ISSN 1330–0008
CODEN FIZBE7

SEARCHING FOR AN EARTHQUAKE PRECURSOR: TEMPORAL VARIATIONS OF RADON IN SOIL AND WATER

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Received 20 September 1999; revised manuscript received 31 January 2000
Accepted 3 April 2000

Radon-emanation detectors of an original design, using the LR-115 solid nuclear-track detector films, have been constructed for radon concentration measurements in soil and water. Temporal radon variations, as well as barometric pressure, atmospheric precipitation and temperature were observed during a year. A negative correlation between the radon concentration in soil and barometric pressure was found. For two recorded earthquakes in 1998, the soil radon anomalies were observed, about one month before each quake. It seems that by using the radon-emanation detector, earthquakes can be predicted.

PACS numbers: 87.52.-g UDC 539.164
Keywords: radon in soil gas, nuclear track detector, radon anomaly, earthquake prediction

1. Introduction

Temporal variations of radon emanation from soil and water can give us in some cases early evidence to tectonic disturbances in the Earth's crust [1]. Therefore, soil gas observation and radon anomalies can be used for the earthquake prediction, though the changes of radon emanation are also influenced by meteorological parameters such as atmospheric pressure, rainfall and soil temperature [2]. 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 on the measured radon concentration.

To predict the size and shape of an earthquake, the precursory phenomena have been investigated, and the dilatancy-diffusion (DD) model [3] and crack-avalanche (CA) model were developed [4]. According to the DD model, a porous cracked saturated rock constitutes the initial medium. With the increase of tectonic stresses, the cracks extend and disengagement cracks appear near the pores with the opening of favourably oriented cracks. This results in a decrease of pore pressure in the total preparation zone and diffusion of water into the zone from the surrounding medium. The appearance of pore pressure and crack increase brings about the main rupture at the end of the diffusion period. According to the CA model, the process proceeds as follows: a cracked focal rock zone is formed due to the increase of tectonic stresses. The shape and volume of this focal zone change slowly with time.

After comparing the two models, one can recognize a common principle: at a certain preparation stage, a region with many cracks is formed. The mechanical processes of earthquake preparation are always accompanied by deformations, and as a result complex short or long-term precursory phenomena can appear. Anomalies of radon concentrations in soil gas were registered a few weeks or months before several earthquakes [5,1].

The precursory phenomena can be observed within the distance D that is roughly the radius of the effective precursory manifestation zone. The size of the manifestation zone can be estimated approximately by using the following formula [8,3]

$$D = 10^{0.43M} \qquad (D \text{ in km}) \tag{1}$$

where M is the magnitude of the earthquake on the Richter scale. For example, a magnitude 5 earthquake will be detected by means of the precursory phenomena at a distance less than about 142 km from the epicentre.

Large changes of the gas emanation occur in the identified area of a forthcoming earthquake and continuous gas monitoring may add further informations. After the check 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 relation between the amplitude and duration of the gaseous anomaly and the magnitude of the expected earthquake has the following form [3]

$$M = k\sqrt{S} \tag{2}$$

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

To express the significance of the seismic event at the measurement site, one uses the ε parameter (earthquake effectiveness) given by Refs. [6] and [7]

$$\varepsilon = 10^{(1.3M-8.19)}R^{-3} \tag{3}$$

where R is the epicentral distance in km.

In addition to the observation of the radon anomalies, tectonic disturbances can be recorded by measuring the anomalous changes of helium, hydrogen, mercury, carbon dioxide and methane concentration in ground waters (for example, in thermal springs) and also the changes of ionic concentration, e.g. of Na^+, Cl^- ions and the soil gas emission [1,3,7].

2. *Experimental arrangement and calibration*

Concentrations of soil gas radon were continuously measured with the nuclear-track emanation detectors which were placed 0.5 m deep in the soil (site A) and 0.1 m above the water surface in a well, 8 m below the soil level (site B) in Osijek. The emanation detectors were constructed of the exterior metallic cylinder and a plastic vessel (cup) closed by filter paper (Fig. 1); a piece (2 cm $\times$ cm) of the LR-115 nuclear track detector film (produced by Kodak-Pathé) was placed inside the cup. The emanation detectors were exposed for one week; subsequently, the detector films were etched in a 10% NaOH aqueous solution at 60°C (333 K) for 120 min and counted visually using a microscope with the 10×16 magnification.

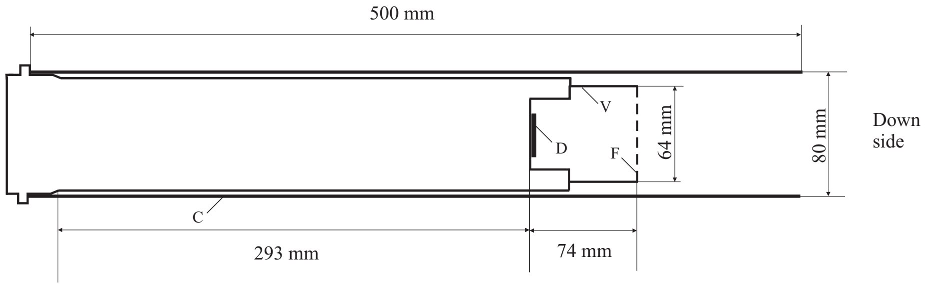

Fig. 1. Radon-emanation detector; C - cylinder , D - detector film , V - cup and F - filter.

The detector was calibrated by exposition in a NRPB radon chamber (Didcot, England) and in the radon chamber at the University of Osijek. We obtained the detector sensitivity coefficient of 20.8 Bq m^{-3} d/tr cm^{-2} (with a standard deviation of 0.47), with the background of 70 *tr* cm^{-2} (d denotes day, tr - detector track) [8].

3. *Results and discussion*

Radon concentrations in soil were measured from April and in water from May 1998 for one year.

The barometric pressure at 88 m altitude, precipitation and temperature of air 2 m above the ground were measured daily at the Meteorological Centre Čepin. The radon monitoring sites A and B are at a distance of about 3 km from the centre, while the sites A and B are also about the same distance apart. From the meteorological data, the weakly averages were determined, that presented the first reduction step in the multitude of data.

For a better synoptic presentation, the two-week averages of the radon concentration in the soil (c_s) and water (c_w), barometric pressure (p), precipitation (h) and air temperature (t) were calculated. They are shown in Figs. 2a and 2b. The standard deviation of the radon measurements was about 10% of the average radon concentration.

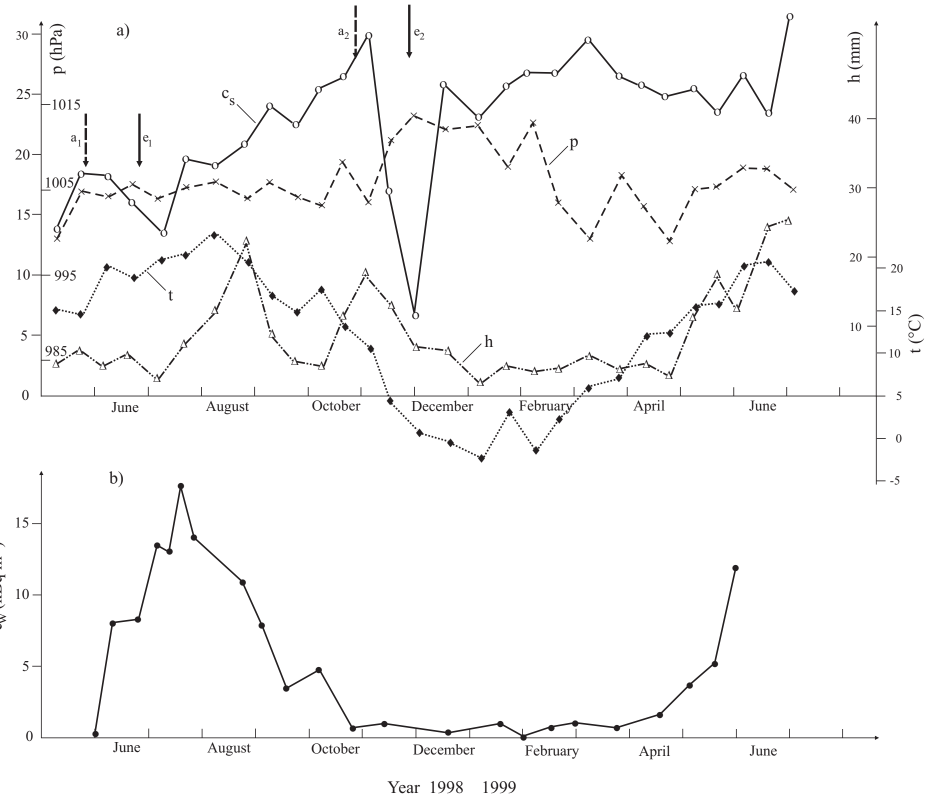

Fig. 2. a) Two-week average values of radon concentration in the soil gas (c_s), barometric pressure (p), amount of precipitation (h) and air temperature (t) versus time. The e_1 and e_2 full arrows denote occurences of earthquakes of the 25$^{\text{th}}$ June and 27$^{\text{th}}$ November 1998, respectively; the a_1 and a_2 dashed arrows denote the respective radon anomalies preceding (one month) the earthquakes. b) Two-week average values of radon concentration in the well water (c_w) versus time.

The earthquake data were collected from the Zagreb and Medvednica Seismological Stations of the Geophysics Department of the University of Zagreb. The majority of the earthquakes were either of a too small magnitude or too far away from radon monitoring site and they should not have affected the radon concentration in the area of observation. According to the standard dislocation model and criteria for the quake selection [2], earthquake of every magnitude (M, Richter scale) at the distance (d_m) less or equal to 10 km from the monitoring site was observed; also for 10 km $< d_m \leq$ 100 km for $M \geq 2$; for 100 km $< d_m \leq$ 200 km for $M \geq 3$; and for $d_m >$ 200 km for $M \geq 4$.

The earthquake with the magnitude of 2.8 was observed at the distance of 70 km, south-west (the region of the town of Modriča), from the monitoring site (Osijek), on 25$^{\text{th}}$ June 1998 (the arrow e_1 in Fig, 2a and in Fig. 3). The other earthquake was of the magnitude $M = 2.7$, with the epicentre at the distance d_m=200 km, to the west (area of the mountain Medvednica) on 27$^{\text{th}}$ November 1998 (the arrow e_2 in Fig. 2a). Figure 3 presents the seismogram showing the recorded earthquake of the 25$^{\text{th}}$ June 1998 (horizontal distance between two neighbouring rectangular pulses corresponds to the 1 min time interval. The quake occured on 25$^{\text{th}}$ June 1998 at 10 h 52 min AM).

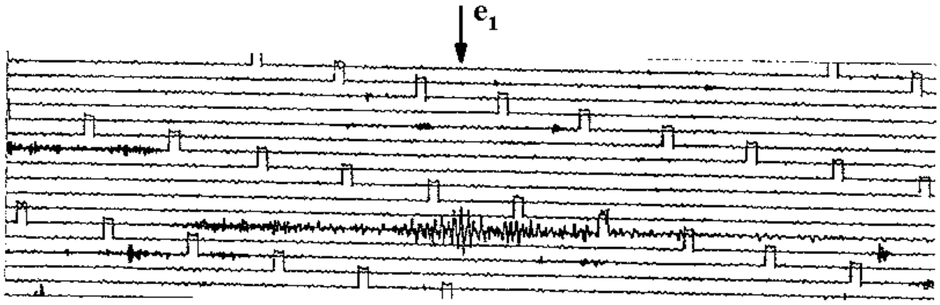

Fig. 3. The seismogram of the earthquake recorded at 25$^{\text{th}}$ *June 1998, at 10* h *52* min*, at the Medvednica Seismological Station of the Geophysics Department, University of Zagreb; horizontal distance between two neighbouring rectangular pulses denotes a time interval of 1 min.*

Figure 2 shows the influence of meteorological parameters on radon data. The decreasing barometric pressure is seen to cause increase of the radon concentration (a peak). The correlation coefficient has a significant negative value, $r = -0.923$, for the sample of seven pairs ($n = 7$) of values of the c_s and p (see Fig. 4). For the test of significance of the value of r, the test variable was $t_s = r\sqrt{n-2}/(1-r^2) = 5.36 > t_{s,0.95}(n-2) = 2.02$) [9].

The the empirical values (selected from Fig. 2a as typical case of the opposite of changes of the values of c_s and p) can be represented by the following equation

$$c_{s,t} = \sqrt{b - ap}\,, \tag{4}$$

where $c_{s,t}$ is the theoretical value of the radon concentration in soil gas. The parameters were $a = 83.73$ and $b = 84985$.

The temporal changes of the radon concentration can be examined for the influence of other causes of the radon anomalies. The influence of the amount of precipitation on radon concentration can also be studied [10]. Figure 2a shows some indications that the rainfall increases the radon emanation from the soil, but the four clear peaks of the precipitation curve seem to be insufficient for a reliable statistical test or conclusion.

The influence of the air temperature on the radon in soil is not so evident. However, the curve displaying the radon concentration (Fig. 2b) shows clearly the significant reduction of radon above the water in the well at lower temperatures.

The main reason for a high radon concentration in water in the summer months and a very low one in winter could be due to the dependence of the radon solubility in water on temperature.

Here we present some data about the earthquake of the 25$^{\rm th}$ June 1998 (e_1). According to Eq. (1), the radius of the precursory manifestation zone of the e_1 earthquake ($M = 2.8$) could be D_1=16 km. That is less than the epicentral distance from the monitoring site (70 km). However, the mentioned criteria for the earthquake selection [2] places the e_1 earthquake in the observation zone ($10 \leq d_m \leq$ 100 km ($M \geq 2$). The earthquake effectiveness parameter of e_1 was $\epsilon_1 = 8.2 \times 10^{-10}$ (from Eq. (3)), that is nearly a factor 10^3 less than the ones of the significant earthquakes known in the literature [7].

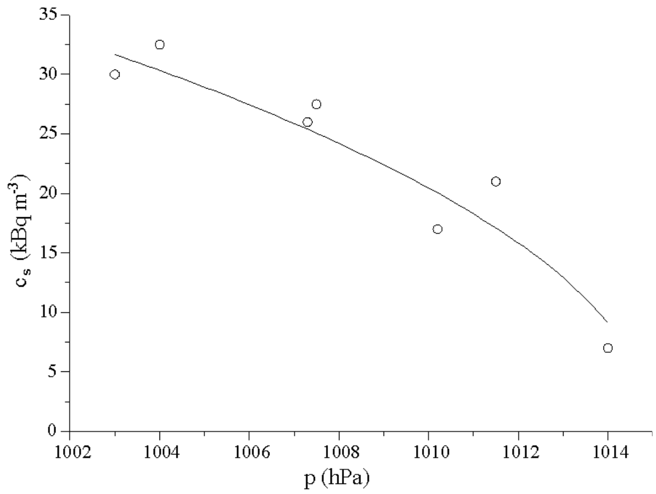

Fig. 4. Radon concentration in soil gas (c_s) versus barometric pressure (p); the points (○) represent the empirical values, the line presents the fitted curve (Eq. (4)).

Let us look at the radon maximum before 25$^{\rm th}$ June 1998 (Fig. 2a). The relative increase of the radon concentration, with the maximum on 25$^{\rm th}$ May 1998 (or one month before the occurence of e_1), could not be explained by the barometric pressure change (because p increased at that time), nor by the precipitation (that was very low), and the temperature was moderate. Therefore, we consider the first radon maximum in Fig. 2a (a_1) to be caused by a tectonic disturbance. Hence, the a_1 anomaly could have the significance of the earthquake precursor of the e_1 earthquake.

The area of the peak of the detected anomaly (a_1) is approximately $S = 40.5\,d$ kBq m^{-3} (d denotes a day). By using Eq. (2), the correction factor should be $k =$ 0.44 (d kBq m^{-3})$^{-1/2}$. So, the used radon-emanation detector, with the calculated k, could indicate a possible new earthquake, as well as its magnitude.

After the first radon peak (anomaly), a radon minimum followed, that is usually observed as a postquake reduction [1].

The radon concentration in water did not show any anomaly about the e_1 earthquake, because the respective radon-emanation measurement started too late. A possible radon anomaly, a large increase of the radon concentration may have occured due to the increasing temperature. One should first study the dependence of radon concentration on water temperature and then observe the temporal radon variations in order to detect an anomaly. The concentration of radon in water did not show any significant dependence on the barometric pressure.

For the earthquake of 27$^{\rm th}$ November 1998 (e_2; $M = 2.7$, $d_m = 200$ km), one would not expect an influence upon the radon emanation at the observation point, because of the large distance ($D_2 = 14.5$ km, e_2=2.6x10^{-12}). However, again a radon peak was observed one month before the e_2 quake, also followed by a minimum, as a postquake reduction (Fig. 2a). Although the barometric pressure (and probably the precipitation at the time of the the radon maximum) influenced the radon concentration in the same direction (for the maximum and minimum of the radon concentration in soil), it seems very likely that the radon anomaly a_2 (radon maximum on the 27$^{\rm th}$ October 1998) preceded the e_2 earthquake. The very low radon minimum about the time of the e_2 quake could be explained as an interference (on the radon curve) of tectonic and air pressure changes.

An examination of the possible radon anomaly a_2 by using Eq. (4) and respective procedure (p_0, $c_{s,0}$, $c_{s,t0}$), did not give a reliable answer.

In the search for a reliable earthquake precursor, continuous measurements of radon in soil and water, as well as of the meteorological parameters continues.

4. *Conclusion*

The monitoring of radon concentration in soil, as well as the measurements of barometric pressure, atmospheric precipitation and air temperature, have made possible the observation of an effect of tectonic disturbances on radon in soil. During the observation year-long period, summer 1998 to summer 1999, the seismograms indicated two earthquakes (the e_1 in June 1998, $M = 2.8$, d (epicentral distance from the monitoring site) of 70 km, and e_2 in November 1998, $M = 2.7$, $d_m = 200$ km), for which one could observe radon anomalies as the temporal radon variations (at least for the e_1 quake). In both cases, the radon anomalies appeared one month before the quakes. From the area under the radon maximum of the first anomaly (a_1, preceding the e_1) and known earthquake magnitude, the correction coefficient value of the empirical equation (2) was calculated; that makes possible an earthquake prediction by means of the radon-emanation detector, as well as its magnitude. The negative correlation between the soil-gas concentration of radon and the barometric pressure has made it possible to derive the regression curve which can be used to account for the effect of the meteorological parameter. A few occurences of atmospheric precipitation indicated a positive influence upon the radon concentration in soil. The temperature variation influenced significantly the radon in the well water only, and the respective temporal radon variation did not show a visible anomaly related to the recorded earthquakes. It seems, radon in the soil gas, measured by our radon-emanation detector, could be used to observe the earthquake precursors.

Acknowledgements

The authors are grateful to Dr. V. Kuk for the seismic data and very useful discussions. The authors thank Ž. Lazanin for the meteorological data. This work was supported by the Croatian Ministry of Science and Technology.

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PREDVIĐANJE POTRESA: VREMENSKE VARIJACIJE KONCENTRACIJE RADONA U TLU I VODI

Napravili smo detektore emanacije radona s plastičnim detektorima nuklearnih tragova LR-115 za mjerenje radonskih koncentracija u tlu i vodi. Tijekom jedne godine pratili smo vremenske varijacije koncentracije radona, kao i barometarskog tlaka, padalina i temperature. Ustanovili smo negativnu korelaciju između radonskih koncentracija u tlu i barometarskog tlaka. Za dva registrirana potresa u 1998. godini (u sjevernoj Hrvatskoj), ustanovili smo dvije pripadne radonske anomalije, upravo mjesec dana prije potresa u oba slučaja. Čini se da se pomoću izgrađenog detektora emanacije radona mogu predvidjeti potresi.