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Continuous radon monitoring in the Jowshan hot spring as an earthquake precursor, SE Iran

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In this paper, we present the results of the first experience for spring water ^{222}Rn concentration continuous monitoring in Jowshan hot spring, SE Iran, from December 2007 to July 2008. This hot spring is located on the active Gowk Fault. In addition to physic-chemical parameters of water and water chemistry, dissolved radon, and air and water temperatures, were measured at 10-minute time intervals. Measurements and analyses correlated with seismological data within a radius 250 km from the spring. Relatively good relationships between radon level variations and earthquake frequency, especially for events which monitoring site lie within the stress-strain field of earthquake, were observed. Results show that radon precursor time negatively correlate with the distance between the epicenters and monitoring station, but positively correlate with the magnitude of the earthquake events. Nevertheless, continuous monitoring to attain local pattern is necessary. Temperature, electrical conductivity and pH measurements do not show any correlation with seismic activity and radon variations in this time-window of monitoring. Monthly spring water samples analyzing for major components demonstrate no mixing ground-water has been taken place during the period of monitoring. While deep temperature estimation based on the [Na–K–Ca] geothermometery shown coinciding of temperature increasing with radon anomaly in one case. More data and shorter sampling time interval for spring water is required before we can conclude that the variation of estimated deep temperature is feasible to be as an earthquake precursor.

Keywords: ^{222}Rn, earthquake precursor, Jowshan hot spring, continuous monitoring, geothermometery

INTRODUCTION

Earthquakes, as a geological hazard, inflict many deaths and injuries to communities. Iran is located on the Alpine–Himalaya seismic belt. In this country, twelve earthquakes greater than $M = 7.0$ of the Richter scale in magnitude occurred within the last six decades, which means on average one event occurred in every five years. In Kerman province, SE Iran, several active faults have been identified. Hence, many earthquakes have been taken place in this region. Dec. 26, 2003 Bam ($M_s = 6.6$) and Feb. 22, 2005 Zarand ($M_s = 6.5$), are the most recent disastrous ones.

Globally, the earthquakes have inflicted hundreds of thousands deaths and injuries as well as billions of dollars damage to communities. Thus, scientists have paid much attention to earthquake prediction methods in recent decades (Wakita, 1975; King, 1986, 1989; Thomas, 1988; Johansen *et al.*, 1996, 2000; Wyss and Booth, 1997; Quattrocchi *et al.*, 1999; Toutain and Baubron, 1999; Biagi *et al.*, 2000; Zanzari *et al.*, 2001; Carapezza *et al.*, 2005; Yang *et al.*, 2005, 2006; Hartmann and Levy, 2006; Pulinets and Dunajecka, 2007; Singh *et al.*, 2007; Fu *et al.*, 2008, 2009; Walia *et al.*, 2009, 2010; Chyi *et al.*, 2010, 2011; Laskar *et al.*, 2011; Montazeri *et al.*, 2011; Woith *et al.*, 2011; and references therein).

Deformation of the crust in active regions induced by tectonic forces is considered as the main agent of subterranean emission of gasses and waters into the surface, by thermal and geodynamical processes (e.g., Yang *et al.*, 2003, 2011). Then, temporal variations of chemical composition of gasses released in active areas can be used as precursor for earthquake prediction. From these geochemical variations, the radon emission has been considered as one of the precursors confirmed by the International Association of Seismology and Physics of the Earth's Interior (Wyss, 1997).

Radon gas is moderately soluble in water and it forms structures of the Rn·6H_2O type (clathrates) by means of Van der Waals forces (Nesmeyanov, 1974). Solubility of radon in water helps this gas to migrate almost long distances into the surface (Virk and Singh, 1993; Igarashi *et al.*, 1995; Nishizawa *et al.*, 1998; Yang *et al.*, 2003). Therefore, hot springs associated with active faults are favorable sites for monitoring radon concentration in the fluids which allows the variations to be identified and

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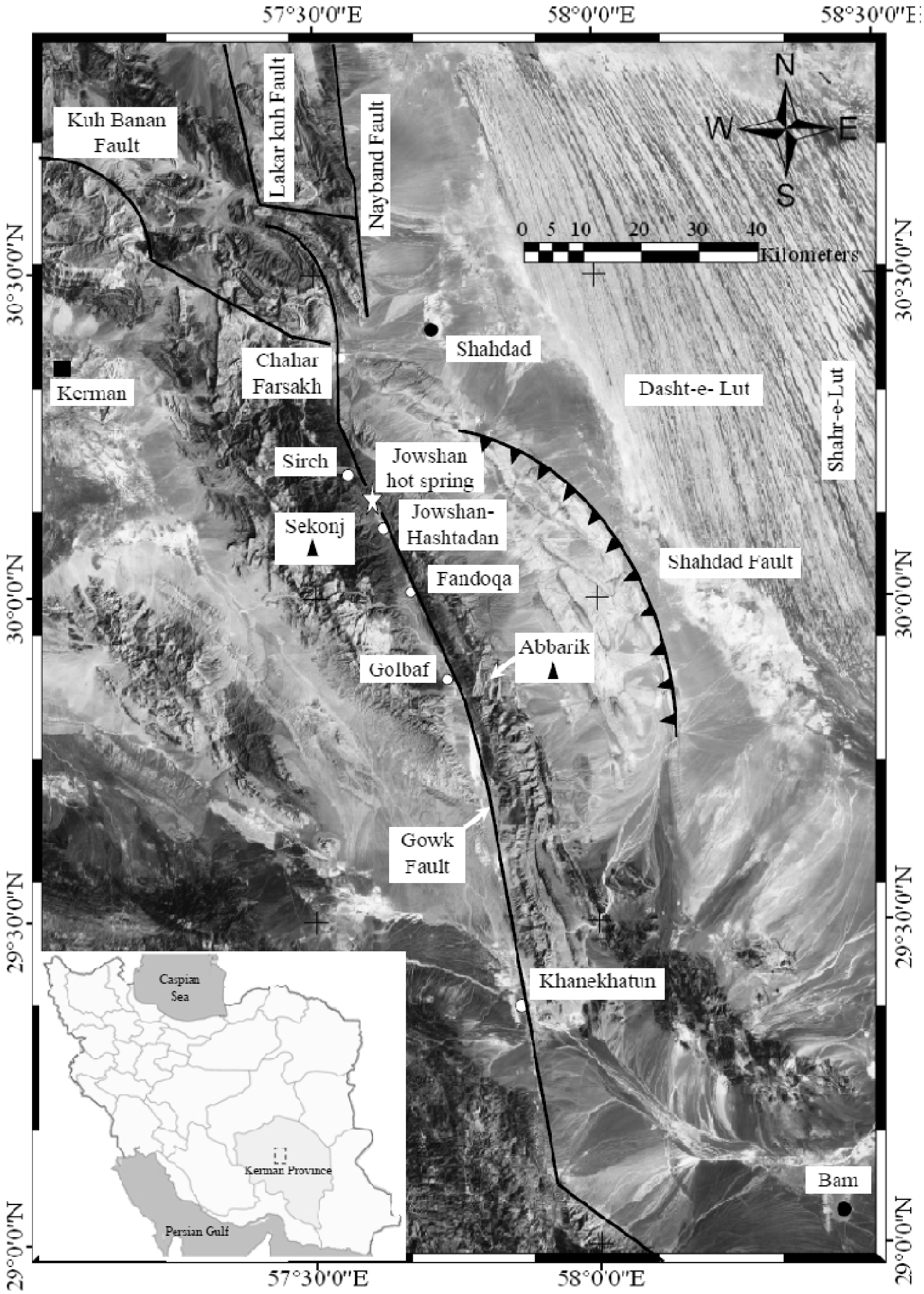

Fig. 1. LANDSAT TM images of the Gowk fault zone: Summary map of the faulting and topography in the Gowk Fault zone, from its junction with the southern tip of the Nayband Fault in the North to the West of Bam Plain in the South. Jowshan hot springs position is indicated by the white star.

correlated to seismicity in order to be used for earthquake prediction. Advection of carrier gases, such as CO_2 and CH_4, may be the main migration process for transport of Rn toward the Earth's surface (e.g., Yang *et al*., 2006). In contrast to gas advection, transport mechanisms of endogenous gases by gas diffusion or by water advection (unless under rare conditions of high-velocity resurgent water) are usually far too slow to cause the observed geochemical anomalies. Bubble movement through micro-fractured rocks (fractured aperture of 0.01 to 10 mm at depths of thousands of meters) appears to be an effective mode of rapid (gas velocities of the order of 10 to 1000 m per day) and long-distance gas migration. The evolution from bubble regimes to continuous phase flow and vice versa is due to gas pressure and fracture width changes, which provide the most suitable for explaining surface geochemical anomalies linked to seismo-tectonic processes (Etiope and Martinelli, 2002).

^{222}Rn is a radioactive, colorless and odorless gas which°is produced by natural decay chain of ^{238}U. Half life of this isotope is about 3.8 days and products ^{218}Po by alpha (α) emitting. Diversity of measurement techniques, as well as inexpensive monitoring, favors ^{222}Rn as a geochemical precursor of earthquakes (Toutain and Baubron, 1999). Activities of ^{222}Rn have been mostly measured with the passive detector by particle track-etching method (counting of alpha-tracks with films). More accurate methods now use either ionization chambers, scintillation methods or autonomous radon sensors that allow continuous monitoring. These latter techniques allow high-frequency sampling (down to minute sampling) and therefore detection of short-duration spikes (e.g., Chyi *et al*., 2010, 2011).

The first observed variation of ^{222}Rn concentration in groundwater before an earthquake was reported by Ulomov and Mavashev (1967), who documented the Tashkent, earthquake. At present, relatively dense networks for continuous monitoring of ^{222}Rn were set up; mainly in China, United States of America, Japan and countries of the former Union of Soviet Socialist Republics (Toutain and Baubron, 1999); which make possible the multiple detection at various sites of single earthquakes. Based on long-term variation patterns, anomalous changes related to earthquakes can be distinguished from background fluctuation.

This paper presents results of continuous ^{222}Rn monitoring and measurement of some other hydro-geochemical parameters (T, EC and major cations and anions of water include of: Ca^{2+}, Mg^{2+}, K^+, Na^+, HCO_3^-, SO_4^{2-} and Cl^-) in the Jowshan complex hot springs (30°09′38.7″ N-57°35′57.5″ E) from 3 December, 2007 to 24 July, 2008. This complex is located 50 km SE of Kerman, SE of Iran, on the Gowk active fault (Fig. 1) and including of six permanent hot spring fountains (>40°C). Three of them are major and mass flow discharged is estimated about 15 liter s^{-1}. One of these major fountains was chosen for continuous monitoring in this study, since they exhibit similar geochemical characteristics, including ^{222}Rn content and chemical composition. Travertine layers in the valley adjacent to springs are the major characteristics in this area; however, no gas emission can be observed.

The Gowk Fault, as a part of the Nayband fault system, being about 160 km long, stretches from the west of Shahdad town to SW of Bam Plain in the NW-SE direction. At least twelve historical earthquakes ($M > 5$ Richter scale) occurred along the Gowk Fault, indicating it is a highly active fault. These twelve events include: November 1854 Tigur ($M_s = 5.8$), 1877 Sirch ($M_s = 5.6$), 1909 Jowshan ($M_s = 5.5$), 1909 Jowshan ($M_s = 5$), 1911 Feiz-Abad ($M_s = 6.4$), 1948 Gowk ($M_s = 6$), 1969 Sirch ($M_s = 5.2$), 11 June 1981 Golbaf ($M_s = 6.7$), 28 July 1981 Sirch ($M_s = 7.1$), 20 November 1989 Golbaf ($M_s = 5.5$), 14 March 1998 Fandoqa ($M_s = 6.9$) and 18 November 1998 Chahar-Farsakh ($M_s = 5.1$) (Berberian *et al*., 2001). The occurrences of Chahar-Farsakh, Jowshan-Hashtadan, Fandoqa, Golbaf and South Golbaf tectonic depressions along the Gowk Fault (Fig. 1), also imply the activity of this fault (Berberian *et al*., 2001). These depressions seem to be pull-apart basins between the segments of this fault (Walker and Jackson, 2002). Gowk is the old name for the modern town of Golbaf, which has taken its name ("Gol" = *lit*. flower) from the carpet-weaving and design motif for which the region is famous.

GEOLOGICAL SETTING

The East Kerman Ranges (Sekonj Mountains and Abbarik Mountains) are cut by the Gowk Fault (Fig. 1). The Sekonj Mountains, west of the Gowk Fault, are formed of gently folded Mesozoic and Tertiary flysch sediments with a continuous sedimentary sequence from the Senonian into Paleocene flysch deposition with no evidence of volcanic activity. The oldest exposed rocks in the region are Jurassic siltstones and sandstones cropping out west of the fault. The Abbarik Mountains, east of the Gowk Fault, are mostly tightly folded and faulted Cretaceous sediments and Eocene volcanic rocks with the Cretaceous rocks thrusting eastwards over the Eocene pyroclastic deposits of a Palaeogene magmatic arc-assemblage. The Late Cretaceous–Paleocene flysch deposits observed at the west of the Gowk Fault are not found on its eastern side (Berberian *et al*., 2001). The Dasht-e-Lut desert (Fig. 1) is a low area of ~400 × 200 km^2 that has been an apparently stable block throughout most of the Tertiary time, with a substratum of flat-lying Paleocene andesitic lavas and tuffs. In the west of this desert the prevailing winds and episodic floods have carved the Neogene silts into the famous Shahr-e-Lut (*lit*.

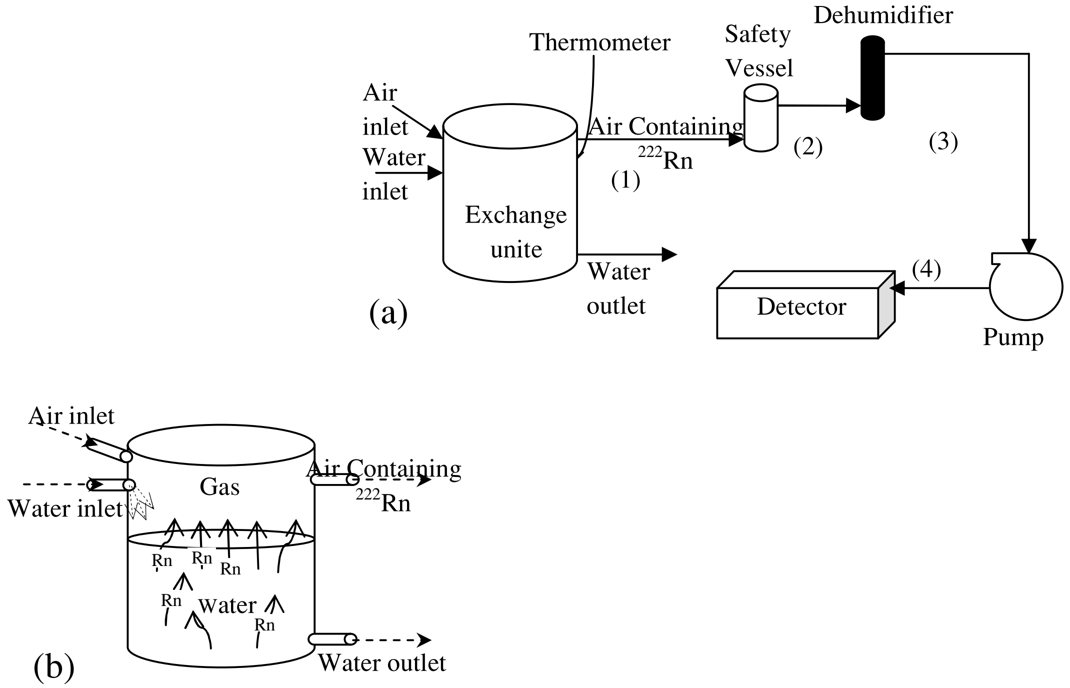

Fig. 2. Schematic setup of the ^{222}Rn measurement system (a); and radon gas exchanger system (b).

"the city of Lut") yardangs, which are ridges and mesas of salt-cemented silt up to 200 m high. On its western side it is bounded by the Nayband Fault and by the marginal Neogene fold-and-thrust belt, which is developed in late orogenic continental molasse deposits that may be up to 3000 m thick and are composed of well-stratified marls containing gypsum, sandstones and conglomerates. These deposits are onlap the Mesozoic and early Tertiary rocks of the Abbarik Mountains east of the Gowk valley. Jowshan hot springs, where we study, are located in a fractured Jurassic Limestone unit.

METHODOLOGY

In this study, for the measurement of ^{222}Rn concentration in water, we used an Alpha GUARD PQ2000 PRO (Genitron Instruments) detector. The instrument has a resolution of 1 Bq m^{-3} and can determine ^{222}Rn concentrations from 2 to 2,000,000 Bq m^{-3}. Alpha GUARD performed for detection of alpha particles in the ionization chamber. The setup of the system is shown in Fig. 2. The Jowshan hot springs are used for hydrotherapy and recreational purposes; hence, set-up of the measuring system at the spring's outlet is not possible. Therefore, we transmitted spring water to the measuring system by polyethylene pipe-line in this study. The spring water enters to an exchange unit and the dissolved ^{222}Rn is exsolved therein by diffusion (Fig. 2b). Since ^{222}Rn measurements varied by water discharges and water flows to the system by gradient in this study, the exchange unit is also used as a flow stabilizer. Furthermore, a thermometer (HOBO Data Logger Company, ONSET Computer Corporation) that measures the air and water temperature every 10 minutes, was set in this unit. Radon gas that leaves water was pumped into the detector and analyzed every 10 minutes while the measurements. Dehumidifying agents ($CaCl_2$) and a safety vessel are used before gas admitted into the detector chamber. An exit path, at the bottom of the unit, helps to establish steady flow of water from spring to the detection system (2 liter m^{-1}).

RESULTS AND DISCUSSION

Figure 3 shows the time series variations of the concentration of ^{222}Rn in the Jowshan spring water. The average ^{222}Rn concentration in this monitoring period (3 December, 2007 to 24 July, 2008) is 42.5 kBq m^{-3} with a standard deviation (σ) of 25.7 kBq m^{-3}.

For correlation of radon variations with seismic events, the main specific characteristics of earthquakes which occurred during radon monitoring in the radius ≤250 km from Jowshan spring are listed in Table 1. Radon concentrations greater than average + 2σ are considered as ^{222}Rn anomalies in this study. According to empirical Dobrovolsky formula and stress-strain theory (Dobrovolsky *et al.*, 1979), strain distribution radii (D), depends on earthquake magnitude (M_L): $D = 10\exp 0.43M_L$. Therefore, earthquake related anomaly can

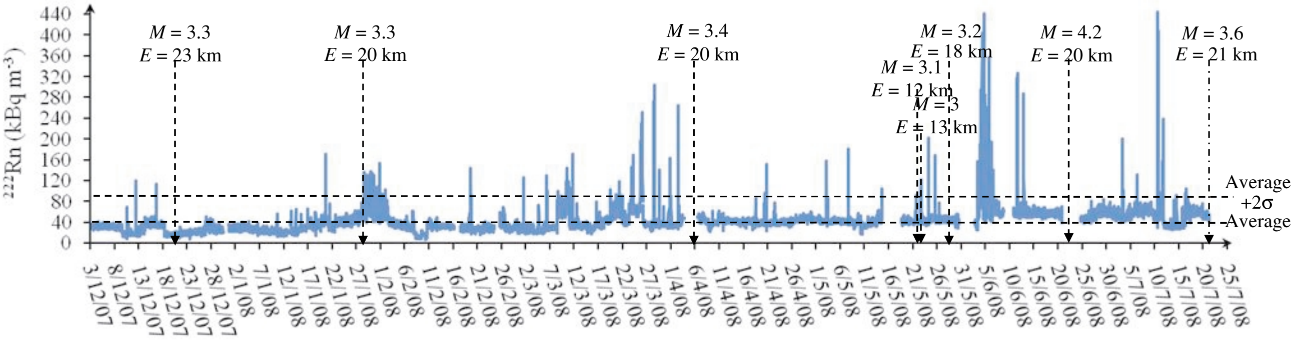

Fig. 3. Time series variations of radon concentration (Average = 42.52 kBq m^{-3}, Standard deviation = 25.69, Average + 2 standard deviation = 93.90, Average – 2 standard deviation = –8.85).

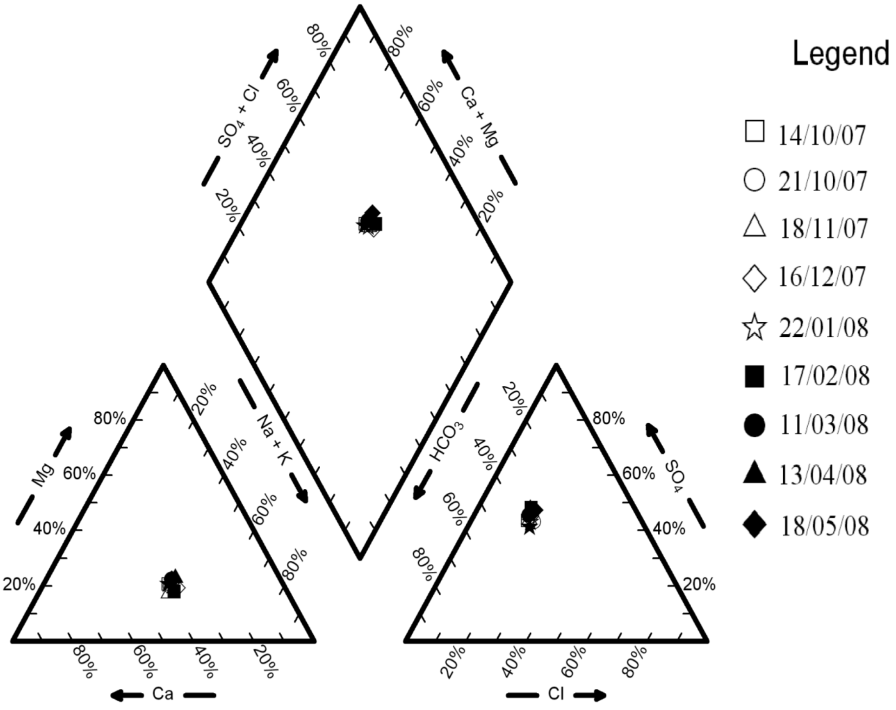

Fig. 4. A piper diagram demonstrates chemistry characteristics of Jowshan spring water.

indicate whether precursor monitoring station lies in the stress-strain field. During continuous radon monitoring of Jowshan hot spring (December 2007 to July 2008), eight earthquakes recorded by regional seismological stations which monitoring site lie within the stress-strain fields. These earthquakes have been specified with bold and underlined font in Table 1. Figure 3 reveals good correlation of these earthquakes with ^{222}Rn anomalies. Jowshan hot spring locates near the conjunction of Gowk, Nayband and Lakar-kuh Faults, which are the most seismic faults in this area. It makes the Jowshan spring water for radon concentration variation is sensitive to the seismic activity, even for distant earthquakes (Table 1).

Occurrence of several micro seismic events in the study region within 28 January to 2 February, and 3 June to 6 June (Table 1) may induce the ^{222}Rn anomalies lasting for few days (Fig. 3). As shown in Table 1 and Fig. 3, the time from the onset of a ^{222}Rn anomaly to the time of the earthquake occurrence (the precursor time) decreases with distance between the epicenter and monitoring station but increases with magnitude. Accordingly, ^{222}Rn anomaly appeared four days before 20 December, 2007

Table 1. Catalog of earthquakes occurred in the region of study

No.	Date dd/mm/yy	Time (local)	Lat. °N	Long. °E	Mag.	*E*	*D*	Precursor time (day)	Anomaly date	Ref.
1	05/12/07	08:15:02	30.55	56.68	3.1	95	21.5			IIEES
2	06/12/07	00:32:04	30.10	56.29	3.6	172	35.3			IIEES
3	07/12/07	07:44:37	30.66	56.819	3	85	19.5			ISC
4	09/12/07	18:47:14	30.593	57.222	2.6	57	13.1			ISC
5	09/12/07	03:13:10	28.57	57.09	2.9	192	17.7			IIEES
6	11/12/07	14:33:35	29.02	56.96	2.8	138	16			IIEES
7	13/12/07	04:35:05	29.93	57.49	2.9	22	17.7	1	12/12/07	IIEES
8	14/12/07	02:15:06	30.419	57.302	2.6	36	13.1			ISC
9	18/12/07	19:12:54	30.784	57.482	2.9	71	17.7			ISC
10	**20/12/07**	**05:23:24**	**30.33**	**57.46**	**3.3**	**23**	**26.2**	**4**	**16/12/07**	**IIEES**
11	22/12/07	13:34:39	28.68	58.10	3.6	171	35.3			IIEES
12	25/12/07	12:21:59	29.972	55.962	2.6	159	13.1			ISC
13	25/12/07	19:04:52	29.16	58.09	4	124	52.5			IIEES
14	25/12/07	20:43:12	31.142	56.763	2.8	141	16			ISC
15	25/12/07	20:53:25	31.235	56.737	2.8	141	16			ISC
16	26/12/07	16:52:58	30.898	56.723	3.1	107	21.5			ISC
17	27/12/07	03:35:21	28.44	56.93	3.8	181	43			IIEES
18	27/12/07	12:51:51	31.30	56.46	3.7	172	39			IIEES
19	30/12/07	11:20:36	29.09	28.08	2.6	127	13.1			IIEES
20	31/12/07	08:34:50	30.47	57.12	3.2	50	23.8			IIEES
21	01/01/08	03:57:43	29.09	58.10	3.1	127	21.5			IIEES
22	04/01/08	00:17:21	28.47	56.97	2.9	193	17.7			IIEES
23	05/01/08	04:31:10	30.84	56.69	2.8	116	16			IIEES
24	07/01/08	03:53:34	27.91	56.75	3.5	247	32			IIEES
25	07/01/08	16:05:03	30.937	56.767	3.3	113	26.2			ISC
26	09/01/08	19:32:40	28.40	56.72	2.8	198	16			IIEES
27	09/01/08	00:29:41	30.764	57.463	2.7	70	14.5			ISC
28	11/01/08	23:45:10	31.826	56.939	3	202	19.5			ISC
29	12/01/08	12:27:53	31.138	57.293	2.7	108	14.5			ISC
30	13/01/08	15:23:02	29.841	56.226	2.9	134	17.7			ISC
31	13/01/08	22:25:31	30.835	56.680	2.7	99	14.5			ISC
32	15/01/08	12:03:50	30.017	55.983	2.8	158	16			ISC
33	18/01/08	04:05:28	27.93	57.70	3	243	19.5			IIEES
34	18/01/08	05:59:40	31.099	56.934	2.6	112	13.1			ISC
35	20/01/08	09:51:11	28.41	56.89	3.7	197	39			IIEES
36	20/01/08	20:07:12	31.261	57.234	2.8	121	16			ISC
37	23/01/08	05:57:23	30.824	56.736	2.6	125	13.1			ISC
38	26/01/08	03:52:30	30.65	56.89	2.7	89	14.5			IIEES
39	27/01/08	20:30:25	29.27	56.44	3	146	19.5			IIEES
40	**28/01/08**	**20:08:55**	**30.164**	**57.748**	**3.3**	**20**	**26.2**	**8**	**20/01/08**	**ISC**
41	29/01/08	08:03:38	30.82	57.38	3.7	68	39	1	28/01/08	IIEES
42	31/01/08	17:41:33	28.50	56.81	3.5	200	32	1.5	29/01/08	IIEES
43	02/02/08	13:26:19	31.670	56.088	3.1	245	21.5	2.2	30/01/08	ISC
44	03/02/08	15:18:29	28.35	57.09	3	199	19.5	2	01/02/08	IIEES
45	04/02/08	08:55:29	28.44	56.83	3.4	196	29	2	02/02/08	IIEES
46	04/02/08	23:39:17	30.412	57.482	2.7	36	14.5	2.1	02/02/08	ISC
47	05/02/08	05:20:43	30.315	56.105	3	125	19.5			ISC
48	08/02/08	17:35:22	30.274	56.790	2.8	65	16			ISC
49	13/02/08	06:15:00	28.667	56.480	2.6	170	13.1			ISC
50	14/02/08	09:22:14	29.27	56.49	2.9	145	17.7			IIEES
51	15/02/08	00:15:44	28.05	57.48	3.5	235	32			IIEES
52	15/02/08	01:05:07	28.04	57.47	29	235	17.7			IIEES
53	20/02/08	22:13:28	31.736	55.940	3.3	150	26.2	1	19/02/08	ISC
54	27/02/08	05:28:24	30.77	56.92	3.7	90	39			IIEES
55	28/02/08	21:21:12	30.760	56.525	3	98	19.5			ISC
56	01/03/08	12:05:56	29.976	56.086	2.6	152	13.1	0.5	01/03/08	ISC
57	09/03/08	05:57:27	32.01	55.79	3.8	250	43	2.3	06/03/08	IIEES
58	10/03/08	12:09:25	30.105	55.914	2.8	157	16	1	09/03/08	ISC
59	11/03/08	17:33:47	27.85	57.23	3.5	245	32	1	10/03/08	IIEES
60	13/03/08	19:08:33	30.522	57.305	2.7	43	14.5	2	11/03/08	ISC

Table 1. (continued)

No.	Date dd/mm/yy	Time (local)	Lat. °N	Long. °E	Mag.	*E*	*D*	Precursor time (day)	Anomaly date	Ref.
61	21/03/08	05:09:33	30.801	56.620	3.1	95	21.5	2	19/03/08	ISC
62	22/03/08	04:31:01	28.45	57.02	4.1	193	57.9	1.4	21/03/08	IIEES
63	23/03/08	11:21:53	28.12	56.64	3.5	249	32	0.8	23/03/08	IIEES
64	27/03/08	23:47:55	29.55	57.72	2.8	70	16	1	26/03/08	IIEES
65	27/03/08	23:51:55	29.55	57.74	3.2	70	23.8	2	25/03/08	IIEES
66	28/03/08	22:34:58	28.85	56.71	4.3	185	70.7	1.3	28/03/08	IIEES
67	31/03/08	17:05:10	27.92	57.26	4.7	242	104.9	0.7	31/03/08	IIEES
68	03/04/08	19:42:27	30.851	56.738	2.7	95	14.5			ISC
69	04/04/08	04:43:17	30.68	57.36	3.3	51	26.2	2.1	02/04/08	IIEES
70	**05/04/08**	**16:58:10**	**31.607**	**56.154**	**3.4**	**20**	**29**	**8**	**28/03/08**	**ISC**
71	10/04/08	18:51:29	30.518	57.854	2.7	41	14.5			ISC
72	11/04/08	10:13:16	29.17	56.58	3	150	19.5			IIEES
73	11/04/08	00:07:42	28.44	56.85	3	199	19.5			IIEES
74	13/04/08	17:10:05	27.97	57.70	3.7	240	39			IIEES
75	13/04/08	03:49:35	29.776	57.910	3	57	19.5			ISC
76	14/04/08	10:08:01	29.01	58.03	2.7	135	14.5			IIEES
77	16/04/08	16:16:24	28.45	56.69	3.7	199	39			IIEES
78	18/04/08	15:44:10	32.067	57.795	3	220	19.5			ISC
79	20/04/08	06:25:33	28.27	57.53	3	215	19.5	0.6	20/04/08	IIEES
80	21/04/08	17:22:52	29.01	56.74	3	147	19.5	1	20/04/08	IIEES
81	23/04/08	01:58:12	28.30	57.13	3.7	216	39			IIEES
82	27/04/08	07:56:58	30.573	57.486	2.8	42	16			ISC
83	30/04/08	07:00:49	30.872	56.709	2.6	95	13.1			ISC
84	04/05/08	12:46:36	29.94	57.41	3.2	37	23.8	1.5	03/05/08	IIEES
85	04/05/08	19:41:09	30.084	57.683	2.8	17	16	1.4	03/05/08	ISC
86	07/05/08	00:20:49	28.19	57.61	5	228	141.2	Co	07/05/08	IIEES
87	08/05/08	18:54:31	28.17	57.65	3.3	228	26.2			IIEES
88	10/05/08	13:54:04	30.917	56.850	2.7	75	14.5			ISC
89	16/05/08	16:54:04	30.783	57.150	3	70	19.5			ISC
90	**21/05/08**	**05:29:49**	**30.20**	**57.64**	**3.1**	**12**	**21.5**	**7.2**	**15/05/08**	**IIEES**
91	**21/05/08**	**07:52:25**	**30.12**	**57.49**	**3**	**13**	**19.5**	**7**	**15/05/08**	**IIEES**
92	23/05/08	01:39:47	28.23	56.66	3.9	240	47.5		21/05/08	IIEES
93	24/05/08	09:51:36	29.21	58.36	3.2	122	23.8		22/05/08	IIEES
94	**27/05/08**	**09:00:00**	**30.029**	**57.655**	**3.2**	**18**	**23.8**	**4.5**	**24/05/08**	**ISC**
95	27/05/08	21:37:21	30.50	57.07	4	66	52.5	2.6	25/06/08	IIEES
96	01/06/08	17:05:43	31.878	55.744	2.9	150	17.7			ISC
97	04/06/08	05:08:42	30.30	57.39	3.9	75	47.5	1.8	03/06/08	IIEES
98	05/06/08	07:05:33	30.575	57.199	3.3	50	26.2	1	04/06/08	ISC
99	05/06/08	13:09:56	30.58	57.05	3.6	70	35.3	1	04/06/08	IIEES
100	07/06/08	06:33:37	29.03	57.11	2.6	139	13.1	0.7	06/06/08	IIEES
101	07/06/08	10:32:02	30.778	56.716	3.3	85	26.2	2	05/06/08	ISC
102	07/06/08	03:18:39	31.065	56.784	2.9	140	17.7	1	06/06/08	ISC
103	15/06/08	00:45:46	28.30	57.35	3.1	185	21.5			IIEES
104	15/06/08	02:33:34	30.72	56.37	2.8	132	16			IIEES
105	18/06/08	22:43:42	29.21	58.32	3.4	120	29		13/06/08	IIEES
106	**21/06/08**	**20:51:18**	**30.28**	**57.55**	**4.2**	**20**	**64**	**10**	**11/06/08**	**IIEES**
107	23/06/08	11:44:52	29.25	58.25	4	131	52.5			IIEES
108	26/06/08	15:46:03	29.16	56.61	2.9	133	17.7			IIEES
109	27/06/08	19:26:52	28.70	57.97	3.2	173	23.8			IIEES
110	27/06/08	21:21:36	28.32	56.94	4.4	220	78			IIEES
111	01/07/08	11:13:06	28.13	57.01	3.4	232	29			IIEES
112	05/07/08	09:33:47	30.812	57.294	2.8	55	16	2	03/07/08	ISC
113	07/07/08	05:56:01	28.09	56.36	3	250	19.5	0.9	06/07/08	IIEES
114	08/07/08	12:15:27	30.050	55.870	2.7	152	14.5			ISC
115	09/07/08	12:39:47	29.982	56.051	2.5	150	11.9			ISC
116	10/07/08	00:26:57	31.358	56.271	2.7	152	14.5			ISC
117	14/07/08	01:11:36	30.47	56.43	3.2	100	23.8			IIEES
118	19/07/08	08:38:56	30.497	57.425	2.7	38	14.5	7	11/07/08	ISC
119	**20/07/08**	**22:03:19**	**30.06**	**57.48**	**3.6**	**21**	**35.3**	**9**	**10/07/08**	**IIEES**

E: distance of earthquake epicenter to the Jowshan hot spring (km), D: strain distribution radii (=10exp0.43M_L) and Co stand for co-seismic event.

Seismological data extracted from www.iiees.ac.ir and www. irsc.ut.ac.ir

Events which Jowshan spring was lie within the stress-strain field of earthquakes are shown bolded and underlined.

Table 2. Results of Jowshan spring water temperature, electrical conductivity and pH measurements in the ^{222}Rn monitoring time-window (3/12/07–24/07/08)

	T (°C)	EC (μmho cm^{-1})	pH
Range	38–40	1370–1530	7.1–7.4
Average	39.19	1475.75	7.3
Standard deviation	0.39	55.67	0.09

earthquake (M = 3.3) which its epicentral distance to Jowshan spring was about 23 km (Table 1), while the precursor time for 28 January, 2008 earthquake (M = 3.3) with 20 km epicentral distance is eight days (Table 1). Also, for 21 June, 2008 earthquake (M = 4.2) which was happened in the 20 km distance to the radon monitoring station (equal to 20 December, 2007 earthquake), anomaly onset ten days before seismic event. Toutain and Baubron (1999) have indicated the dependency of earthquake magnitude and epicentral distance on duration, precursory time interval and amplitude of a radon anomaly; however, comprehensive criteria for the appearance of earthquake-related ^{222}Rn anomalies is not able to offer before the relationship between earthquake and anomaly generating can be well understood.

Temperature, electrical conductivity and pH of Jowshan spring water were also measured semi-weekly in the time-window of ^{222}Rn monitoring (3 December, 2007 to 24 July, 2008). Range, average and standard deviation (σ) of these parameters are presented in Table 2. In addition, samples of water were analyzed monthly for major components; such as Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, SO_4^{2-}, HCO_3^- ions as possible precursors. The results are presented in Table 3. Deep spring water temperatures can be estimated by [Na/K] and [Na–K–Ca] geothermometery (Table 3) following bellow equations (Fournier, 1981).

For T_{deep} (Na/K):

$$T = \left(\frac{1217}{1.483 + \log[\text{Na}/\text{K}]}\right) - 273.15$$

and T_{deep} (Na–K–Ca):

$$T = \left(\frac{1647}{2.47 + \log[\text{Na}/\text{K}] + \beta\left[\log\left(\sqrt{\text{Ca}}/\text{Na}\right) + 2.06\right]}\right) - 273.15$$

$\beta = 4/3$ if $T > 100$°C and $\beta = 1/3$ if $[\log(\sqrt{\text{Ca}}/\text{Na}) + 2.06] < 0$.

Deep Jowshan spring water temperature varied between 68 to 79°C and 189 to 212°C based on the [Na–K–Ca] and [Na/K] geothermometery, respectively. According-

Table 3. Results of chemical analyses of Jowshan spring water samples

Sampling date (dd/mm/yy)	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	TDS	pH	EC	T	T_{deep}(Na–K)	T_{deep}(Na–K–Ca)
14/10/07	130	42.5	154.1	11.7	390.4	355	113.6	999.1	6.8	1537	40	194	69
21/10/07	134	42.6	165.6	15.6	396.5	374	134.9	1019.9	7	1569	40	189	68
18/11/07	140	36.5	165.6	15.6	396.5	370	120.7	1020.5	7.1	1570	40	212	76
16/12/07	130	42.5	179.4	15.6	396.5	394	124.3	1004.3	6.9	1545	38	205	78
22/01/08	130	42.5	165.6	11.7	396.5	360	124.3	994.5	6.8	1530	38	189	69
17/02/08	136	38.9	179.4	11.7	378.2	418	113.6	1030.3	7	1585	39	183	69
11/03/08	124	46.2	156.4	11.7	378.2	374	110.1	998.4	7.1	1536	39	193	69
13/04/08	122	48.6	165.6	11.7	372.1	403	110.1	1030.3	7.1	1585	39.5	189	70
18/05/08	130	48.6	165.6	11.7	366	408	124.3	1033.5	6.9	1590	39.5	189	69
15/06/08	130	42.5	154.1	11.7	396.5	336	124.3	994.5	6.9	1530	40	194	68
Average	130.6	43.14	165.14	12.87	386.74	379.2	120.02	1012.53	6.96	1557.7	39.3	194	70
σ	5.25	3.84	8.99	1.88	11.92	25.99	7.99	15.94	0.12	24.51	0.78	9	4
Average + 2σ	141.18	50.83	183.13	16.64	410.59	431.18	136	1044.41	7.19	1606.7	40.9	211	78

Ionic concentration unit: mg l^{-1}, EC unit: μmho cm^{-1}, T: Jowshan spring water temperature (°C), T_{deep}(Na–K) and T_{deep}(Na–K–Ca): spring water deep temperature estimated by [Na/K] and [Na–K–Ca] according to Fournier (1981) formula (°C), σ: standard deviation.

ing to [Na–K–Ca] geothermometery, the estimated deep water temperature has been increased in 16 December, 2007 (Table 3) which is consistent with time of observed radon anomaly (Table 1). Increasing of deep water temperature before earthquakes may be ascribable by stress-strain accumulation. Nevertheless, none of any other spring water samples analysis match with ^{222}Rn anomaly during this monitoring time period, variation of estimated deep water temperature cannot be proved as an earthquake precursor yet, and more data is necessary.

The results of spring water chemistry shown in the piper diagram indicate that Jowshan spring water is belonging to the $Na–SO_4$ type hot spring (Fig. 4). Furthermore, the results show that no mixing event has been taken place during monitoring period. Therefore, we can conclude that the ^{222}Rn concentration variations were not affected by mixing process.

It is well known that variations of radon concentration in water may occur as a result of water temperature variation and rainfall in addition to the earthquake activity in one area. In this arid region, however, only 40 mm rainfall occurred during the measuring time interval. Thus, the influence of rainfall on ^{222}Rn concentrations can be ignored in this study. ^{222}Rn activity usually increases with water temperature, but its solubility decreases with increasing temperature (Toutain and Baubron, 1999). In the time-window of 3 December, 2007 to 24 July, 2008, results of continuous spring water temperature measuring did not shows any significant changes and it is not able to be used for correlation with ^{222}Rn variations and seismic events.

CONCLUSIONS

In this study, ^{222}Rn anomalies of spring water were observed, before 47 earthquakes from 119 events, especially in cases which monitoring site is within the seismic stress-strain field. Jowshan hot spring is considered to be sensitive to the earthquake activity due to its location near the conjunction of Gowk, Nayband and Lakarkuh Faults. Furthermore, precursor time is negatively correlated with the distance between the epicenters and monitoring station, but positively correlated with the magnitude of observed earthquakes. Nevertheless, continuous monitoring of ^{222}Rn level is necessary to confirm this conclusion. Temperature, electrical conductivity and pH measurements do not show any correlation between seismic activity and radon variations in the period of monitoring. Monthly spring water samples analyzing demonstrate no ground-water mixing has been taken place during radon monitoring. While deep temperature estimation based on the [Na–K–Ca] geothermometery showed coinciding of temperature increasing with radon anomaly in one case, more data and short time interval spring water analyzing is required to confirm deep estimation temperature as an earthquake precursor.

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