ArtEmis

artEmis improving earthquake forecasting

draft science background and summary

Artemis will place over 100 sensors for radon detection and measurements along fault zones in earthquake prone areas in Greece and Italy, and a minor set along the Swiss Alps.
Radon emission and variations in concentration has since long been proposed and used as an earthquake precursor. One will find over 600 publications when searching for radon as an earthquake precursor.
There are several problems associated with radon measurements published in the literature: a large set of measurements have been performed in air or soil, that carry substantial uncertainties due to large variations of the natural background. Other reports rely on rather large distances between measurements sites and the epicenter, uncertain time window etc.

The present project will shed light on many issues related to radon measurements and analysis, by (i) measuring radon with a high spatial resolution due to the large number of sensors, (ii) measurements in groundwater in real time, and (iii) by deploying advanced data analysis via machine learning algorithms.

ArtEmis' ultimate aim is to improve earthquake forecasting. While it is possible to forecast earthquakes in specific regions (e.g. an earthquake of a certain magnitude will occur in the next 50 years at a certain location with a certain probability), with present knowledge, predictions of earthquakes (i.e. when and where exactly an earthquake is going to occur) are not possible. However, using the definition accepted in literature by Max Wyss* (see below), requiring accurate information about the location within a certain radius, estimation of the magnitude and a time window when an earthquake will occur, we will be able to test our precursor signals against short-term predictions of earthquakes.

An important aim of artEmis is to provide new/novel knowledge about the quantitative relation of various proxies that can act as precursors, that are to be measured in groundwater, and to correlate these data to subsequent earthquakes. Since the likelihood of a large earthquake during the duration of the project is not very high, information gathered on the relation of potential precursors to seismic activity will be somewhat limited. Hence, one needs to realize that artEmis will require continuation and if possible, expansion for further advancement of our knowledge. Provided the artEmis sensor system is working well, members of artEmis will engage to find financial support for the continuation and expansion of the network, as outlined in the communication and dissemination strategy.

One of the best measurements of Radon in ground water was made prior to the Kobe earthquake, at a well at 17m depth, that gave a clear indication 9 days prior to the 7.2 earthquake 1995, (G. Igarashi et al., *Science* 269 (1995) 60. DOI:

10.1126/science.269.5220.60). The signal from this measurement is distinct and yields a substantial peak one week before the event, as seen in the publication. Note that simultaneous measurements at the same mine, but at a well of only 4 m depth, connected to a shallower aquifer did not give any changes in radon prior to the earthquake. The group of seismologists at Kobe used an advanced radon detector for in water measurement, developed by the team of physicists measuring neutrinos at the **Kamiokande** experiment in Japan. At the Kamiokande experiment one had observed an increase in radon concentration 2.5 days prior to a **3.9 Richter scale** earthquake 45 km from the mine in 1991. Note that the depth of the mine of the Kamiokande experiment lies at 1000m underground.
Following the work by Gaetano De Luca, Giuseppe Di Carlo and Marco Tallini with respect of the Amatrice earthquake (Scientific Reports (2018) 8:15982, DOI:10.1038/s41598-018-34444-1) the ArtEmis sensor will combine radon concentration with temperature, conductivity and pressure signals, where the sensitivity of radon matches roughly the one from the Kamiokande experiments. To measure radon concentration in water is more challenging than measurements in air due to the short mean path of alpha particles in water as well as the challenging environment for most detector materials. At the same time, it is a prerequisite to reduce the large number of 'false' peaks associated with radon measurement in air or soil caused by the natural variation of radon due to changes in temperature, air pressure, wind, humidity, rainfall, sun cycle, etc.

Observation of a direct link between a precursor like changes in radon concentration with a subsequent earthquake requires a certain **linearity** in the process forming an earthquake:

1. Radon stemming from the decay of U exists almost ubiquitously at deeper layers. Increased stress along fault zones generates new cracks at a certain density inside the strained seismogenic volume, resulting in larger emission rates of radon from an area a few times larger than the rupture length of the incoming earthquake. In the interseismic period, the emission of radon from deeper layers is constant. When the occurrence time of the impending earthquake approaches, the preparatory process in the seismogenic volume is occasionally expressed with precursory phenomena. These are related with the stress increase forming larger number of cracks and larger amount of emitted radon. Very simplified, the location of the final rupture is related to the area of increased stress and hence the area of increased radon emission. Since detection of radon at the surface of the earth is at the level of single atoms the measurements get a very high sensitivity.
2. The transport of radon to the surface goes via carrier gases (CO_2, methane, ..) and/or water. This will depend on the detailed geological structure of the site, implying that for the case of artEmis, each well to be studied may have its special conditions. There might also be '**silent**' wells where the radon signal does not vary during earthquakes e.g., like the shallow one close to the Kobe earthquake. To find the most adequate wells for the project is still an open issue and will require constant observation during the project time. Still, since measurements will be performed

over many wells, we expect to balance the limited knowledge of the conditions at each individual well.

3. Given that artEmis covers a rather wide geographical area, with dense measurement in test sites, and the occurrence of many smaller earthquakes in the study areas, we expect to provide new knowledge about correlations between radon concentration in groundwater and earthquakes, and at least to establish a threshold effect for observations. To establish firm relations between the sites where measurements are done, and subsequent earthquakes will require more time than that of the artEmis project. Finding ways to prolong and/or expand the project are planned.
4. An appropriate sensor density providing sufficient granularity would require one sensor per 100km^2, i.e. one within the area of 10km*10km in order to achieve adequate statistical significance. The area of the Ionian islands comprises 2400km^2, implying that we will have a higher density of sensors. Given the high frequency of small earthquakes in the study area this could be justified. For the Abruzzi region, covering an area of 10.000km^2, we will have a lower granularity in our measurement. ArtEmis project will yield information about optimal distribution of sensors.
5. Enabling observations of precursor phenomena within a certain circular area of radius rho, one can find the following relation between the magnitude M of an earthquake and the distance rho to the epicentre, (I.P. Dobrovolsky, S.I. Zubkhov, V.I. Miachkin, Pure Appl. Geophys. 117(1979) 1025):

   $$\rho = 10^{0.43\,\mathrm{M}}\ \mathrm{km}$$

   Or in a more general form (J. Planinic*, V. Radolic, B. Vukovic Nuclear Instruments and Methods in Physics Research A 530 (2004) 568–574)

   $$D = a\mathrm{e}^{M}$$

   The formulae indicate that the larger the earthquake, the larger the radius where precursor phenomena can be observed. The artEmis project will give insight on the parameters of that relation.
6. The ML (AI) approach to analyse the date will make use of such relations and similar approaches to linearize(model) the process. A special horizontal group on modelling is in charge of developing meaningful descriptors. The aim is to find correlations to seismic data in order to verify the potential of radon and other measured quantities as relevant and reliable precursor.

*A definition to evaluate precursors that can be used by artEmis, has been suggested by *Max Wyss, Evaluation of proposed earthquake precursors (American Geophysical Union, Washington D.C. 1991)),* stating *'an earthquake prediction needs the following parameters to be specified with errors less than or equal to those indicated: the location ±1/2 rupture length, the size ±1/2 rupture length or ±0.5 magnitude units, the time ±20% recurrence time, and the probability of occurrence, e.g. the number of successes divided by the sum of successes and false alarms.'*