

Earthquake precursor measurements employing a network of radon sensors

Gururaj Kumar^{1,2,*,**}, Jürgen Gerl², Ayse Atac Nyberg¹, Torbjörn Bäck¹, Gaetano DeLuca³, Papadimitriou Eleftheria⁴, Vincenzo Guerriero⁵, Jiří Hůlka⁶, Vassilis Karakostas⁴, Alexandra Lightfoot⁷, Bastian Löher², Mats Nilsson¹, Peter Sjödin¹, Marco Tallini⁸, and Ramon Wyss¹

¹ KTH Royal Institute of Technology Stockholm, 10044, Stockholm, Sweden

² GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

³ Istituto Nazionale di Geofisica e Vulcanologia (INGV), 00143, Roma, Italy

⁴ Aristotle University of Thessaloniki, 54124, Greece

⁵ University of L'Aquila, department of Civil, Construction-Architectural and Environmental Engineering, 67100, L'Aquila, Italy

⁶ National Radiation Protection Institute(SURO), Prague 14000, Czech Republic

⁷ ETH Zurich, Switzerland and Swiss Seismological Service (SED), 8006, Zurich, Switzerland

⁸ University of L'Aquila, 67100, L'Aquila, Italy

Received: 2 December 2024 / Received in final form: 28 April 2025 / Accepted: 2 July 2025

Abstract. Earthquakes, as one of the most prominent natural disasters, pose a severe threat to societies in regions near active fault lines. Being able to forecast when, where and how strong an earthquake will be is beyond current scientific capabilities. At present, forecasting methods yield earthquake occurrence probabilities within a specific time frame spanning several years. Measurements of changes of radon concentrations in groundwater have shown pronounced changes preceding imminent earthquakes. The potential in using radon as a precursor for earthquakes has been explored by multiple groups over many years. Radon measurements in soil have shown large variations in activity, partly due to atmospheric influences. The ArtEmis project seeks to offer new insight into the correlation between imminent earthquakes and changes in radon emission from the upper crust by employing novel concepts for measurements and analysis. The paper presents system aspects of the ArtEmis project, a description of the ArtEmis sensor prototype and first results.

1 Introduction

Natural radioactivity has been a bane and a boon ever since its discovery. One element of particular interest in the history of Radioactivity is radon (Rn). The ArtEmis sensor observes the decay of ^{222}Rn , that has a half-life of 3.8 days. It is a daughter nucleus of natural uranium, ^{238}U , and is ubiquitously present in areas containing traces of uranium. Since it is a noble gas, and easily inhaled, it is monitored in mines and buildings, where it constitutes a potential health hazard to people. Radon is an α -emitter and decays through a chain of daughter nuclei until reaching the stable isotope ^{206}Pb . The majority of radon detectors operate by detecting the kinetic energy of the emitted α -particles. The ArtEmis project intends to measure the Rn concentration in groundwater, where the range of the emitted α -particle is only half a micrometer and more

challenging to observe directly. Addressing this difficulty, the ArtEmis sensor is measuring the γ -radiation emitted of ^{222}Rn progeny, which are easier to detect in water. This approach maintains a sensitivity on par with the best currently available detectors for direct α -particle detection.

Following the first indications of radon to act as an earthquake precursor in the 1960s [1], numerous studies have been conducted during subsequent decades [2–7]. One of the best examples of radon acting as a precursor stem from measurements in a mine close to Kobe, Japan, prior to the large earthquake of 1995 [8]. Despite the immense knowledge gathered on the subject, there is no accepted general relationship between changes in radon concentration and imminent earthquakes [5]. In addition, many measurements relied on radon concentration in soil, which can be strongly influenced by e.g., atmospheric changes [2,9] and flooding events [10].

The ArtEmis project will create new insight into the correlation between imminent earthquakes and changes in radon emission from the upper lithosphere. This will be

* e-mail: g.kumar@gsi.de

** e-mail: gururajksmg@gmail.com

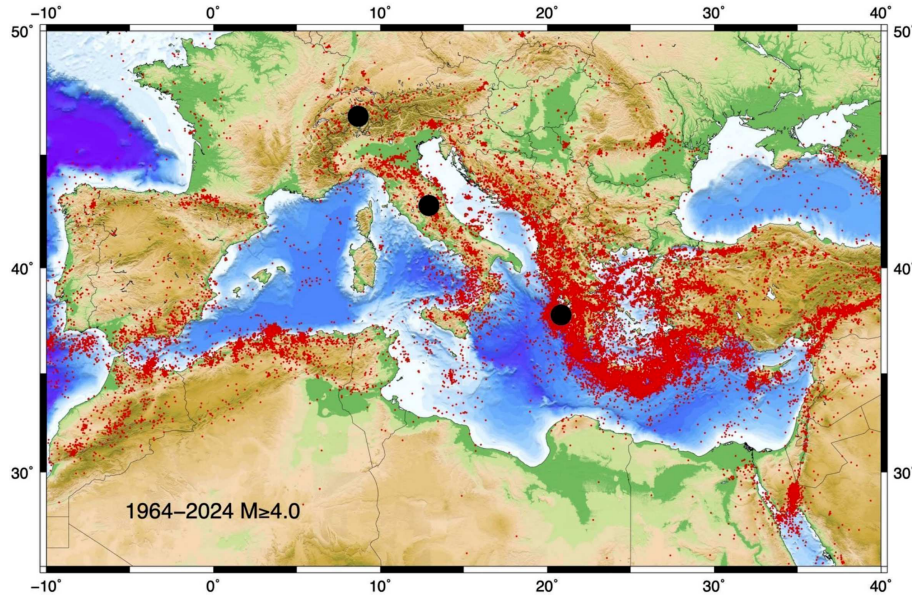


Fig. 1. Spatial distribution of a complete data sample with earthquakes of $M \geq 4.0$ (red dots) during 1964–2024 (On-line Bulletin, last accessed on 04 September 2024, <https://doi.org/10.31905/D808B830>). Black dots indicate the ArtEmis pilot sites.

achieved by a novel system design, anchored along three venues of development [11]:

- 1) the ArtEmis sensor will measure changes of radon concentration in groundwater and springs along fault zones, selected by seismological and hydrological studies [12]. Special emphasis is put on site selection, knowing that pronounced differences may exist between nearby situated groundwater sources. In this manner, a greater sensitivity to processes occurring in deeper layers of the Earth is anticipated, while maintaining a low and stable background, thereby minimizing the influence of atmospheric perturbations. The sensor also measures temperature, pressure and humidity. Extensions of the device with additional sensors, e.g., water acidity measurements, are planned.
- 2) The ArtEmis sensor combines high sensitivity with low cost, enabling the installation of around 100 sensors within this project. The large number of sensors is a prerequisite to overcome statistical and site dependent uncertainties from previous measurements [5–7]. Within the ArtEmis project, a dense network of sensors are planned to be placed in the Abruzzi in Italy, the central Ionian Islands in Greece and a few selected sites in Switzerland. The sensor data will be collected in real time. The ambition of the project is to later deploy additional sensors in Europe, enabling better coverage of earthquake prone areas with permanently installed systems. Figure 1 shows the occurrence of selected earthquakes in Europe from 1964–2024 along with the locations of our prototype sensor installations.
- 3) The data will be analyzed by means of advanced machine learning algorithms that correlate the radon, temperature, and pressure data with seismological data. The integration of standardized measurements with seismological data and other possible covariants



Fig. 2. Example of casing containing the γ -detector and ancillary sensor. The length is approximately 10 cm and stands water pressure up to 3 m.

will result in an improved understanding of the complex interaction of active faulting and the surrounding geochemistry of the environment.

This paper reports first results from the ArtEmis sensor prototypes. Note that the entire system is still under development.

2 Design of the ArtEmis sensor

The central element of the ArtEmis sensor is a γ -detector employing a CsI(Tl) crystal combined with a Silicon Photomultiplier (SiPM) [13] for the scintillation light detection. Figure 2 depicts the sensor head consisting of sealed

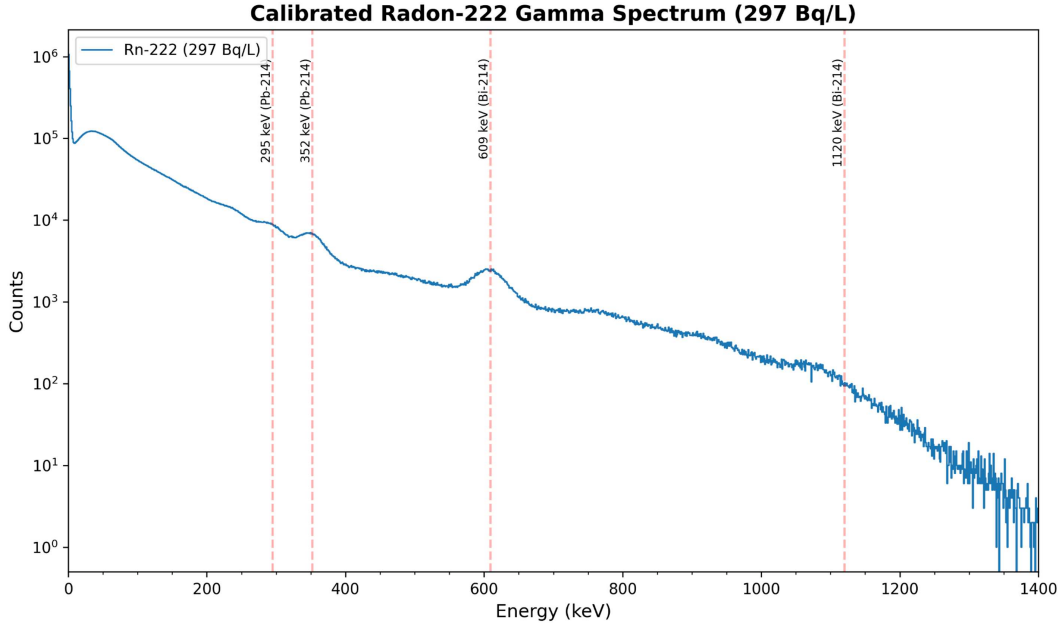


Fig. 3. Rn spectrum taken at SURO, where the identified peaks are fingerprints of ^{222}Rn daughters. Due to measurement inside the water, the spectrum is strongly dominated by Compton events.

sensing components, along with its electronics (Photo by: Jürgen Gerl). The detection efficiency of CsI(Tl) crystals is known to be stable in the temperature interval that the project encounters inside the wells [14]. The primary design principle is to develop a cost-effective sensor, capable of being deployed in water at depths of up to 3 meters. To achieve this goal, all sensor constituents can be bought over the shelf. The different units are placed on electronic boards, and with microprocessors connected to a transmitter and sender unit, using a Raspberry Pi processor for data handling. The sensor head consists of a sealed plastic casing, which encapsulates the devices. The casing is robust to withstand relevant water pressure. Data from the detectors are transmitted with the help of ethernet/LAN connection or the 3G/4G mobile network. Technical details of the sensor unit will be published in a forthcoming paper [15].

Various cost-efficient breakout board sensors are employed to measure additional parameters like temperature and pressure. The result of the design is a low-cost and flexible sensor unit. The crystal, which serves as scintillator material, is selected for its performance and cost. The crystal has dimensions of $20\text{mm} \times 60\text{mm}$, and signal amplification is obtained using a linear pre-amplifier and a discriminator generating a time-over-threshold (ToT) signal. This ToT signal serves to digitize the signals and make them readable into a 1-D histogram. Standard protocols are applied to make the data flow smoothly. Safety measures in case of power failure and internet connectivity failure are implemented.

3 Calibration

The sensor has been tested at National Radiation Protection Institute (SURO) in the Czech Republic [16], where the prototype was put into the center of a one

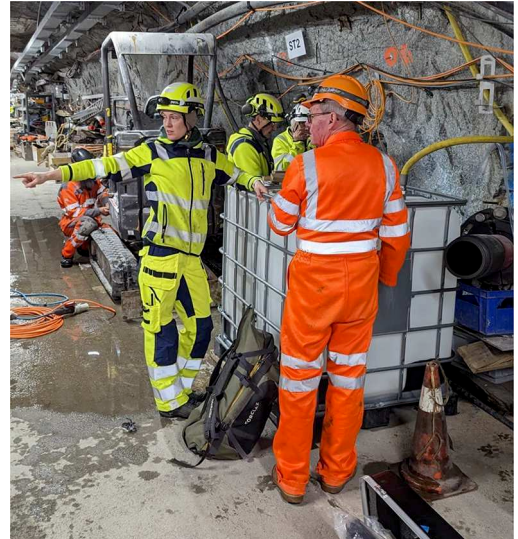


Fig. 4. Installation of prototype sensor in the Bedretto Laboratory (Switzerland).

cubic-meter water container, with a well-defined infused Rn activity. The measurements were taken overnight for two days to determine the detector sensitivity and to obtain the spectrum formed by Rn daughters. The measurements were performed for two separate Rn concentrations namely 5.8Bq/l and 297Bq/l . Figure 3 shows the spectrum obtained with the 297Bq/l activity with 10 hours of data acquisition. The main peak at 609 keV shows an energy resolution of about 8% in accordance with expectations. All the prominent gamma lines of the Rn progenies are clearly visible. Background subtraction around the peak was performed using a lin-

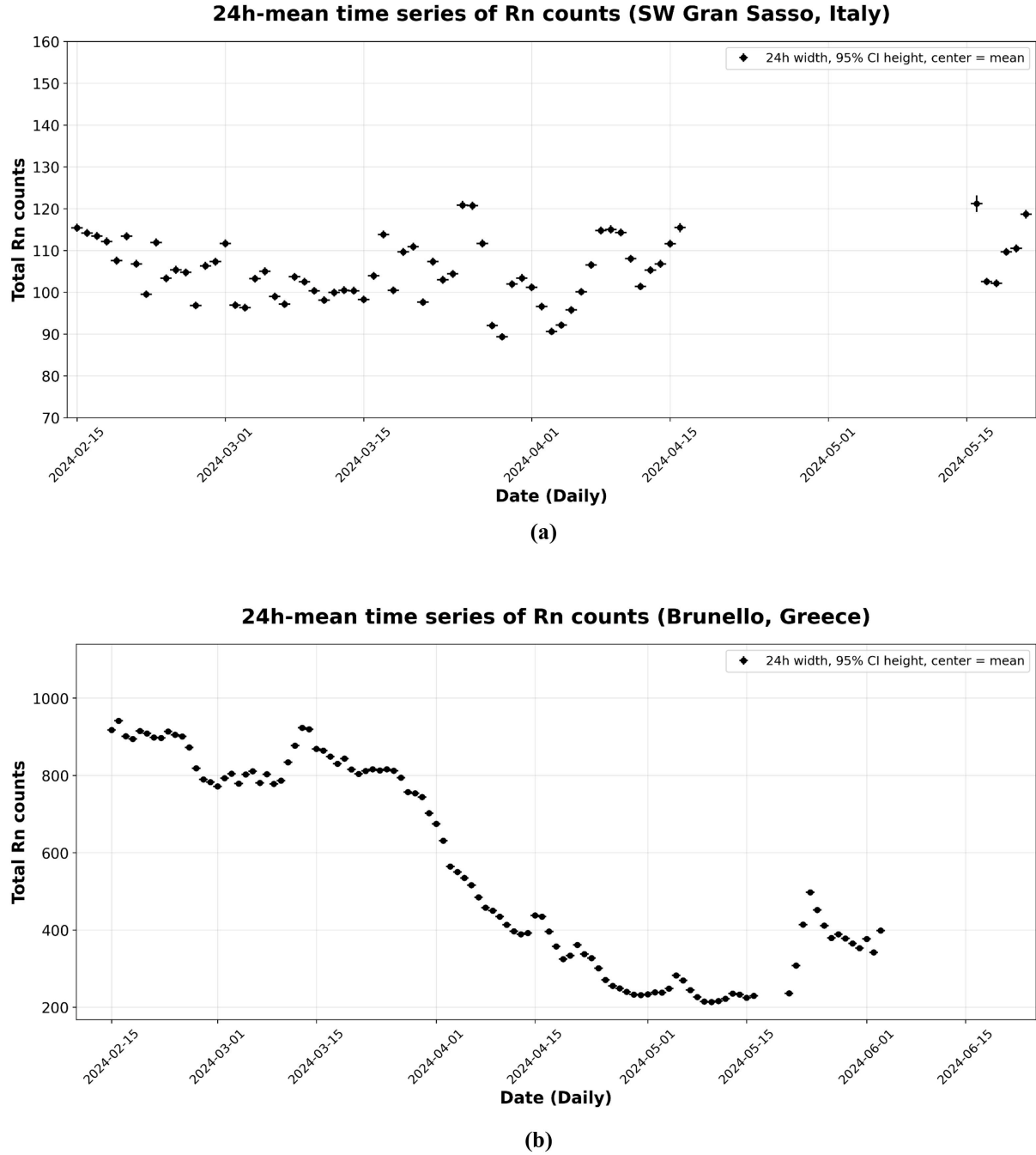


Fig. 5. (a) Time series of radon counts measured at the South West Gran Sasso tunnel and (b) Lefkada Island (Brunello).

ear fit to isolate the net peak counts. Contrary to measurements in air, Compton-scattered events are strongly dominating the spectrum. This is in agreement with Geant4 [17] simulations of the CsI(Tl) detector, accounting for the surrounding water and environmental setup. The simulations confirmed that an equivalent water sphere of 50 cm radius limits the effective detection volume. They further show that environmental gamma rays, e.g. from ^{40}K (e.g. from well walls) are strongly suppressed by absorption in the water before reaching the CsI(Tl) detector. This explains why no other lines are visible in the spectrum.

Using the 5.8 Bq/l water, the 609 keV peak was detectable above the Compton background in 300 s within 2 sigma statistical uncertainty. This infers a detection sensitivity for this characteristic line of $<1 \text{ Bq/l/h}$. In practice, this line will mainly be used to check for gain changes, e.g. due to temperature drifts, which can then be corrected by software. In normal well settings, water volumes exceed the equivalent sphere. Therefore, the detector will see no environmental background but only radon decay products. This enables the Rn concentration to be obtained from the counting statistics of the full spectrum. Therefore, the

sensitivity is $\ll 1$ Bq/l/h and thus the observed Rn fluctuations are predominantly due to natural reasons, among them the seismic activities we are looking for.

4 Installation

Following the tests at SURO, six prototypes were built, that besides the gamma detector also contain a PTH sensor (pressure, temperature, humidity), microphone (fast pressure changes) and 3D accelerometers and gyroscopes (slow pressure changes). Site selection was done by a team of seismologists and hydrologists with deep knowledge of the area [12]. Selected places require access to electrical power and the internet. A number of sites were selected in all three countries that can serve for the installation of the ArtEmis sensors. Eventually, three sites were selected in the Abruzzi region, two at Lefkada island and one in the underground laboratory of ETH Zürich inside the Bedretto tunnel. Two of the sites in the Abruzzi are placed within the Gran Sasso tunnel, home to the largest underground laboratory for nuclear and particle physics. This site offers excellent infrastructure and access to the large Gran Sasso aquifer below the tunnel. The third site was a spring with running water. In Lefkada island, the sensors were installed in two wells, with a depth of 2–7 meters. For installations in wells the sensor can be kept floating with the help of a buoy that provides a constant depth of the device. At the Bedretto laboratory in Switzerland, the sensor is placed in a container with a constant inflow of water from the tunnel. Figure 4 shows a snapshot of our team during the installation in Bedretto lab. (Photo by: Gururaj Kumar). Also at Gran Sasso, one sensor is placed under similar conditions, whereas the other one has been mounted by a special device to the wall. Each time, it is assured that the water volume is sufficient to warrant the quality of measurements.

Following installation, real time data is transmitted and collected to a server for treatment. A database has been set up at KTH Stockholm from which histograms of Radon activity data can be obtained. Radon data is collected in real time in 2 min intervals. First results have been obtained and processed by machine learning algorithms to study the optimal way of analyzing the data. Following the test installations, it was noted that the communication between different units were not stable, partly due to shortcomings of the local power supply. During the second half of 2024 and in the beginning of 2025, improvements of the sensor design, in particular power management and data transfer have been conducted. The six sites where ArtEmis prototype sensors have been installed are being replaced with modified sensors of the new design during early 2025 and further sensors are planned to be installed that year.

5 Results

The first spectra from the installed sites were detected and the fingerprint of ^{222}Rn was clearly seen in the obtained γ -spectrum. The water provides excellent shielding of the

sensor. Hence, the total number of counts in the spectrum is considered instead of just the peak counts. This simplifies the analysis of large data streams and enables us to pin down changes of Rn concentration with time. Statistical uncertainties [18] are taken for the full spectral sums, accumulated over 24-hour periods. The 3σ values are significantly smaller than the size of the bullet points in Figures 5a and 5b. In the next step of the analysis, values of PTH, and sound will also be correlated with Rn activity measurements.

The time series of the collected data in turn will be correlated to seismological data, which are continuously monitored, recorded and analyzed in real time from the dense local seismological stations along with stations of the European Seismological network. First results of time series are shown in Figures 5a and 5b. The data displayed has been collected at the South West (SW) Gran Sasso tunnel and at a well in Lefkada island. Interpretation of the time series data in collaboration with our geological and seismological partners is ongoing. However, a more comprehensive data set is required before any firm conclusions can be drawn. Interruptions in the data, visible in the figures, were caused by power outages and internet connectivity issues. These disruptions prompted the mentioned revision of both hardware and software, leading to a more robust sensor design. First tests of machine learning (ML) algorithms have been performed within the data available [19]. The data set is still much too limited as to warrant ML development or AI models that serve the purpose of providing correlation with seismic events and/or geographical extensions.

The ArtEmis project will be concluded at the end of 2026. The ambition of the partners is to continue and expand the measurements, to develop and strengthen long-term earthquake forecasting by means of advanced sensor systems.

Acknowledgments

The author acknowledges the support given by the EU commission to fund the project, the ArtEmis Collaboration and the large group of people supporting the installations of the sensors.

Funding

The funding for this project is granted by EU commission (Project: 101061712 — ArtEmis — HORIZON-EURATOM-2021-NRT-01).

Conflicts of interest

The authors have nothing to disclose.

Data availability statement

Data associated with this article cannot be disclosed due to legal reasons.

Author contribution statement

Conceptualization, Gururaj Kumar, Jürgen Gerl, Ayse Atac Nyberg and Ramon Wyss.; Methodology, Gururaj Kumar, Jürgen Gerl, Ayse Atac Nyberg and Ramon Wyss; Software, Bastian Löher, Peter Sjödin and Gururaj Kumar; Validation, Gururaj Kumar.; Formal Analysis, Gururaj Kumar, Jürgen

Gerl and Ayse Atac Nyberg; Investigation, Gururaj Kumar; Resources, Gururaj Kumar, Jürgen Gerl, Ayse Atac Nyberg, Torbjörn Bäck, Gaetano DeLuca, Papadimitriou Eleftheria, Vincenzo Guerriero, Jiří Hůlka, Vassilis Karakostas, Alexandra Lightfoot, Bastian Löher, Mats Nilsson, Peter Sjödin, Marco Tallini and Ramon Wyss;; Data Curation, Gururaj Kumar; Writing – Original Draft Preparation, Gururaj Kumar, Jürgen Gerl, Ayse Atac Nyberg and Ramon Wyss; Writing – Review and Editing, Gururaj Kumar, Jürgen Gerl, Ayse Atac Nyberg and Ramon Wyss; Visualization, Gururaj Kumar; Supervision, Jürgen Gerl and Ayse Atac Nyberg; Project Administration, Ayse Atac Nyberg Ramon Wyss; Funding Acquisition, Ayse Atac Nyberg and Ramon Wyss.

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Cite this article as: Gururaj Kumar, Jürgen Gerl, Ayse Atac Nyberg, Torbjörn Bäck, Gaetano DeLuca, Papadimitriou Eleftheria, Vincenzo Guerriero, Jiří Hůlka, Vassilis Karakostas, Alexandra Lightfoot, Bastian Löher, Mats Nilsson, Peter Sjödin, Marco Tallini, Ramon Wyss. Earthquake precursor measurements employing a network of radon sensors, *EPJ Nuclear Sci. Technol.* **11**, 48 (2025). <https://doi.org/10.1051/epjn/2025045>