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Preliminary analysis of radon time series before the Ml=6 Amatrice earthquake: possible implications for fluid migration

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Abstract

On August 24, 2016 a Ml=6.0 earthquake occurred in Central Apennines, Italy, between the towns of Norcia and Amatrice, causing severe destruction and casualties in a wide area around the epicenter. We present a preliminary analysis of continuous radon concentration data collected from the second half of 2012 to the day after the earthquake by a long term radon monitoring station, installed at Cittareale (RI, Italy), about 11 km south-west of the epicenter. We combine the field data analysis with the outcome of dedicated laboratory experiments, aimed to study real time radon emission dynamics from rock samples subject to normal and shear stress loads in absence of fluid transport and migration phenomena. Our results suggest the possibility of a minor role played by phenomena related to fluid migration for the Amatrice seismic event with respect to other recent Apennine earthquakes.

I INTRODUCTION

Current research on soil radon emanation in terms of analyses of long time series has revealed its potential informative power regarding the link between temporal variation of this noble gas concentration and seismogenic processes [*Stefansson*(2011), *Piersanti et al.*(2016)]. In fact, the radioactive nature of radon makes it a potentially efficient marker to study and monitor fluid flows. In recent years, new laboratory experiments gave unambiguous evidence of the link between the rock state of stress and variations in the radon emanation properties [*Tuccimei et al.*(2010), *Mollo et al.*(2011)]. However, the analysis is complicated by the susceptibility of radon emissions to meteorological parameters and site-specific features [*Jaishi et al.*(2014), *Piersanti et al.*(2015)]. We had the possibility of analyzing a three-years long time series of radon concentration acquired by a monitoring station installed at about 11 km south-west of the 24 August, 2016, Ml=6.0 Amatrice earthquake epicenter. We present the preliminary results obtained limiting the impact of meteorological effects on the measured radon time series and combining them with the results of a series of laboratory experiments to study radon concentration variations in connection with a process of gradual deformation in shear.

II METHODS

II.1 Soil radon observations

Radon data were collected by a high sensitivity, high efficiency active radon monitoring station based on a Lucas cell [*Lucas*(1957)], installed at Cittareale (CTTR, $42°37'3.0''N$ $13°9'33.5''E$) in May 2010, at about 960 m above sea level. In August 2012 a new radon concentration detector replaced the previous one. In this work we decided to employ only data from the latest (and currently working) detector. The station is located in a basement hosting the municipal archive of the city (occasionally accessible to technical staff only) and measures radon concentration with an adjustable acquisition time (currently is 115 minutes); its efficiency is 0.06 $count\, min^{-1}/Bq\, m^{-3}$ and the minimum detectable concentration is as low as 6 $Bq\, m^{-3}$. CTTR acquires simultaneously local temperature values by means of a specific sensor co-located with the radon one. All other daily values of meteorological parameters employed in our analysis (external temperature, pressure, precipitation) are approximated as short term (12-24h) weather forecast by an Italian weather website (http://www.ilmeteo.it/). The complete time series of radon concentration data recorded at station CTTR from August 1, 2012 to August 25, 2016, together with the time series of local temperature are shown in Figure 1a and Figure 1b, respectively. CTTR radon concentration data show a marked seasonal signal, ascribable to a major correlation with temperature (see blue monthly moving-average of radon time series in Figure 1a and daily average of local temperature in Figure 1b), as laboratory tests [*Iskandar et al.*(2004)] and long term radon monitoring studies [*Jaishi et al.*(2014), *Piersanti et al.*(2015)] indicate. The meteorological corrected radon concentration values that we will show and discuss in the following sections have been obtained applying the procedure described in [*Piersanti et al.*(2016)].

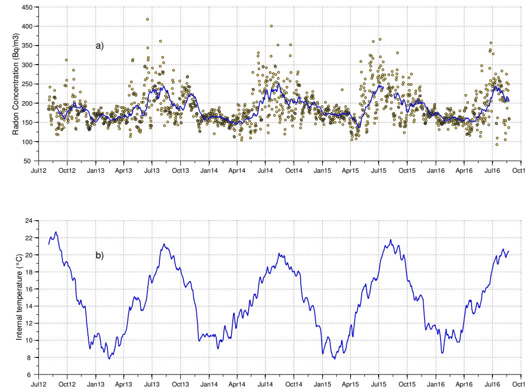

Figure 1: *a) Radon concentration* $(Bq\, m^{-3})$ *at CTTR for the period August 1, 2012 - August 25, 2016 both as daily average (yellow dots) and as monthly moving-average (blue line). b) Daily averaged time series of local temperature for the same period as in (a).*

II.2 Laboratory

We conducted four laboratory experiments to study radon concentration variations in connection with a process of gradual deformation in shear. The use of controlled conditions of loading and ambient conditions (temperature and humidity), helps reducing the number of implicated variables affecting the natural radon emanation process and simplifies the interpretation of the results. We use the rotary shear apparatus SHIVA (Slow to High Velocity Apparatus) installed in the High Pressure-High Temperatures (HP-HT) laboratory of the INGV of Rome simulating close to natural seismic deformation condition at depth of the upper-crust [*Di Toro et al.*(2010)]. The sample assembly is made of two cylinders 50 mm of external diameter sandwiched in frictional contact under a constant normal load of 5 MPa on tuffs and 15 MPa on tonalities, within a pressure-vessel. The vessel [*Violay et al.*(2013)] is a device made of stainless steel equipped with sealing O-rings that ensure isolation of the sample pair and guarantee fluid confinement. Rock type selection (tuff and tonalite) was driven by the radon initial concentration, porosity and shear modulus. We used the same instrument employed in the field to continuously acquire radon/thoron concentration variations during the progress of the experiment, with an acquisition time of 1 sec. We use a simple pump to flux air in closed loop between the inlet valve of the vessel and the outlet flange of the radon detector to allow air circulation within the vessel and from the vessel to the detector (Figure 2). Variations of radon concentration are referred to an initial condition set at the achievement of secular equilibrium. Secular equilibrium was ensured pre-stressing the sample pair in a uniaxial press for four days. Experiments consisted in a step-wise increase in shear-stress ($\tau \approx 0.2 MPa, dt \approx 5\, min$) under constant normal load until sample failure, resulting in a fast rotation of the rotary column at prescribed velocity and pronounced wearing and axial shortening of the contact surfaces. The shear-stress was then re-established and increased again, for several cycles, until the initial bare rock is crushed to powder. Deviation from the prescribed experimental conditions were possible due to the onset of mechanical oscillations in shear stress or a fast increase in the deformation rates, requiring a manual intervention. All experiments were well reproducible in both the mechanical behaviour and recorded radon emission variations.

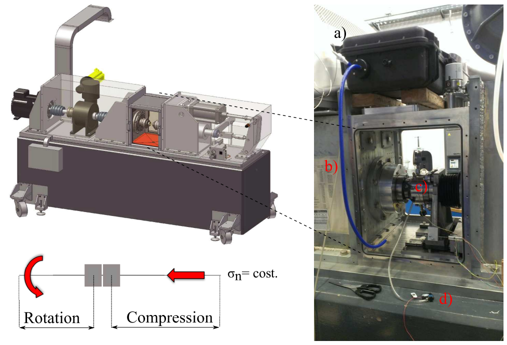

Figure 2: *The experimental apparatus (SHIVA, on the left modified from [Di Toro et al.(2010)]) essentially made of a rotary axes, a stationary axis and a sample chamber. The experimental assembly consists of the radon detect. (labelled with a), the connection (b) allowing for close loop circulation of fluids from the vessel (c) to the radon detect.; the air pump for air flux (d).*

III RESULTS

III.1 Soil radon observations

Our analysis is based on the phenomenological observation of the trend of radon concentration time series during the months of July and August for the four years from 2013 to 2016 and successively on their correlation with variations of meteorological parameters measured in the same periods, through an empirical correction procedure aimed at limiting the impact of their variations on the measured radon concentration levels (see for details [*Piersanti et al.*(2016)]). In Figure 3a daily averaged time series of radon concentration for the period July-August (2013-2014-2015-2016) are shown. Radon concentration data acquired at station CTTR show for these four time windows values variability comparable with the one of the complete time series but with higher absolute concentration values, as expected for summer months [*Iskandar et al.*(2004), *Jaishi et al.*(2014)]. Namely, we registered sharp peaks ranging from a few tens up to 400 $Bq\,m^{-3}$. The average values of radon concentration evaluated for the period July-August and for the month of August alone are reported in Table 1, in the second and in the fourth column respectively. It is worth noting that 2016 average value is the lowest of all the four years and it is lower than the average values registered during the previous three years by more than 3 standard deviations (see last two rows of Table 1).

Table 1: *Mean values of radon concentrations in* $(Bq\,m^{-3})$.

	Jul-Aug (uncorr.)	Jul-Aug (corr.)	Aug (uncorr.)	Aug (corr.)
2013	227	149	212	96
2014	228	129	222	90
2015	233	158	216	179
2016	214	71	196	63
avg.	229	145	217	122
std.dev.	(± 3)	(± 15)	(± 5)	(± 50)

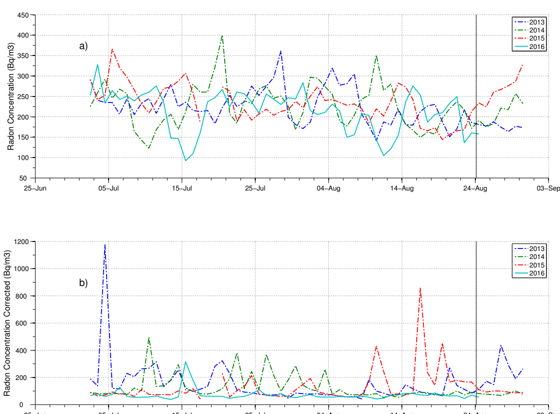

Figure 3: *a) Daily-average time series of radon concentration for the period July-August for 2013,2014,2015,2016. The black vertical line marks the occurrence of the Ml=6 earthquake. b) The same as in (a) but with daily average time series corrected for meteorological parameters* ($C_{T_{max}}, C_{R_{max}} = 5; C_{P_{max}} = 1$).

In Figure 3b we show the time series of Figure 3a corrected for meteorological parameters, according to the empirical correction procedure developed by [*Piersanti et al.*(2016)] in order to remove the effect of meteorological phenomena on measured radon concentrations. As described in cited work, the correction parameters are determined through a numerical optimization scheme whose results, in agreement with results obtained for the Pollino range stations (South Italy, Calabrian arc), indicate temperature and precipitations as the most impacting variables on radon concentration data ($C_{T_{max}}, C_{R_{max}} = 5$), while the role of the atmospheric pressure variations is not well constrained ($C_{P_{max}} = 1$). The features of all the considered time series change noticeably after the correction. We focus our attention on the 2016 July-August corrected one (cyan solid line in Figure 3b) that is significantly flattened with respect to all the others (see also the average values of corrected radon concentration in the third and fifth column of Table 1). Indeed, the 2016 July-August uncorrected time series show three low concentration peaks, the latest occurring two days before the earthquake (Figure 3a). The peculiar behavior of 2016 July-August radon timeseries is confirmed also by the observation of relative variations of radon concentration during the period selected for our analysis. Figure 4 shows that the largest relative variations of the whole radon time series occur just in the 90 days preceding the earthquake.

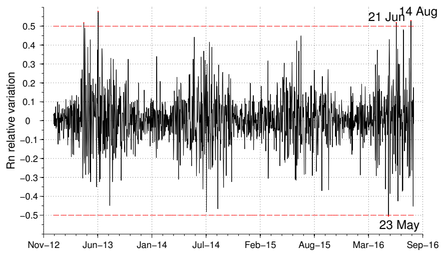

Figure 4: *Relative variations of radon concentrations for the period January 1, 2013 - August 25, 2016*

III.2 Laboratory

We conducted two experiments on tonalite and two on tuff to test the instrument sensitivity and the reproducibility of radon concentration variations in case of laboratory faults. In the following we will focus on tonalite since we consider it more representative of a seismogenic setting with respect to tuff. Experiments conducted at normal load of 15 MPa (experiments n. 1063 and s1095) show that the experimental fault responds to a gradual increase in shear stress (blue solid curve in Figure 5) by sliding at slip rates (black solid curve) varying from less than a few $mm\,s^{-1}$ up to 4 $cm\,s^{-1}$. These episodic slip events are concomitant to a large increase in the axial shortening which typically ranges from 0 to 2 mm (red solid curve). After the application of the normal load and with the progressive increase in shear stress the number of radon counts (converted in counts per hour in Figure top panel) was gradually decreasing (Figure 5 top panel) until the onset of the largest event where we observed the largest decrease in radon counts. It is worth noting that this large negative radon concentration variation occurred, in the case of both the experiments, before sample failure and still far from a condition of seismic sliding (slip rates $> 0.1 m\,s^{-1}$). Moreover, the correlation between the state of loading if the sample pair and the radon concentration variation follow almost instantaneously. The negative radon concentration variation prior sample failure was also reported in previous static analysis ([*Tuccimei et al.*(2010)]) on tuff where the radon concentration variation was measured as a cumulative value prior and after the application of a normal load under an uniaxial press.

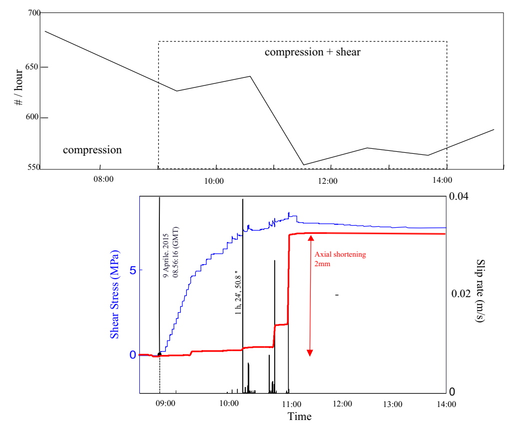

Figure 5: *Radon variation concentration (top panel) as a function of the shear stress increase (blue solid line, bottom panel) in case of experiment number s1095. The mechanical response of the system made of fault + experimental apparatus is also shown (bottom panel) in terms of slip rate (black solid curve) and axial displacement (shortening, red solid line). The number of radon counts (averaged in counts/hour in top panel) decreases with increasing shear stress at constant normal load (compressive load of 15 MPa) and has a maximum negative slope corresponding to the highest recorded slip pulse with slip-rate of 0.04 m/s. The axial shortening (generally associated to sample grinding and wearing) was of the order of 0.1 mm.*

IV DISCUSSION

We have presented the results of an analysis of radon concentration data acquired at CTTR station from 2013 to the day after the Ml=6.0

Amatrice earthquake supplemented with data obtained from dedicated, original laboratory experiments. The field observations confirm the strong impact of meteorological parameters variations on observed radon time series, especially temperature and precipitations. At the same time, both daily average time series and the ones corrected for meteorological parameters evidence for July-August 2016 a different behavior with respect to the same time window of the previous years, showing overall lower average values of radon emanations and an increase of relative variations among different detections. When a meteorological parameter correction is applied, the previous behaviors are confirmed and a flattened trend in the days preceding the earthquake can be also evidenced. Data obtained from laboratory experiments, aimed to study real time radon concentration variations in connection with a process of gradual deformation in shear and in absence of fluid transport and migration phenomena, give results compatible with the CTTR radon time series behavior during the 2016 July-August period. These combined observations could pave the way to the hypothesis of a minor role played by processes associated with fluid transport and migration for the Amatrice seismic event with respect to other recent Apennine earthquakes. Nevertheless, the available data, being limited to a single station, do not allow us to rule out the possibility that different portion of the seismogenic volume could have been subject to different styles of fluid dynamics related phenomena. In this respect, a multi-station monitoring of seismogenic areas would represent an important evolution of the presented investigative approach.

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