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Report on correlation between radon outgassing and aftershocks activity along the Bam Fault in Kerman province of Iran

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ABSTRACT

After the Earthquake in Bam in December 26, 2003, a team was dispatched to this area to monitor the relationship between Variation in the Radon (^{222}Rn) concentration and the magnitude of aftershocks. Meteorological parameters such as air pressure, temperature and humidity were measured. Radon concentration at depth of 90 cm of soil was also measured using AlphaGuard (Model 2000PRO) in 10 minutes periods. The measurement site was near the fault location and the radon concentration was systemically measured for a period of three months. A correlation between radon concentration and the available aftershocks data is discussed. More than 150 small to moderate aftershocks with a magnitude ranging from M=2.1 to 6.5 in scale of Richter occurred in the region during the period of this study at the various distances (below 20 km of epicenter) from the radon monitoring sites. When the magnitude of aftershocks increased, variations of radon concentration could be observed more clearly.

Keywords: Radon; earthquake prediction; Bam; meteorological parameters; AlphaGurad.

1. INTRODUCTION

A reliable method for short-term seismic activity prediction is an important geological challenge. Studies of geochemical and hydrological anomalies preceding significant earthquakes have been reported from China, Japan, Uzbekistan, Mexico, Italy, India, Russia, Armenia, Romania and Germany. A number of authors [1-8] make this kind of predictions on the basis of soil-gas information, mainly the radioactive radon gas (^{222}Rn) data. Thus, an enhanced seismic activity responsible for changes in the convective velocity may account for anomalous temporal variations of the radon concentration and that of other gas species in the subsurface soil air [7-9]. Although radon gas monitoring alone has not yet been reliable in predicting tectonic disturbances precisely, in many cases time variation of radon concentration in soil or groundwater has been considered as an indicator of tectonic disturbances. The variation of the radon concentration usually exhibits correlation between the radon concentration measured in the surface soil and the magnitude of the earthquake and hence, higher reliability for earthquake prediction.

In principle, this is explained by the fact that gas fluxes along active faults or through micro-fractures influence the transport of radon from its origin to the surface [10]. It has been proposed that radon concentration is sensitive to crustal stress/strain variations, and could reveal earthquake preparatory mechanisms [11]. The amplitude of the temporal variations of the soil gas radon concentration depends on the meteorological conditions [12-16], geological features in a given area, and distance from the epicenter of an earthquake [7, 9]. Further studies are needed to differentiate the changes that are due to tectonic disturbances from other causes, and to determine the effect of the meteorological parameters, geological features and distance from the epicenter on the measured radon concentration.

2. MATERIALS AND METHODS

2.1. Theory of the study

The precursory phenomena can be observed within the distance D that is roughly the radius of the effective precursory manifestation zone. Based on experimental evidence, the size of the manifestation zone can be estimated approximately by using the following equation [17, 18]:

$$D = 10^{0.43M} \qquad \text{(Equation 1)}$$

where "M" is the magnitude of the earthquake on the Richter scale, and "D" is the distance, in km. For example, a magnitude 6.5 earthquake in Bam could be detected by means of the precursory phenomena at a distance less than about 623 km from the epicenter. Large changes of the gas emanation occur in the identified area of a forthcoming earthquake and continuous gas monitoring may add further information. After checking of all published data on pre-earthquake radon anomalies, it was recognized that the shape of the peak and the amplitude could be used as a diagnostic parameter for the forthcoming seismic event. The relationship between amplitude and duration of the gaseous anomaly and the magnitude (M) of the expected earthquake is expressed as follows [18]:

$$M = k\sqrt{S} \qquad \text{(Equation 2)}$$

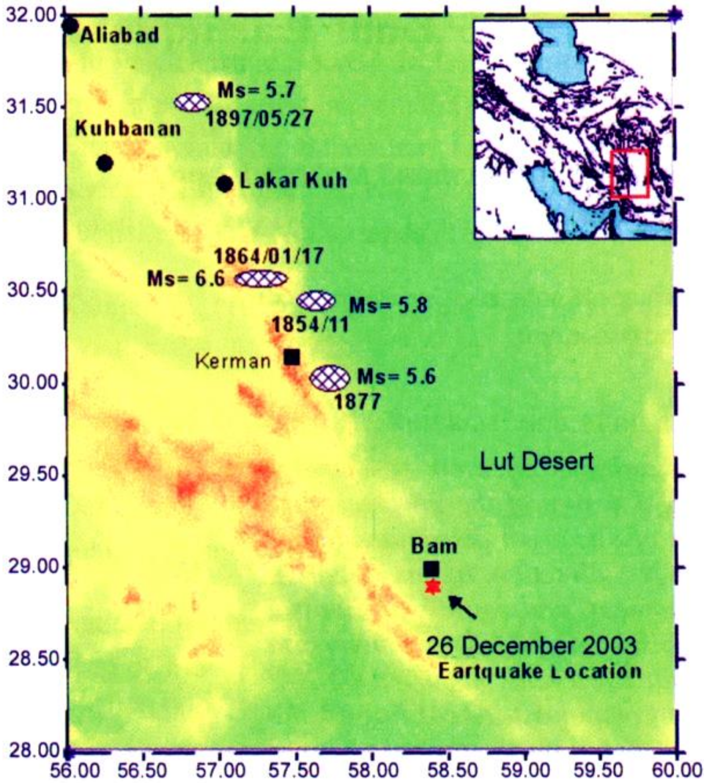
Where "k" is a correction factor and "S" is the area of the detected peak anomaly.

In this study, radon measurements were carried out in the soil of Bam area. The influence of barometric pressure, temperature and humidity were also measured. Therefore, the principle of this article is to investigate the possibility of employing radon monitoring techniques for predicting earthquakes/aftershocks in Iran in order to check whether such technique could be used to provide reliable precursor information about aftershocks activities along the Bam Fault.

2.2. Bam earthquake activity

The December 26, 2003 Earthquake with M_w=6.5, occurred at 01:56:56 GMT, in Southern Iran near the city of Bam, (Figure 1). The earthquake was associated with two fresh surface ruptures 5 km apart trending north-south and 2 km wide zone of hairline fractures developed between the two main ruptures in the north of Bam. The Bam Fault with near north-south direction passes from the vicinity of the city of Bam (less that 1 km distance to the east of Bam), and between the cities of Bam and Baravat. International Institute of Earthquake Engineering and Seismology (IIEES) located the epicenter at 29.02˚N, 58.30˚E with a focal depth of 8 km. The Bam Earthquake occurred in a region where seismic activity is very low based on instrumental and historical earthquake catalogues for the last 2000 years.

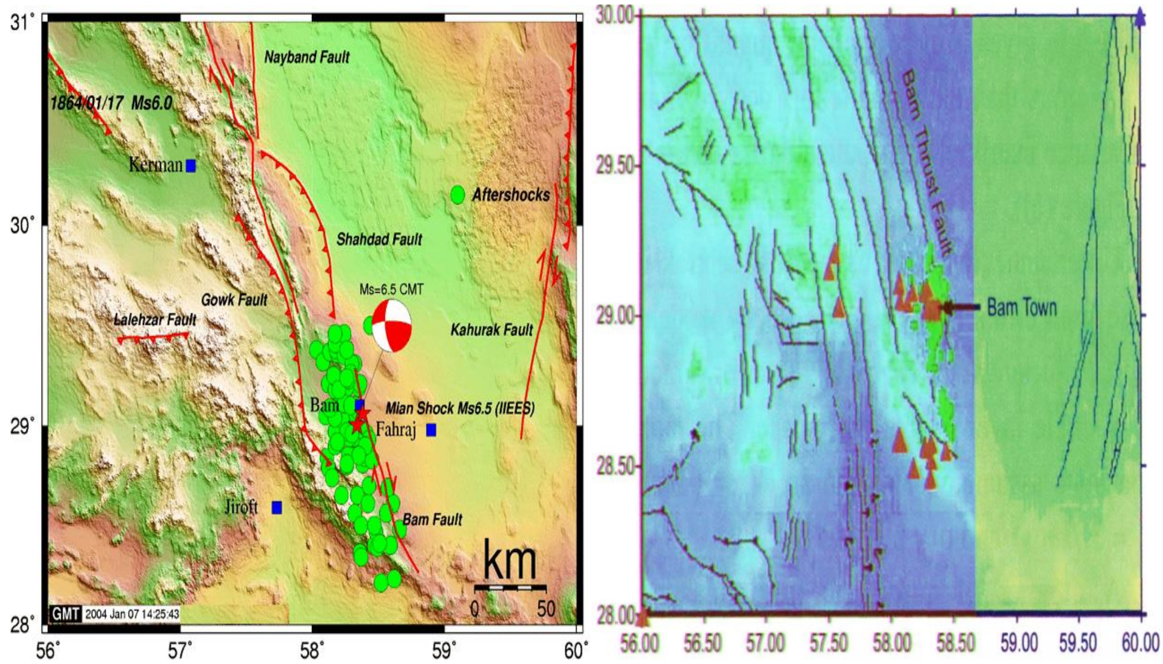
Figure 1: *Location of 26 December 2003 main shock (Asterisk), Bam and Kerman city, villages (block Circle), and historical events.*



2.3. Aftershock sequence

Following the Bam Earthquake, IIEES recorded 158 aftershocks with magnitude between $2.0<M_L<5.1$ during the first month (from Jan 3 to Jan 30, 2003) [19]. For detailed study of the aftershocks, nearly two days after the main event, IIEES deployed local temporary seismic stations in the epicentral area. This network consisted of nineteen medium-band and short period stations with an operating period of more than four months, starting December 28, 2003. Figure 2 shows the distribution of these events over monitoring ^{222}Rn and aftershocks.

Figure 2: *Distribution of temporary local Monitoring radon ( ) measurement and aftershocks ( ).*



2.4. Experimental procedure and monitoring sites

Radon monitoring stations were located at two sites, *29˚, 4p, 11″ N and 58˚, 23p, 37″ E*, precisely on the Bam Fault where there have been high occurrences of seismic activities (Figure 2 in star signs). Both sites were placed exactly along the bam fault which had been occurred after Bam earthquake. The data were not acquired at the same time for both sites, but they were on the same fault to reveal the correlation between soil-gas radon concentration and occurrence of earthquake. The study was carried out using an active method involving an AlphaGuard PQR2000, AlphaPump and relative accessories which is a device capable of accurately measuring radon concentrations every 10 minutes. The radon activity was measured in kBq/m^3. The accessory and sampling rod was pushed by hammer at more than 50 cm in soil. The sampling probe has dimensions of 11×7×3 cm including diffusion chamber with silicon diode, electronic board, screen, sensors for temperature, pressure and humidity which simultaneously records them. The minimum detection radon level is 0.1 kBq/m^3 with 12% uncertainty at 1 sigma after 24 hours. At this level, the susceptibility to outside influences is 3 counts per hour. Air was pumped from ground to the measuring chamber with a flux of 1 L/min. Choosing forced air suction in order to avoid stratification effects, very common for radon, was due to its elevated weight. The radon-monitoring sites are usually chosen in the areas where higher radon concentration in the surface soil layer can be expected.

For this propose, the radon monitoring site was placed exactly on the Bam Fault, which located between Bam and Baravat Cities. The data from radon concentration monitoring were collected in soil at 90 cm depth exposed for a period of 90 days in close proximity to a section of the Bam Fault. Data were collected each 10 minutes during three month using an AlphaGuard connected to a laptop computer. The measurement results were then compared with seismic data recorded by local seismometers to assess the correlation between them. In order to differentiate the changes due to tectonic disturbances and that of the meteorological parameters, the barometric pressure, relative humidity and temperature were also measured.

3. RESULTS AND DISCUSSION

Radon emanation is known to be extremely sensitive to changes in atmospheric conditions. Therefore, some meteorological parameters, such as air temperature, barometric pressure and relative humidity were recorded in this study simultaneously with the radon measurements. A correlation was used to allow the recognition of radon concentrations caused by changes in weather variables from those related to aftershocks.

Time series of radon concentration data were recorded at Bam from December 2003 to March 2004 as they have been shown in Figure 3 along with the fluctuations in the meteorological parameters. The average value of radon concentration was 12.928 kBq/m^3 with a standard deviation of 2.159 kBq/m^3. The radon concentration data were recorded 5 days after the Bam Earthquake.

The first noticeable radon peak was recorded in Jan 1, 2004 (Figure 3a) with radon concentration about 4% above the mean value. The radon anomaly was followed by a seismic event of 2.3 M which occurred in Jan 1, 2004 in the Bam area (Latitude 29.11, Longitude 58.24).

From Jan 2 to mid Jun 3 (not shown completely in the Figure 3a), 2004, no significant anomaly relatable to aftershocks was recorded in soil-gas radon. However, there were some aftershocks with Magnitude 2.3, 2.4, 2.7 and 3.2 M. Also, Table 1 demonstrates some registered peaks in radon concentration above mean value (M.V), aftershocks besides pertinent Latitude and Longitude.

The eleventh peak in soil-gas radon was recorded in Jan 5, 2004 at 11:30 with radon concentration above 35% the mean value and temperature above 42% the mean value (Figure 3a). This recorded anomaly was followed by an aftershock of 2.3 M in Jan 5, 2004 at 11:42 which occurred in Bam area (Latitude 28.74, Longitude 58.15).

There were several correlations between radon anomalies in soil-gas and aftershocks which have been shown in Figure 3a. The results show that aftershocks follow a regular sequence soon after radon anomalies in soil-gas as recorded by the AlphaGuard. However, the patterns are different for radon data. Furthermore, the temperature alterations were between 13 and 25 ^{0}C in Jan 1 to 5.

The relevant fluctuations in temperature are shown in Figure 3b. At the beginning of the experiments, temperature profile showed the largest shifts between 5 and 44 ^{0}C till 13 Feb. After that period, the width of the profile increased and the registered maximum was 41 ^{0}C in 3 Apr. On the other side, the pressure profile was approximately constant amid 890 and 910 mbar till 14 Jan and also between 23 Feb and 14 March. Between 24 Jan up to 3 Feb, when the radon concentration was roughly high, the temperature presented harsh changes and the pressure was minimum about 810 mbar. When the pressure presented the lowest value in 20 Feb, the radon concentration reduced in 21 Feb. Both pressure and radon concentration decreased after 17 Mar till 11 Apr as the temperatures' ranges presented identical alterations. In contrast, the humidity increased up to 60 % rH. The humidity values ranged mostly between 20 and 60 % rH with maximum values between 24 Jan and 3 Feb.

When occurrences of aftershocks were frequent, the radon concentration varied from 4 Jun to 18 Jan 2004. Also, when the radon concentration was normal the occurrences of aftershocks decreased between Jan 18 to Jan 30, 2004. Obviously, additional radon concentration measurements are recommended to achieve a more comprehensive survey.

Figure 3: *Experimental data of (a) radon concentration and seismic events, (b) temperature, (c) pressure and (d) related humidity which was measured after Bam earthquake. [**bq:** radon activity and **ML:** aftershocks magnitude].*

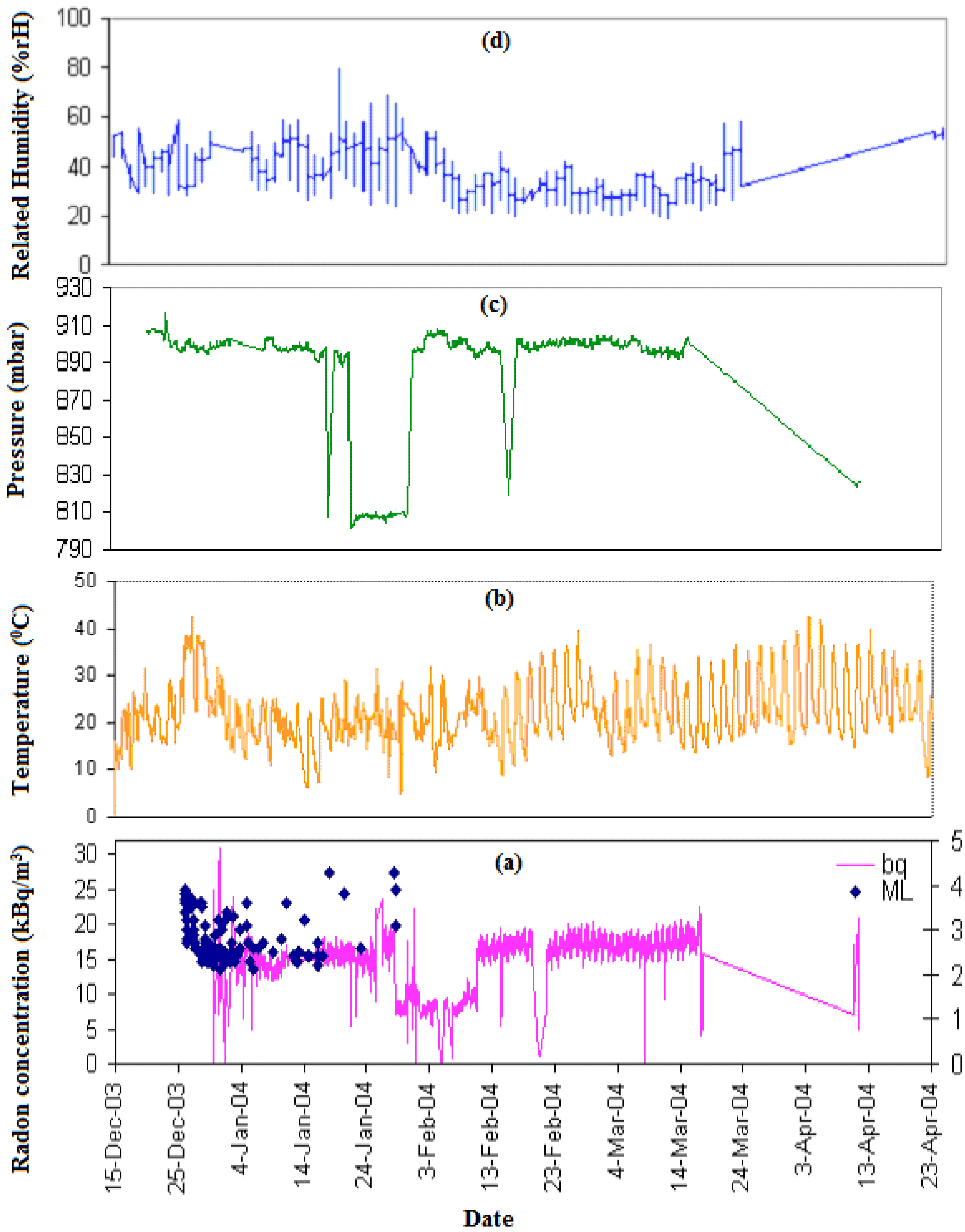


Table 1: Recorded peaks in soil-gas radon over concentration mean values, aftershocks and positions.

Peak number and date in 2004	**Radon concentration above mean value (M.V)**	**Followed with seismic event**	**Geographic position (Latitude and Longitude)**
2; 2 Jan at 9:31	63%	2.5 M at 9:49	29.25; 58.16
3; 2 Jan at 13:30	65%	2.7 M at 13:31	28.90; 58.17
4; 2 Jan at 18:20	71% (T<35% M.V)	3.3 M at 18:21	28.41; 58.51
5; 3 Jan at 13:30	7%	2.5 M at 13:48	29.46; 58.17
6; 3 Jan at 19:50	14%	3 M at 19:51	29.18; 58.20
7; 3 Jan at 22:20	9% (T >35% M.V)	2.6 M at 22:40	28.85; 58.35
8; 4 Jan at 18:10	40%	3.6 M at 18:29	29.96; 58.30
9; 4 Jan at 20:30	36%	3.1 M at 20:43	28.81; 58.26
10; 5 Jan at 6:00	36%	2.7 M at 6:02	29.10; 58.29
11; 5 Jan at 11:30	35% (T >42% M.V)	2.3 M at 11:42	28.74; 58.15

Since temporal variation of the soil-gas activity caused by changes in meteorological conditions plays a key role in this study, a general correlation between variation in radon concentration and the occurrence of small aftershocks was found. Significant peaks in radon concentration were observed within approximately one week before the occurrence of small aftershocks. Then, the concentration values decreased dramatically just prior to and during periods while the aftershocks occurred. Such correlation is very similar to that recently observed in association with a magnitude 5 earthquake along the Bam Fault. The most plausible explanation for the observed correlation is as follows:
1) Prior to a given earthquake, stress build up within a particular fault region leads to the formation of micro-fractures which results in an expansion of radon emissions; 2) During and immediately

following aftershocks, stress release occurs which subsequently results in the closing of micro-fissures; 3) Closure of micro-fractures leads to a subsequent reduction in radon emission; 4) Time-series radon data in soil-gas during a 90 days observation established more than 50% of the radon-concentration growth correlated with aftershock events of 2-4 magnitude on the Richter scale.

This report can presumably predict the next extreme events within the specified time interval about a decade with a probability of 40% over radon concentration, temperature, pressure and humidity. The Arabic plate from southwest of Iran and the Eurasian plate from north are shortening 30 mm per year, causing impact on Iran's area. Such geological phenomenon increases the rate of mountains' growth in Iran because the north-tectonic plate is approximately stable. It may be inevitably deformed in folds and faults towards northeast of Iran besides different earthquakes. Reports on earthquakes in a period of a decade can be used in predicting severe events in the future. Since the experimental data collected along the Bam faults consistently supports the hypothesis of a strong relationship between radon outgassing and seismic activity, further research is necessary to better understanding the nature of this relationship.

4. CONCLUSION

Investigation into radon concentration as a precursor over earthquake can be effectively used in some well-documented sites. However, current knowledge is far from being able to predict the time or location of an earthquake. An additional study with more relevant sampling sites and more frequent soil analyses would be necessary to achieve such exhaustive aim. The necessity for long term observation in order to collect enough data in a rigid interpretation of the data is deeply needed. To predict a future aftershock, all precursory phenomena must be investigated.

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