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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 ^{193}Rn to ^{231}Rn [1]. The most stable isotope is ^{222}Rn (hereafter radon) with a half-life of 3.823 days. Four isotopes, ^{222}Rn, ^{220}Rn, ^{219}Rn and ^{218}Rn occur in trace quantities in nature as decay products of, respectively, ^{226}Ra, ^{224}Ra, ^{223}Ra and ^{218}At [1,2]. ^{222}Rn and ^{218}Rn are intermediate steps in the decay chain of ^{238}U, ^{219}Rn is an intermediate step in the decay chain of ^{235}U and ^{220}Rn occurs in the decay chain of ^{232}Th [1-3]. ^{220}Rn is also known as thoron [1]. 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. ^{219}Rn is also called actinon [1]. It has lesser half-life time than ^{222}Rn and ^{220}Rn (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

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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 (10^1 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 seismo-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 relevant important data including: (1) the earthquake details; (2) the % (δα) 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 (4) 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	USA	5.6	8-4-85	+	100	Not reported	Not reported	300	[67]
	Aladale, California	USA	3.7	June/1983	+	1200	3	15	13	[68,69]
P.R. China										
	Pohai Bay	PR China	7.4	6/18/1969	+	60	170	Not reported	170	[70,71]
	Ningshin	PR China	4.3	5-8-71	+	200	40	Not reported	42	[71]
	Hsingtang	PR China	4.9	6-6-74	+	290	16	Not reported	18	[71]
	Haicheng	PR China	7.3	4-2-75	+	38	270	Not reported	50	[71]
	Haicheng	PR China	7.3	4-2-75	+	17	50	Not reported	50	[71]
	Haicheng	PR China	7.3	4-2-75	−	43	66	Not reported	140	[71]
	Haicheng	PR China	7.3	4-2-75	+	20	8	Not reported	140	[71]
	Haicheng	PR China	7.3	4-2-75		Not reported	Not reported	Not reported	26	[71]
	Liaoyang	PR China	4.8	Not reported		Not reported	Not reported	Not reported	32	[71]
	Tangshan	PR China	7.8	6/27/1976	+	15	970	Not reported	50	[71]
	Tangshan	PR China	7.8	6/27/1976	+	50	15	Not reported	100	[71]
	Tangshan	PR China	7.8	6/27/1976	−	40	1370	Not reported	130	[71]
	Tangshan	PR China	7.8	6/27/1976	+	27	162	Not reported	130	[71]
	Tangshan	PR China	7.8	6/27/1976		Not reported	Not reported	Not reported	1800	[72]
	Chienan	PR China	6.0	3/7/1977	+	70	3	1	200	[73]
	Sabteh	PR China	5.2	4/8/1972	+	55	12	Not reported	70	[73]
	Takung	PR China	5.8	9/27/1972	+	34	12	Not reported	54	[73]
	Luhuo	PR China	7.9	2/6/1973	+	120	9	Not reported	200	[74]
	Yiliang	PR China	5.2	4/22/1973	+	41	14	Not reported	340	[73]
	Songpan	PR China	5.2	5/8/1973	+	40	14	Not reported	345	[71]
	Mapien	PR China	5.5	6/29/1973	+	89	9	Not reported	200	[74]
	Lungling	PR China	7.5	5/29/1976	+	20	510	Not reported	20	[71]
	Lungling	PR China	7.5	5/29/1976	+	15	425	Not reported	190	[71]
	Lungling	PR China	7.5	5/29/1976	+	8	160	Not reported	210	[71]
	Lungling	PR China	7.5	5/29/1976	+	12	130	Not reported	215	[71]
	Lungling	PR China	7.5	5/29/1976	+	7	75	Not reported	360	[71]
	Lungling	PR China	7.5	5/29/1976	+	20	290	Not reported	420	[71]
	Lungling	PR China	7.5	5/29/1976	+	200	12	Not reported	450	[71]
	Songpan-Pingwu	PR China	7.2	8/16/1976	+	29	480	Not reported	40	[71]
	Songpan-Pingwu	PR China	7.2	8/16/1976	+	11	420	Not reported	100	[71]
	Songpan-Pingwu	PR China	7.2	8/16/1976	+	20	190	Not reported	100	[71]
	Songpan-Pingwu	PR China	7.2	8/16/1976	+	70	1	Not reported	320	[73]
	Songpan-Pingwu	PR China	7.2	8/16/1976	−	12	200	Not reported	320	[71]
	Songpan-Pingwu	PR China	7.2	8/16/1976	+	90	48	Not reported	340	[71]
	Songpan-Pingwu	PR China	7.2	8/16/1976	−	60	160	Not reported	340	[71]
	Songpan-Pingwu	PR China	7.2	8/16/1976	+	55	160	Not reported	390	[71]
	Songpan-Pingwu	PR China	7.2	8/16/1976	+	110	34	Not reported	560	[71]
	Songpan	PR China	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]

	Gazli	Ex-USSR	7.3	5/17/1976	+	220	4	Not reported	470	[71]
	Gazli	Ex-USSR	7.3	5/17/1976	+	25	90	Not reported	550	[71]
	Not reporetd	Ex-USSR	7.0	Not reported		Not reported	Not reported	Not reported	700	[72]
	Gazli	Ex-USSR	7.3	5/17/1976		Not reported	Not reported	Not reported	400	[72]
	Isfarin-Batnen	Ex-USSR	6.6	1/31/1977	−	30	60	Not reported	190	[71,72]
	Isfarin-Batnen	Ex-USSR	6.6	1/31/1977	−	20	125	Not reported	200	[71]
	Alma-Ata	Ex-USSR	7.1	3/24/1978	+	32	50	Not reported	65	[71]
	Zaalai	Ex-USSR	6.7	11/1/1978	−	30	470	Not reported	270	[71]
	Zaalai	Ex-USSR	6.7	11/1/1978	−	40	470	Not reported	300	[71]
	Zaalai	Ex-USSR	6.7	11/1/1978	+	20	75	Not reported	150	[71]
	Zaalai	Ex-USSR	6.7	11/1/1978	−	20	70	Not reported	150	[71]
Italy										
	Irpinia	Italy	6.5	11/23/1980	+	25	150	150	220	[76]
	Irpinia	Italy	6.5	11/23/1980	+	170	180	180	200	[76]
	Mt Etna	Italy	3.5(Md)	3-11-01		Not reported	4-5 days	6	650	[18]
India										
	Uttarkashi	India	7	10/20/1991	+	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		Not reported	Not reported	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 the mean	Not reported	2 months	Not reported	[62]
	Kobe	Japan	7.2	1/17/1995	−	5	Not reported	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	[83]
	Chengkung	Taiwan	6.8(Mw)	10-12-03		Not reported	Not reported	Not reported	55	[83]
	Taitung	Taiwan	6.1(Mw)	1-4-06		Not reported	Not reported	Not reported	55	[83]
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	[85]
Turkmenistan										
	Ahkhabad	Turkmenistan	5.7	3/14/1983		Not reported	Not reported	Not reported	Not reported	[87]
Antarctica										
	Scotia sea	Antarctica	7.5(Ms)	4-8-03		Not reported	Not reported	6	1176	[87]
Algeria										

	Boumerdes	Algeria	6.7(ML)	5/21/2003		Not reported	1-3days	2.0-7.0	1120	[88]
Greece										
	Kato Achaia, Peloponnese	Greece	6.5(ML)	6-8-08		Other techniques	3-5 days	2-3 months	20	[7]
	Kato Achaia, Peloponnese	Greece	6.5(ML)	6-8-08		Other techniques	3-5 days	2-3 months	20	[26]
	Kato Achaia, Peloponnese	Greece	6.5(ML)	6-8-08		Other techniques	3-5 days	2-3 months	20	[27]
	Kato Achaia, Peloponnese	Greece	6.5(ML)	6-8-08		Other techniques	3-5 days	2-3 months	20	[25]
	Mytilene, Lesvos Island	Greece	5.0(ML)			Other techniques	3-5 days	2-3 months	80	[25]
Multiple events										
Iceland										
	Southern	Iceland	2.7	7/3/1978	+	380	22	25	14	[89]
	Iceland	Iceland	3.4	8/28/1978	+	60	17	30	5	[89]
	Seismic	Iceland	3.4	8/28/1978	+	280	17	27	21	[89]
	Seismic	Iceland	4.3	11/19/1978	−	80	18	10	16	[89]
	Seismic	Iceland	1.9	6/29/1979	+	40	19	25	9	[89]
	Seismic	Iceland	2.8	9/5/1979	+	40	17	20	8	[89]
	Seismic	Iceland	2.8	9/5/1979	+	100	33	33	5	[89]
	Tjörnes Facture Zone	Iceland	4.1	12/15/1979	+	100	50	50	56	[89]
USA										
	South California	USA	2.9	9/24/1977	+	44	1	5	21	[90]
	South California	USA	2.8	12/20/1977	+	40	10	24	12	[90]
	Malibu	USA	4.6	1/1/1979		4 spikes	4 spikes	Not reported	54	[90]
	Pasadena	USA	2.9	9/24/1977	+	25	14	5	21	[90]
	Pasadena	USA	2.8	12/20/1977	+	72	3	Not reported	12	[90]
	Malibu	USA	4.7	1/1/1979	+	225	9	Not reported	54	[90]
	Imperial Valley	USA	6.6	10/15/1979	+	Not reported	2	Not reported	300	[72]
	Raquette Lake	USA	3.9	Not reported		Not reported	10	7	14	[72]
	Blue Mountain Lake	USA	1.5	Not reported	+	36	Not reported	Not reported	1	[72]
	Pearblossom	USA	3.5	11/22/1976	−	50	Not reported	Not reported	25	[71]
	Jocasse	USA	2.3	2/23/1977	+	62	31	Not reported	1	[71]
	Malibu	USA	4.7	1/1/1979	+	310	42	Not reported	20	[71]
	Big Bear	USA	5	6/28/1979	+	72	82	Not reported	85	[71]
	Big Bear	USA	5	6/28/1979	+	400	12	Not reported	31	[71]
	Imperial Valley	USA	6.6	10/15/1979	+	200	45	Not reported	335	[71]
	Imperial Valley	USA	6.6	10/15/1979	+	72	116	60	310	[71]
	Imperial Valley	USA	6.6	10/15/1979	+	64	95	2-7 months	265	[71]
	Imperial Valley	USA	6.6	10/15/1979		Not reported	145	1 year	260	[71]
	Caruthersville, Missouri	USA	4.0	Aug/1981	−	340–504	5 months	Not reported	40	[91]
	Central Arkansas (earthquake swarm)	USA	4.0–4.5	Jan/1982		Not reported	1 year	Not reported	160	[91]
	SW Illinois	USA	4.2	5/15/1983	+	483	2 months	Not reported	120–320	[91]
	New Madrid Seismic Zone	USA	3.5	1/28/1983	+	60	2 months	Not reported	50	[91]
	San Andreas fault	USA	4	12/15/1977		400	30	15	45	[92]
	San Andreas fault	USA	4.2	8/29/1978	+	200	90	240	75	[92]
	Kettleman Hills (California)	USA	5.6	4-8-85		Not reported	Not reported	2weeks	300	[67]
	San Bernadino (California)	USA	5	1-10-85		Not reported	Not reported	6weeks	20 & 90	[67]
Equador										
	Reventador	Equador	6.9	6-3-87		Not reported	Not reported	50	367	[93]

	Reventador	Equador	6.9	6-3-87	+	230	Not reported	15-50	377	[93]
	Reventador	Equador	6.9	6-3-87	+	400	Not reported	15-35	339	[93]
	Reventador	Equador	6.9	6-3-87	+	100	Not reported	50	388	[93]
	Reventador	Equador	6.9	6-3-87	+	100	Not reported	15-40	183	[93]
	Reventador	Equador	6.9	6-3-87	+	300	Not reported	15-40	350	[93]
Japan										
	Subducted zone	Japan	7.9	6-3-84		Not reported	2	9	1000	[94]
	Not reporetd	Japan	6.7	6-2-87		Not reported	4	3	130	[94]
Taiwan										
	Northern Taiwan	Taiwan	5.8	10/18/1980		Not reported	Not reported	19	39	[95]
	Northern Taiwan	Taiwan	5.2	5/14/1981		Not reported	Not reported	11	23	[95]
	Northern Taiwan	Taiwan	4.6	6/21/1981		Not reported	Not reported	15	14	[95]
	Northern Taiwan	Taiwan	5.0	7/18/1981		Not reported	Not reported	4	37	[95]
	Northern Taiwan	Taiwan	5.3	10/31/1982		Not reported	Not reported	51	45	[95]
	Near the Auntung hot spring (5 events)	Taiwan	5.2-6.2	Dec/2003-April/2006		Not reported	Not reported	Not reported	11.0-65.0	[96]
India										
	North Andaman	India	5.0	01/14/2005		Not reported	Not reported	Not reported	1215	[97]
	Uttarkashi	India	7.0(Ms)	10/20/1991		Not reported	Not reported	5	293	[98]
	Chamoli	India	6.5(Ms)	03/29/1999		Not reported	Not reported	Not reported	393	[98]
	Chamba	India	5.1(Ms)	03/24/1995		Not reported	Not reported	3	10	[98]
	Kharsali	India	4.9	07/23/2007		Not reported	Not reported	Few days	60	[99]
Indonesia										
	Indonesia	Indonesia	9.1	12/26/2004		Not reported	Not reported	Not reported	2275	[97]
	West Sumatra	Indonesia	5.8	9-2-05		Not reported	Not reported	Not reported	2120	[97]
	North Sumatra	Indonesia	5.1	6-1-05		Not reported	Not reported	Not reported	2070	[97]
Turkey										
	Western Turkey	Turkey	3	4-6-07		Not reported	Not reported	Not reported	Not reported	[100]
	Western Turkey	Turkey	4.2	11-11-07		Not reported	Not reported	Not reported	Not reported	[100]
Greece										
	Chalkida,Evia Island	Greece	5.1(ML)	11-17-14		Other techniques	15 days	1-3 weeks	80	[101]
Seismic Periods										
India										
	Kangra Valley & Hindu Kush area (6 events)	India	3.8-6.8	3/23/1984-3/17/1987		6 spikes	Not reported	Not reported	150-400	[102]
	Kangra Valley & Hindu Kush area (7 events)	India	Not reported	March/1984-July/1987		7 spikes	Not reported	Not reported	Not reported	[103]
	Hindu Kush area (26 events)	India	4.2-6.4	Oct/1988-Dec/1991		9 spikes	Not reported	Not reported	400-500	[103]
	Kangra Valley (1 event) & Dharamsala (1 event) & North West Himalayas (14 events)	India	2.8-6.6	Aug1989-Dec/1991		4 spikes	Not reported	Not reported	Not reported	[103]

	Sunder Nagar & Himachal Pradesh (3 events)	India	3.2-5.4	Jan/1997-Dec/1997		3 spikes	Not reported	15-66days	Not reported	[104]
	North-West Himalayas (25 events)	India	2.1-6.8	1992-1999		Not reported	Not reported	Not reported	53-393	[105]
	Tehri Garhwal, Himalaya (20 events)	India	1.2-5.7	3/11/2004-12/26/2004		Not reported	Not reported	Not reported	16-250	[106]
	Tehri Garhwal, Himalaya (21 events)	India	1.5-3.7	1/01/2005-12/20/2005		Not reported	Not reported	Not reported	16-250	[106]
	Tehri Garhwal, Himalaya (4 events)	India	2.6-4.6	1/02/2006-5/12/2006		Not reported	Not reported	Not reported	16-250	[106]
	North-West Himalayas (9 events)	India	2.2-5.0	March/2007-June/2008	+	2.6-72.8	Not reported	2-13days	19-196	[107]
	North-West Himalayas (3 events)	India	2.2-5.0	Dec/2006-Sept/2007	+	49-61	Not reported	4-13days	97-201	[29]
	North-West Himalayas (6 events)	India	2.2-5.0	Dec/2006-Dec/2007	+	18.2-47.3	Not reported	3-14days	22-339	[29]
	Not reporetd	India	Not reported	Nov/2005-Nov/2008		Not reported	Not reported	Not reported	Not reported	[58]
Japan										
	Earthquakes nearby the Fukushima Prefecture (16 events)	Japan	6.0-6.7	Jan/1984-July/1988		Not reported	Not reported	Few days	100-130 & 400	[108]
Croatia & Bosnia-Herzegovina										
	Modrica, Medvednica mountain, West & South west of the monitoring site (7 events)	Croatia and Bosnia-Herzegovina	2.7-3.8	April/1998-April/2000		Not reported	Not reported	30	70-320	[109]
	Not reporetd (19 events)	Croatia	2.6-4.9	01/27/2003-12/15/2006		Not reported	Not reported	Not reported	47-199	[110]
	Not reporetd (10 events)	Croatia	2.7-4.9	6/02/2005-5/26/2007		Not reported	Not reported	Not reported	4.0-295.0	[110]
Slovenia										
	Not reporetd (13 events)	Slovenia	0,7-3.2 (ML)	1999-2001		Not reported	Not reported	2.0-33.0	Re/Rd from 0.4 to 2.0	[111]
Taiwan										
	Taiwan (30 events)	Taiwan	4.5-6.6 (ML)	03/01/2003-06/30/2004		16 peaks	0.2-12	1.3-20.0	4.9-174.2	[112]
	Taiwan (37 events)	Taiwan	3.7-6.7 (ML)	11/01/2000-05/11/2003		Not reported	Not reported	1.12-13.00	1.5-257.5	[25]
United Kingdom										
	English Channel (1 event), Dudley (3 events), Manchester (11 events)	U.K.	1.2-5.0	08/26/2002-10/29/2002		Not reported	6-9-h spikes	Not reported	90.1-250.2	[113]
Spain										
	Tenerife Island	Spain	Greater than 2.5	From April 2004-2005		Not reported	Not reported	Several months	Not reported	[114]
Iceland										
	South Iceland	Iceland	6.5(Mw)2 events & several magnitude 5+ events	June/2000		Not reported	Not reported	40-144	90.0	[115]
Taiwan										

	Taiwan (20 events)	Taiwan	3.7-6.2 (ML)	3/15/2005-8/12/2006		Not reported	Not reported	1.6-13.9	7.6-145.8	[116]
	Hsincheng fault (38 events)	Taiwan	3.0-7.0	1/01/2006-7/14/2008		29 anomalies	Not reported	Not reported	Not reported	[16]
	Hsinhua fault (28 events)	Taiwan	3.0-7.0	1/01/2006-7/14/2008		28 anomalies	Not reported	Not reported	Not reported	[16]
Turkey										
	Denizli Basin	Turkey	3.3-4.8	5/04/2000-12/11/2000		Not reported	Not reported	Not reported	3.0-23.0	[117]
	East Anatolian Fault (59 events)	Turkey	2.5-5.5	6/22/2004-6/27/2005		Not reported	Not reported	Not reported	Not reported	[118]
	Afyonkarahisar province	Turkey	2.6-3.9	Sep/2009-Sep/2010		Not reported	Not reported	Not reported	Not reported	[119,120]
Iran										
	Jooshan (SE of Iran)	Iran	2.6-5.4	Jan/2012-Feb/2012		Not reported	Not reported	3-6days	3.9-163.8	[32,33]
Romania										
	Vrancea seismic area (Carpathians) (266 events)	Romania	2.0-4.9	Nov/2012-Nov/2011		Not reported	Not reported	2 weeks-1 month	Not reported	[34]

Table 1: Earthquake precursory data based on radon gas. Earthquake data, % of disturbance in reference to the baseline values (δα) or technique of analysis, together with duration of measurements, reported precursory time and effective distance (ED) from the epicenter of the earthquake and related references.

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 [25-27,38-58]. 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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