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Soil radon as a possible link to earthquake occurrence in Greece.

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Radon (222Rn) is a naturally occurring radioactive gas which is directly produced by the decay of the 238U series. It is significant for the studies of Earth, in hydrogeology and atmosphere. Radon is used as a trace gas due to the long half-life (3.82-days) which allows migration at long distances. In addition, it is an alpha emitter, fact which enables detection of low levels of radon. The usefulness of radon measurements in earth sciences is a topic of increasing interest over the last years. Radon exhalation anomalies have been associated with seismic or volcanic events that follow in time. Even though models have been proposed in order to interpret the relation between the observed radon emission irregularities and the underlying geological processes which lead to an earthquake, the exact mechanisms are still an important field of study.

A station for quick and continuous monitoring of soil radon has been installed in a very active tectonic region in SW Greece (Kardamas, Ileia Prefecture, Peloponnese). Monitoring is performed by means of Alpha Guard-AG, Genitron Ltd. equipped with an appropriate unit designed for pumping and measurement of radon in soil gas (Soil gas Unit, Genitron Ltd.). Pumping is performed at a rate of 1 L/min through an 1-m soil probe to minimize meteorological influences and a 25-m radon proof 25-mm tube to avoid simultaneous measurement of soil 220Rn. Proper dust and moisture filters are employed. During December 2010, the measurement interval has been reduced to 1 min. To our knowledge, this is much less than any corresponding interval reported in the literature (∼15 min up to 1 month). The whole setup is remotely controlled by a PC operating under a Windows XP OS. This computer handles AG through the Microsoft DOS software (AVIEW, Genitron Ltd.) licensed for the certain instrument of this study. Microsoft DOS is emulated under a licensed Vmware emulator. The remote operation of the PC (and consequently AG) is achieved through TeamViewer GmbH remote desktop program, via a dynamical internet address. The whole operation of AG (including data manipulation and transfer) is controlled from a Linux host through an internet connection.

Data representation and signal processing methods have been employed in a 6-month radon signal recorded prior to the 6 June 6.4M earthquake occurred in Ileia on year 2008. In addition, fractal analysis was employed to investigate possible existence of power-law dependence in the recorded signal. All the techniques were considered adequate for the identification of abnormalities on a scientific basis. Manipulation was performed at the time domain as well as at the time-frequency domain. The latter was achieved through time-scale wavelet representations applied on real measurement data.

The mean soil radon concentration was found fairly constant (∼ 25-30 kBq m-3). Numerous soil radon concentration anomalies were detected. These were arbitrarily corresponded in terms of magnitude and duration to seismic events of the near area. All detected anomalies were sudden, significantly ($p<0.001$) deviating (+/- 3 s.d.) from the average values and, for the majority of the cases, consisted of transient concentration increase followed by consequent decrease. Two very high anomalies (∼500-600 kBq m-3) were detected three and two months prior to the 6.4 M earthquake of 8/6/08. These anomalies consisted of a continuous decrease of 1 day duration, a sudden increase of approximately 1 hour and a gradual decrease up to baseline values.

The Short Time Fourier Transform (STFT) of the recorded signal exhibited in a very descriptive way the

significant anomalies. Both coarse and fine representations were employed. A series of anomalies were identified on a more sophisticated way compared to the +/- 2s.d. employed in the literature. Various anomalies emerge depending on the grey-colour levels cut-offs. The Continuous Wavelet Transform (CWT) as superior to the STFT, identified in a more descriptive way the significant radon anomalies. Both techniques identified clearly two strong disturbances and approximately 12 smaller. Descriptive representations of significant anomalies and earthquake occurrence present possible links to earthquakes.

An interesting finding is that parts of the radon signal follow a power-law dependence especially 1 day before and 1 day after the first detected significant radon anomaly. To our knowledge this power-law relation is the first reported for radon monitoring signals and may be related to a critical transition phase of the region before the earthquake occurrence.

Probable explanations for the detected anomalies may be given through the dilatancy-diffusion (DD) model and the crack-avalanche (CA) model. According to the DD model, a porous cracked saturated rock constitutes the initial medium. With the increase of the tectonic stresses the cracks extended as well and disengagement cracks appear near the pores, the favourably oriented cracks being opened. This results in a decrease of pore pressure in the total preparation zone and water flows into the zone from the surrounding medium. The return of pore pressure and crack increase brings about a main rupture at the end of the diffusion period. According to the CA model, the process is as follows: a cracked focal rock zone is formed by the increasing tectonic stresses. The shape and volume of this focal zone change slowly with time. After comparing both 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, afterwards complex short- or long-term precursory phenomena can appear. Additional explanations may be provided by microcrack propagation theory and the self-asperity model of two rough and rigid fractional-Brownian-motion-type profiles slipping one over the other, with a roughness which is consistent with field and laboratory studies. According to these, significant quantities of radon may be released and migrated during either the crack-formation or the Brownian slipping.