |                 |                | [71] |
| Imperial Valley   | USA              | 6.6       | 10/15/1979   |                 |                |            |              |                 |                | [71] |
| Imperial Valley   | USA              | 6.6       | 10/15/1979   |                 |                |            |              |                 |                | [71] |
| Imperial Valley   | USA              | 6.6       | 10/15/1979   |                 |                |            |              |                 |                | [71] |
| Imperial Valley   | USA              | 6.6       | 10/15/1979   | Not reported    | 1 year         |            |              |                 |                | [71] |
| Caruthersville,   | USA              | 4.0       | Aug/1981     |                 |                |            |              |                 |                | [91] |
| Central Arkansas  | USA              | 4.0–4.5   | Jan/1982     |                 |                |            |              |                 |                | [91] |
| SW Illinois       | USA              | 4.2       | 5/15/1983    |                 |                |            |              |                 |                | [91] |
| New Madrid        | USA              | 3.5       | 1/28/1983    |                 |                |            |              |                 |                | [91] |
| San Andreas fault | USA              | 4         | 12/15/1977   |                 |                |            |              |                 |                | [92] |
| San Andreas fault | USA              | 4.2       | 8/29/1978    |                 |                |            |              |                 |                | [92] |
| Kettleman Hills   | California       | 5.6       | 4-8-85       |                 |                |            |              |                 |                | [67] |
| San Bernadino     | California       | 5         | 1-10-85      | Not reported    | 2 weeks       |            |              |                 |                | [67] |

**Equador**

| Location          | Country          | Magnitude | Date         | Method          | Duration       | Magnitude | Date         | Method          | Duration       | Ref. |
|-------------------|------------------|-----------|--------------|-----------------|----------------|------------|--------------|-----------------|----------------|------|
| Reventador        | Equador          | 6.9       | 6-3-87       |                 |                |            |              |                 |                | [93] |
| Location                  | Event Details | Reported Earthquakes | Preceding Seismic Activity | Seismic Activity Duration | References |
|---------------------------|---------------|----------------------|-----------------------------|---------------------------|------------|
| Reventador, Ecuador       | 6.9, 6-3-87   | * 230                | Not reported                | 15-50                     | 377        |
| Reventador, Ecuador       | 6.9, 6-3-87   | * 400                | Not reported                | 15-35                     | 339        |
| Reventador, Ecuador       | 6.9, 6-3-87   | * 100                | Not reported                | 15-40                     | 388        |
| Reventador, Ecuador       | 6.9, 6-3-87   | * 100                | Not reported                | 15-40                     | 183        |
| Reventador, Ecuador       | 6.9, 6-3-87   | * 300                | Not reported                | 15-40                     | 350        |
| Japan                     |               |                      |                             |                           |            |
| Subducted zone, Japan     | 7.9, 6-3-84   |                      | Not reported                | 15-40                     | 1000       |
| Not reported, Japan       | 6.7, 6-2-87   |                      | Not reported                | 15-40                     | 130        |
| Taiwan                    |               |                      |                             |                           |            |
| Northern Taiwan, Taiwan   | 5.8, 10/18/1980 | Not reported | Not reported                | 19                        | 39         |
| Northern Taiwan, Taiwan   | 5.2, 5/14/1981 | Not reported        | Not reported                | 11                        | 23         |
| Northern Taiwan, Taiwan   | 4.6, 6/21/1981 | Not reported        | Not reported                | 15                        | 14         |
| Northern Taiwan, Taiwan   | 5.0, 7/18/1981 | Not reported        | Not reported                | 4                         | 37         |
| Northern Taiwan, Taiwan   | 5.3, 10/31/1982 | Not reported  | Not reported                | 51                        | 45         |
| Near the Auntung hot spring, Taiwan | 5.2-6.2, Dec/2003-April/2006 | Not reported | Not reported                | 11.0-65.0                 |            |
| India                     |               |                      |                             |                           |            |
| North Andaman, India      | 5.0, 01/14/2005 | Not reported  | Not reported                | 1215                      |            |
| Uttarkashi, India         | 7.0(Ms), 10/20/1991 | Not reported | Not reported                | 5                         | 293        |
| Chamoli, India            | 6.5(Ms), 03/29/1999 | Not reported | Not reported                | Not reported              | 393        |
| Chamba, India             | 5.1(Ms), 03/24/1995 | Not reported | Not reported                | 3                         | 10         |
| Kharsali, India           | 4.9, 07/23/2007 | Not reported        | Not reported                | Few days                  | 60         |
| Indonesia                 |               |                      |                             |                           |            |
| Indonesia, Indonesia      | 9.1, 12/26/2004 | Not reported  | Not reported                | 2275                      |            |
| West Sumatra, Indonesia   | 5.8, 9-2-05    | Not reported        | Not reported                | 2120                      |            |
| North Sumatra, Indonesia  | 5.1, 6-1-05    | Not reported        | Not reported                | 2070                      |            |
| Turkey                    |               |                      |                             |                           |            |
| Western Turkey, Turkey    | 3, 4-6-07      | Not reported        | Not reported                | Not reported              |            |
| Western Turkey, Turkey    | 4.2, 11-11-07  | Not reported        | Not reported                | Not reported              |            |
| Greece                    |               |                      |                             |                           |            |
| Chalkida, Evia Island, Greece | 5.1(ML), 11-17-14 | Other techniques | 15 days                     | 1-3 weeks                 | 80         |
| Seismic Periods           |               |                      |                             |                           |            |
| India                     |               |                      |                             |                           |            |
| Kangra Valley & Hindu Kush area, India | 3.8-6.8, 3/23/1984-3/17/1987 | 6 spikes | Not reported                | 150-400                   |            |
| Kangra Valley & Hindu Kush area, India | Not reported, March/1984-July/1987 | 7 spikes | Not reported                | Not reported              |            |
| Hindu Kush area, India    | 4.2-6.4, Oct/1988-Dec/1991 | 9 spikes | Not reported                | Not reported              |            |
| Kangra Valley, India      | 2.8-6.6, Aug/1989-Dec/1991 | 4 spikes | Not reported                | Not reported              |            |
| Location                              | Country          | Range         | Events | Spikes | Duration     | Peaks   | Magnitude | Notes         |
|--------------------------------------|------------------|---------------|--------|--------|--------------|---------|-----------|---------------|
| Sunder Nagar & Himachal Pradesh      | India            | 3.2-5.4       | 3      | 3 spikes | 15-66 days   | 1-2     | Not reported | Not reported  |
| North-West Himalayas (25 events)     | India            | 2.1-6.8       | 1992-1999 | Not reported | Not reported | Not reported | Not reported | 53-393        |
| Tehri Garhwal, Himalaya (20 events)  | India            | 1.2-5.7       | 3/11/2004-12/26/2004 | Not reported | Not reported | Not reported | Not reported | 16-250        |
| Tehri Garhwal, Himalaya (21 events)  | India            | 1.5-3.7       | 1/01/2005-12/20/2005 | Not reported | Not reported | Not reported | Not reported | 16-250        |
| North-West Himalayas (9 events)      | India            | 2.6-4.6       | 1/02/2006-5/12/2006 | Not reported | Not reported | Not reported | Not reported | 16-250        |
| North-West Himalayas (3 events)      | India            | 2.2-5.0       | March/2007-June/2008 | * | 2.6-72.8     | Not reported | 2-13 days | 19-196        |
| North-West Himalayas (8 events)      | India            | 2.2-5.0       | Dec/2006-Dec/2007 | * | 49-61        | Not reported | 4-13 days | 97-201        |
| North-West Himalayas (6 events)      | India            | 2.2-5.0       | Dec/2006-Dec/2007 | * | 18.2-47.3    | Not reported | 3-14 days | 22-339        |
| Not reported                         | India            | Not reported  | Nov/2005-Nov/2008 | Not reported | Not reported | Not reported | Not reported | Not reported  |
| Japan                                |                  |               |        |        |              |         |           |               |
| Earthquakes nearby the Fukushima     | Japan            | 6.0-6.7       | Jan/1984-July/1988 | Not reported | Not reported | Few days | 100-130 & 400 |
| Prefecture (16 events)               |                  |               |        |        |              |         |           |               |
| Croatia & Bosnia-Herzegovina         |                  |               |        |        |              |         |           |               |
| Modrica, Medvednica mountain          | Croatia and      | 2.7-3.8       | April/1998-April/2000 | Not reported | Not reported | 30          | 70-320        |
| Croatia & Bosnia-Herzegovina         |                  |               |        |        |              |         |           |               |
| Not reported                         | Croatia          | 2.6-4.9       | 01/27/2003-12/15/2006 | Not reported | Not reported | Not reported | 47-199        |
| Not reported                         | Croatia          | 2.7-4.9       | 6/02/2005-5/28/2007 | Not reported | Not reported | Not reported | 4.0-295.0    |
| Not reported                         | Slovenia         | 0.7-3.2       | 1999-2001 | Not reported | Not reported | 2.0-33.0 | Re/Rd from 0.4 to 2.0 |
| Slovenia                             |                  |               |        |        |              |         |           |               |
| Taiwan                               |                  |               |        |        |              |         |           |               |
| Taiwan (30 events)                   | Taiwan           | 4.5-6.6       | 03/01/2003-06/30/2004 | 16 peaks   | 0.2-12       | 1.3-20.0 | 4.9-174.2   |
| Taiwan (37 events)                   | Taiwan           | 3.7-6.7       | 11/01/2000-05/11/2003 | Not reported | Not reported | 1.12-13.00 | 1.5-257.5   |
| United Kingdom                       |                  |               |        |        |              |         |           |               |
| English Channel (1 event), Dudley     | U.K.             | 1.2-5.0       | 08/26/2002-10/29/2002 | Not reported | 6-9-h spikes | Not reported | 90.1-250.2   |
| (3 events), Manchester (11 events)   |                  |               |        |        |              |         |           |               |
| Spain                                |                  |               |        |        |              |         |           |               |
| Tenerife Island                      | Spain            | Greater than 2.5 | From April 2004-2005 | Not reported | Not reported | Several months | Not reported |
| Iceland                              |                  |               |        |        |              |         |           |               |
| South Iceland                        | Iceland          | 6.5(MW)/2     | June/2000 | Not reported | Not reported | 40-144    | 90.0         |
| Taiwan                               |                  |               |        |        |              |         |           |               |
advanced approach is the detrended fluctuation analysis (DFA) [27,57].
According to the reports [27,57] and several other papers [38,51] the
detrended fluctuation analysis is the most advantageous technique to
trace the long-memory of a system driven to rupture. Significant other
techniques are the time-evolution of the fractal dimension [26] and the
Hurst exponent [25-27,57] and the temporal changes of various metrics of
entropy [26]. Note that the techniques can trace patterns of long-
memory that are hidden in the pre-earthquake time-series. They can
also identify features related to the self-organization of the earthquake
generating system. It is also important to note that the vast majority
of papers of Table 1 refer to measurement of radon in soil. Only some
papers refer to radon in underground or thermal water and only one
to radon detected in atmosphere prior to earthquakes [62]. Note that
in this paper advanced Fourier based approach was implemented for a
significant long-lasting signal retrieved prior to the Kobe earthquake,
Japan.

Various physical mechanisms have been reported to relate the sub-surface physical changes with the variation in radon emanations [25].
Regarding modelling, the available models propose explanations in
terms of strain changes within the earth’s crust during preparation of
earthquakes [5,33,34,40]. It is the displacement of rock mass under
tectonic stress that opens up various pathways and exposes new
surfaces when cracks open. The stress-strain developed within the
earth’s crust before earthquakes leads to changes in gas transportation
from the deep earth to surface [41,42]. As a result, unusual quantities of
radon emerge out of the pores and fractures of the rocks on the surface.
Due to the seismic activity, changes in underground fluid flow may also render anomalous changes in concentration of radon and its progeny
[43]. Under the so called compression model, according to [63] and
[64] 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.

Among the various theoretical models, the dilatancy diffusion
model proposed by Martinelli [5,65] is a noteworthy approach.
According to this model [5,25-27] the earthquake generating medium
is considered to consist of porous cracked saturated rocks. When a
tectonic stress develops, the cracks extend and appear near the pores
with the opening of favourably oriented cracks [5,25-27]. 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 [5,25-27].

A well-accepted model is the the Crack-Avalanche model [5,25-
27,66]. According to the Crack-Avalanche model as tectonic stress
increases during the earthquake preparation, a zone of cracked rocks
is formed in the region of a future earthquake focal zone under the
influence of the tectonic stresses. In the study of the surrounding
medium this region may be considered as a solid inclusion with
altered moduli. The inclusion appearance causes a redistribution of
the stresses accompanied by corresponding deformations. As the
tectonic stresses change with time, the shape and size of the zone change as well. According to the theory of stress corrosion, the anomalous behavior
of radon concentration may be associated with this slow crack growth,
which is controlled by the stress corrosion in the rock matrix saturated
by groundwater.

A very recent model has been proposed by [25-27] based on the
aspects expressed by [38,39]. This model is called asperity model.
According to the asperity model, the focal area consists of a backbone
of strong and large asperities that sustain the earthquake-generating
system. A strongly heterogeneous medium surrounds the family of
strong asperities. The fracture of the heterogeneous system in the focal
area obstructs the backbone of asperities. At this stage, critical anti-
persistent MHz electromagnetic anomalies and radon anomalies occur
[25-27,38,39].

Comparing the aforementioned models, it can be claimed that as
an earthquake approaches a region of several cracks is formed [8]. The
earthquake is associated with deformations and as a result short or long term precursory phenomena like anomalies in radon concentration may occur. As mentioned already, radon can be considered as a short-term earthquake precursor. Nevertheless, no universal model exists to serve as pre-earthquake signature [25-27,38,39]. Moreover, there is no definite rule to link any kind of pre-earthquake anomaly to a specific forthcoming seismic event, either if this is intense or mild [25-27,38,39]. For these reasons, despite the fairly abundant circumstantial evidence, the scientific community still debates the precursory value of premonitory anomalies detected prior to earthquakes [38]. On the other hand, well established criteria exist to identify pre-earthquake patterns hidden in time-series, which are based on the concepts of fractality, self-organisation, non-extensivity and entropy [25,27,38-38]. Especially according to [38], certain questions still remain: (i) How can a certain observation be recognised as pre-seismic? (ii) How can an individual precursor be linked to a distinctive stage of an earthquake preparation process? (iii) How can certain precursory symptoms in anomalous observations be identified so as to indicate that the occurrence of an earthquake is unavoidable? The above issues clearly indicate that radon monitoring in soil is a very important field of research from geological point of view.

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