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RADON MONITORING FOR EARTHQUAKE PREDICTION IN SLOVENIA

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Radon (^{222}Rn) concentration in water of several thermal springs was measured with the aim of obtaining a correlation with the seismic activity of the region. Though a qualitative correlation was found for a spring with deep water circulation, we are far from being able to predict either the time or the place of an earthquake. An additional study with more relevant sampling sites and more frequent water analyses would be necessary to achieve this.

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1. Introduction

Anomalous changes in radon concentration of ground water have been observed prior to certain large earthquakes, first in Russia [1] and then in China [2]. Since then, in addition to hydrological studies, numerous radon concentration determinations in ground waters and in soil gas have been performed in many seismically active areas in several countries [3,4] in order to elaborate a methodology to predict earthquakes. Thus in many countries extensive radon studies have been carried out [5-45]. For earthquake prediction, radon is determined either in grab samples of air and water or it is measured continuously [26,28,29,32,33]. Radon itself or its decay products are detected by ionization chambers [6,12], alpha scintillation cells [2,15,32,35], alpha track detectors [9,16,23,28,30,46], silicon solid state detectors [36], gamma spectroscopy [8,25,33] or by liquid scintillation counting [13,29]. In addition to radon, seismic data and meteorological parameters, sometimes also thoron (^{220}Rn) [26,31], gases like Ar, N_2, CH_4, CO_2 [32,34,47], or other chemical constituents and physico-chemical parameters of water are systematically measured [18,22,30,33,48,49]. For the selection of reliable sampling sites and frequency of sam-

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pling and analysis, a thorough knowledge of the geology, hydrology and tectonics of the area under consideration is needed [25,28,31,45]. As known from the literature, radon monitoring in soil gas and waters has been shown to be a successful method for predicting earthquakes. Radon levels are correlated with meteorological and hydrological data as well as with seismic activity, and often abrupt changes in radon levels appear as precursors of earthquakes [4,33-35,45,46,50]. Since in the neighbouring regions of Friuli (Italy) and Carinthia (Austria), radon monitoring as an earthquake prediction tool is already applied [7,51], we carried out a research programme with the aim of implementing and checking this methodology in our own seismically active region. The analysis of radon concentrations in waters from the uranium ore deposit area at Žirovski vrh [52,53] led to no reliable correlation between radon concentration and earthquakes in this region. Since these analyses were carried out monthly, we decided to increase the frequency of measurements and extended sampling to tectonically relevant sites in Slovenia.

2. *Seismotectonics of the Slovenian territory*

Seismic phenomena in Slovenia are manifested in the active fault zones, which are several tens of kilometres long and several kilometres wide. The active fault zone represents a netlike pattern of active faults and fractures [54,55]. On the basis of geological and geomorphological studies, as well as neotectonic studies, their seismic activity in the Würm Glacial, i.e. 10,000 to 20,000 years ago, was determined [55,56]. Superficially active fault zones resulted from the earthquakes which occurred in shallow depths [55]. Geomorphological signs and a netlike pattern of faults and fractures are relevant for the dip-slip, reverse and strike-slip movements of tectonic blocks. In active fault zones, epicentres of earthquakes have been registered in the last 1200 years [56]. The seismotectonics of Slovenia is most probably influenced by three kinds of deep lithospheric mass: the Adriatic mass in the west, the Pannonian mass in the south-east, and the Central Alps mass in the north. The most mobile is the Adriatic mass, exerting pressure towards the NW with its frontal part (in Friuli) causing reverse faulting and underthrusting under the Southern Alps [57]. In western Slovenia, reverse fault zones arose with simultaneous left and right horizontal side movements. North of the Friuli reverse zones, which extend to the Julian Alps, there are rightward and leftward strike-slip fault zones with tectonic block movements because of the blocking effect of the Central Alps mass to the north. The latter mass also affected the formation of strike-slip fault zones in north-eastern Slovenia. Here, in addition, it meets the WNW directed pressure of the Pannonian mass.

3. *Experimental*

For this preliminary study, four sites for sampling water in the vicinity of Ljubljana, the capital of Slovenia, were selected (Fig. 1): Skaručna (S), a spring in alluvial deposit, Pirniče (P), a thermal spring located in a contact zone of alluvial deposit

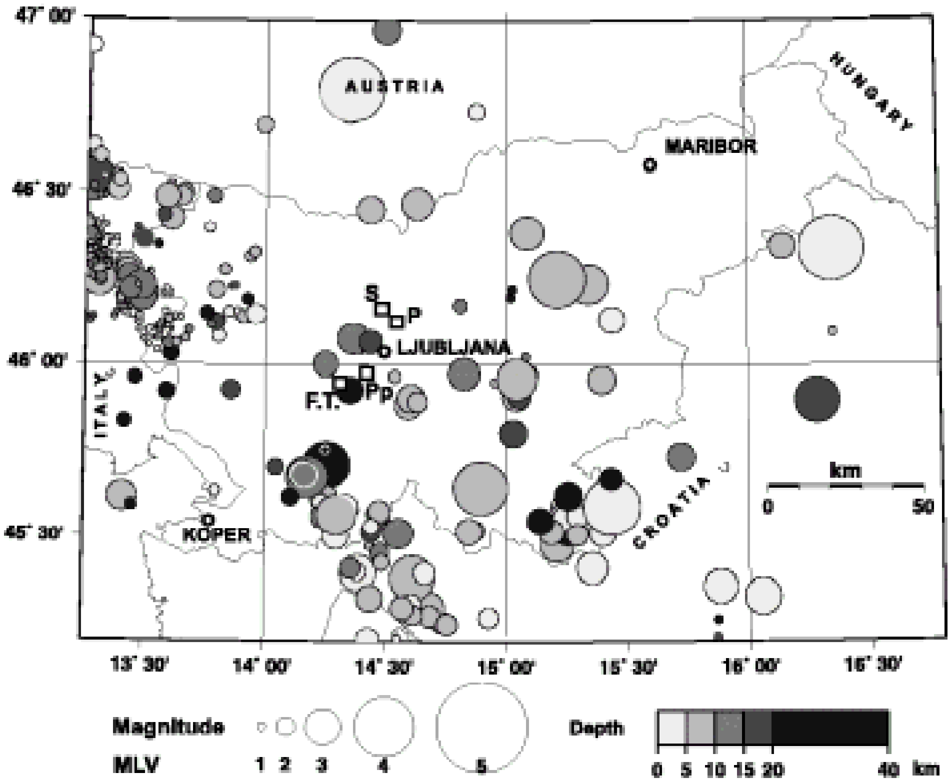

Fig. 1. Map of Slovenia, with sampling sites: S-Skaručna, P-Pirniče, Pp-Podpeč, F.T.-Furlanove Toplice. Epicentres of earthquakes in 1981-82 are presented by circles: radius is proportional to magnitude, colour presents depth.

with dolomite, Podpeč (Pp) and Furlanove Toplice (F.T.) - both thermal springs with deep water circulation in karstified limestone at the border between alluvial deposit and the karst region. Measurements and sampling at each spring were performed every Monday from January 1981 to December 1982 at Podpeč, and from January 1981 to December 1981 at other locations. The temperature of the air and water was recorded and samples were taken to be analysed in the laboratory. Radon was measured weekly and Cl^-, SO_4^{2-}, water hardness and pH monthly. Average weekly barometric pressures and 5-day rainfall were obtained from the Hydrometeorological Survey of Slovenia. For radon determination, a water sample was enclosed in a 0.6 dm^3 glass flask and transported to the laboratory, where radon was isolated in a trap cooled with liquid nitrogen [58] and transferred into a scintillation cell [59]. Alpha activity was counted after three hours. Cell constants (efficiency) were about 2 s^{-1} Bq^{-1} (radon in equilibrium with its short-lived decay products), background from 0.5 to 1.0 min^{-1} and counting times from 30 to 60 min. The lower limit of detection [60] was around 200 Bqm^{-3}.

4. *Results and discussion*

Results of monitoring radon in the selected waters are presented in Fig. 2, together with seismic activity (recorded and provided by the Geophysical Survey of Slovenia), water temperature, barometric pressure and rainfall (the latter two obtained from the Hydrometeorological Survey of Slovenia). The highest radon concentrations were found in Furlanove Toplice water, while in Skaručna and Pirniče values are about five times lower. Podpeč lies in between. There is no correlation between earthquake activity and radon concentration in Furlanove Toplice. Thus, for instance, the earthquake in the middle of March 1982 was followed by an increase in radon concentration, while a series of smaller earthquakes in the middle of June 1982 were preceded by a decrease of radon concentration. Further falling of radon concentration in this period may be assigned to heavy rains in June, which is also supported by an abrupt decrease of water temperature. On the other hand, the rainfall in May was too low to decrease the water temperature, thus the decrease in radon concentration in this period might be assigned to earthquake activity and not to dilution by rainfall waters. All other decreases of radon concentration in water from Furlanove Toplice seem to be related to rainfall and not to seismic activity. Variations in radon concentration in Skaručna and Pirniče waters are very small, with an exception in the summer 1981. A steady increase in radon concentration in both waters from the mid of June to the mid of August might be attributed to a number of small earthquakes in this period. But, on the other hand, the concentration in both waters fell off substantially after that time even though the seismic activity did not alter. At this stage, we are not able to interpret these observations. Podpeč water seems to be promising for earthquake prediction. The great majority of radon concentration maxima coincide well with the occurrence of earthquakes. Unfortunately, radon data from the beginning of 1982 are missing, and the relation to the earthquake in March was not recorded. One of the exceptions is June 1982 when, in spite of several small earthquakes, radon concentration fell significantly. As in the Furlanove Toplice case, this decrease could be attributed to a heavy rainfall in this period. No correlation between radon concentration and barometric pressure was observed. We consider the obtained results as very preliminary and, therefore, we have not done a theoretical analysis of the data.

5. *Conclusions*

From all sampling sites selected, only the water from Podpeč was found to be promising for predicting earthquakes on the basis of a correlation between radon-in-water concentration and seismic activity [4,61]. With only a few exceptions, occurrence of earthquakes is preceded by a peak in radon concentration. At this stage, a correction due to rainfall dilution of water has not been taken into account. The oscillations of radon emanation are also considerable in the Furlanove Toplice spring. Some characteristic peaks and falls are in an evident relation to earthquakes, but others, which could be even more intense, do not show any relation to earthquakes. At this preliminary stage, it was obvious that weekly or even daily radon

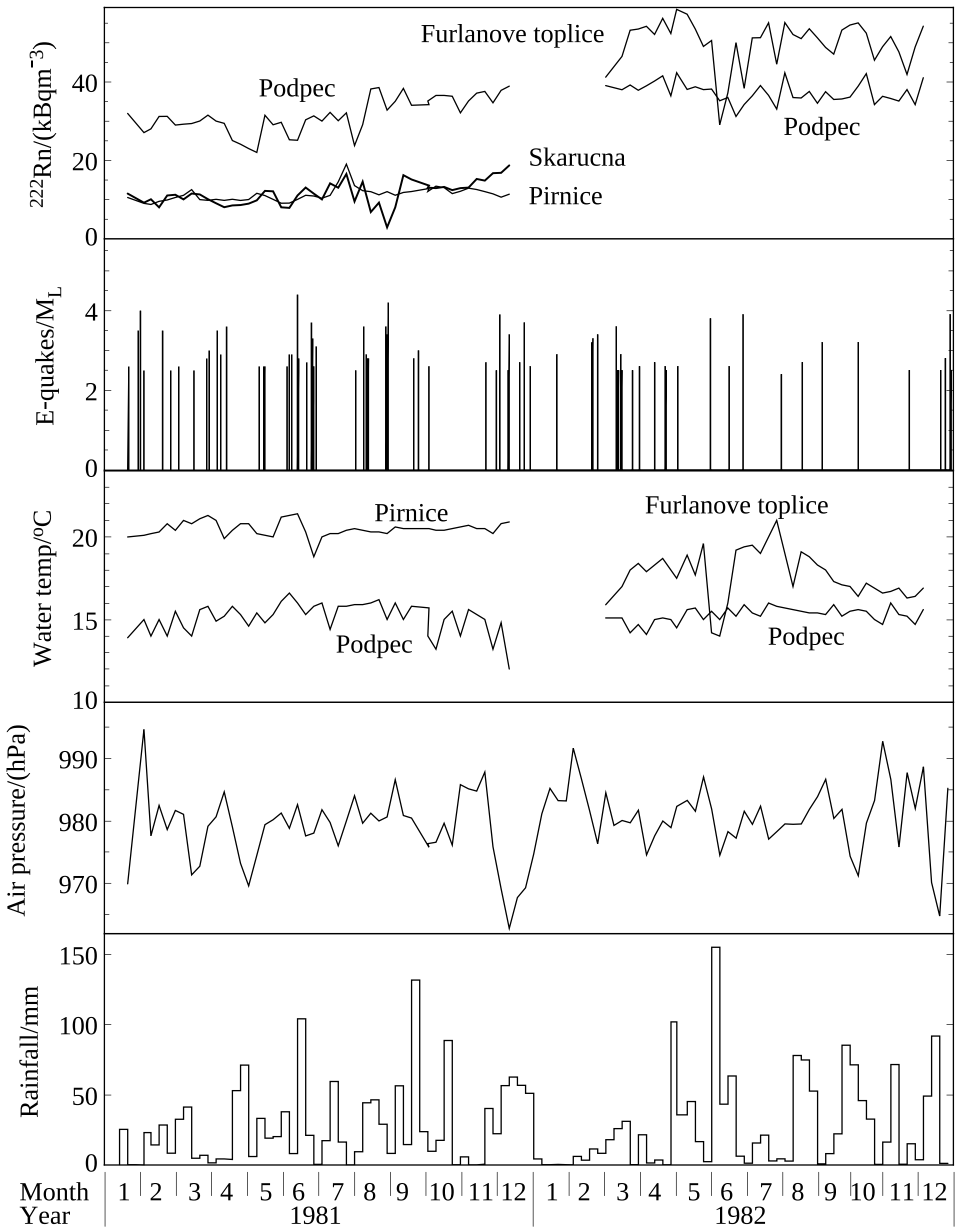

Fig. 2. Radon concentrations in selected spring waters together with seismic activity (earthquakes with epicentre distances up to 150 km), water temperature, barometric pressure, and rainfall.

analyses are not frequent enough to follow the seismic events adequately. Recently, reliable instruments for continuous radon in water determination have become commercially available [8,40,62]. We shall continue our research at two locations: (i) along the Soča (Isonzo) river several thermal waters were selected to continuously measure radon concentration (every 15 minutes) [63], electric conductivity and temperature (once an hour), with periodic chemical and isotopic analyses of water and carbon dioxide [64]; (ii) at the Krško polje, in the vicinity of a 635 MW nuclear power plant, radon in soil gas in five boreholes above a fault will be continuously measured [63]. Even though our goal is earthquake prediction, we primarily expect to enrich our knowledge of geologic and tectonic phenomena in these regions and to promote their better understanding [8,17,39,40,42,65-67].

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MJERENJE RADONA U VODI RADI PREDVIĐANJA POTRESA U SLOVENIJI

Mjerili smo količinu radona (^{222}Rn) u vodi iz više izvora radi utvrđivanja moguće korelacije sa seizmičkom aktivnosti u Sloveniji. Iako smo našli kvalitativnu korelaciju za jedan izvor s dubokim kruženjem vode, nismo još u mogućnosti predvidjeti mjesto ili vrijeme potresa. Za to su potrebna proširena mjerenja na više mjesta i sa češćim uzorkovanjem vode.