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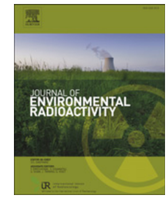

Spatial distribution of soil radon as a tool to recognize active faulting on an active volcano: the example of Mt. Etna (Italy)

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This study concerns measurements of radon and thoron emissions from soil carried out in 2004 on the eastern flank of Mt. Etna, in a zone characterized by the presence of numerous seismogenic and aseismic faults. The statistical treatment of the geochemical data allowed recognizing anomaly thresholds for both parameters and producing distribution maps that highlighted a significant spatial correlation between soil gas anomalies and tectonic lineaments. The seismic activity occurring in and around the study area during 2004 was analyzed, producing maps of hypocentral depth and released seismic energy. Both radon and thoron anomalies were located in areas affected by relatively deep (5–10 km depth) seismic activity, while less evident correlation was found between soil gas anomalies and the released seismic energy. This study confirms that mapping the distribution of radon and thoron in soil gas can reveal hidden faults buried by recent soil cover or faults that are not clearly visible at the surface. The correlation between soil gas data and earthquakes depth and intensity can give some hints on the source of gas and/or on fault dynamics.

1. Introduction

Radon is a radioactive, noble gas which is present in all the rocks of the Earth. It is currently used by the scientific community as a tracer of natural phenomena linked to soil degassing along faults, fractures and crustal discontinuities (Israel and Bjornsson, 1967; King et al., 1996; Mazur et al., 1999; Jonsson et al., 1999; Choubey et al., 1999; Durrani, 1999; Baubron et al., 2002; Vaupotič, 2003). Recently, radon was also used on Mt. Etna both as a precursor of volcanic phenomena (Alparone et al., 2005; Morelli et al., 2006; Neri et al., 2006; Giammanco et al., 2007) and in the study of the dynamics of active faults (Immè et al., 2006a,b; Neri et al., 2007; La Delfa et al., 2007a; Giammanco et al., 2009; Siniscalchi et al., 2010), including those that are hidden by recent lavas or tephra cover (Burton et al., 2004). This paper shows ~200 measurements of radon sampled in a key area of Etna from a tectonic point of view, covering an area of ~20 km^2. Our study is the first one that covers such a wide area by performing such a high number of radon and thoron measurements in soil. Therefore, the results are interesting not only for their implications on tectonics and earthquake mechanisms, but also for a better understanding of how radon distributes over large surfaces and how it behaves in terms of transport dynamics in soil with different permeability.

Radon has a mass of 86 and it has thirty-seven known isotopes according to ENSDF (2011), or forty-three according to Sonzogni (2008) and Nuclear Wallet Cards (2009). The three most common radon isotopes in nature are ^{222}Rn (radon), ^{220}Rn (thoron) and ^{219}Rn (actinon). The ^{222}Rn is produced by α decay from ^{226}Ra, it has a mean half-life of 3.8 days and belongs to the decay family of ^{238}U. Thoron is produced by α decay of ^{224}Ra, it has a mean half-life of 55 s and belongs to the radioactive decay chain of ^{232}Th. Actinon has a mean half-life of only 4 s and derives from ^{235}U.

Of the three main isotopes, ^{222}Rn is the most useful for geochemical surveys because its half-life is long enough to allow its diffusive transport through relatively thick layers of soil or other materials. For this reason, under conditions of scarce dilution (poor aeration), such as those encountered in some closed indoor environments, its concentration in the atmosphere can be high (ICRP-65, 1993; Žunić et al., 2006; Brogna et al., 2007; Malczewski and Żaba, 2007).

As the half-life of ^{220}Rn is relatively short, it is proven to be useful only in areas where advective transport of soil gas is particularly high and/or in areas where there are rocks containing significant amounts of Th-rich mineral phases, such as biotite,

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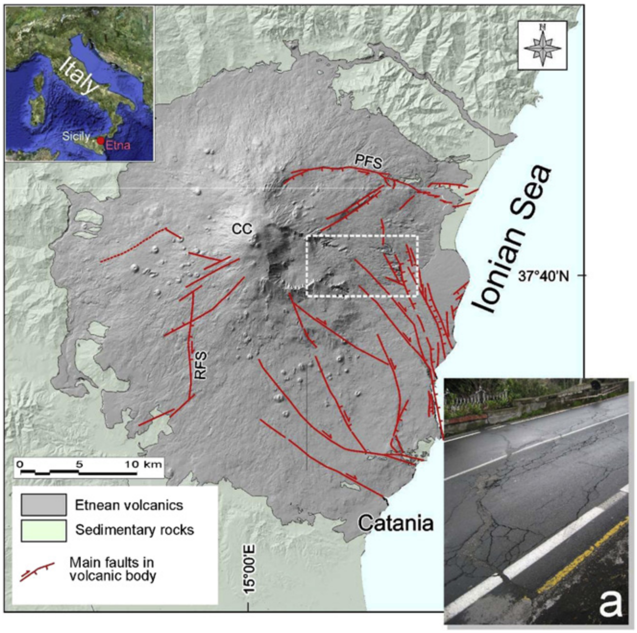

Fig. 1. Simplified structural map of Mt. Etna (after Neri et al., 2009) and location of the study area (white dashed box). Inset (a): seismogenetic surface faulting (NW–SE) affecting a road on the eastern flank of Mount Etna, occurring during the first stage of the 2002–2003 eruption. The northwestern portion of this fault is located in the studied area. CC = Central craters; PFS = Pernicana fault system; RFS = Ragalna fault system.

apatite and sphene. However, the highest concentrations of this element occur in accessory phases such as allanite, thorite, uraniumthorite, thorianite, monazite and zircon (Casillas et al., 1995; Wang et al., 2001).

Lastly, the role of ^{219}Rn in geochemical exploration is negligible, due to its very short half-life that causes its decay in the soil before it can reach the atmosphere. Only emissions of radon and thoron gases from the soil, therefore, can give information on the increase of magmatic and seismic activity, mostly in the areas with high crustal permeability (Giammanco et al., 2007, and references therein).

Mt. Etna (Sicily, Southern Italy) is the largest active volcano in continental Europe, with a diameter of more than 35 km and a height of about 3329 m (Neri et al., 2008). Its frequent eruptions occur both from the four summit craters and from the three fissure zones (or "rift") which are present on its flanks to converge uphill towards the summit (Acocella and Neri, 2003, and references therein). The area surrounding the volcano has been populated since pre-Roman times. Diffuse urbanization of this area and anthropic activities (i.e. vineyards, fruit orchards) have substantially changed the existing landforms and often obliterated the shallow geomorphology features since the Middle Ages. Moreover, commonly with other active volcanoes, constructive/destructive processes typically operate frequent and deep morphological changes, especially in the summit area (Behncke et al., 2004; Neri et al., 2008).

Several earthquakes occur every day in the area of Mt. Etna, more numerous in the eastern flank (http://www.ct.ingv.it/ufs/analisti/). Despite their typical low to very low magnitude ($M < 2$), they deserve to be studied for a complete understanding of the volcano dynamics (Acocella et al., 2003; Burton et al., 2005, and references therein). As we will demonstrate in this paper, a correlation between seismicity and soil radon measurements carried out in 2004 was found, which permitted to discover several active hidden faults located in the mid-lower eastern flank of the volcano, and allowed us to set up a method potentially useful to forecast seismic activity.

2. The study area

The present study was carried out in the mid-lower east flank of Mt. Etna, in an area between the villages of Milo and Zafferana Etnea (white dashed box in Fig. 1). Measurements of radon and thoron emissions from soil were performed in this area because of the presence of numerous active faults, both seismogenic and aseismic (Burton et al., 2004; Walter et al., 2005; Neri et al., 2005; Monaco et al., 2008), which generated frequent historical quakes with maximum magnitude of 4.5 (15 October 1911, Imposa and Patané, 1985). Furthermore, the area is subject to slow but constant gravitational sliding towards the SE (Solaro et al., 2010 and references therein). This mobile sector is bounded to the north by the E-W-running Pernicana Fault System (PFS in Fig. 1), with average motion rate ranging between a few millimeters and 2–3 cm a^{-1} (Acocella and Neri, 2005) and to the southwest by the Ragalna Fault System (RSF; Neri et al., 2007; Fig. 1), affecting an onshore area of >700 km^2 (Neri et al., 2004). The unstable sector is also divided into at least seven minor blocks characterized by different kinematics and bounded by faults (Solaro et al., 2010). The last violent seismic sequence affecting the study area occurred in 2002, during the first stages of the 2002–2003 flank eruption that triggered a vast gravitational sliding of a large portion of Etna's east flank (Neri et al., 2004).

3. Sampling and analytical methods

Between January 21st and October 7th of 2004, 227 measurements of radon and thoron from soil were carried out. Measurements were performed following a sampling grid of points that was kept as regular as possible, although the final geometry was affected by logistics (inaccessible areas, private properties, etc.). Because measurements were carried out in different periods (and seasons) of the year, they could be affected by variable environmental conditions and/or by variable degassing levels of the volcano/tectonic system. This could make the data not intercomparable. However, recent works carried out on soil CO_2 emissions from several areas of Mt. Etna (Giammanco and Bonfanti, 2009; Giammanco et al., 2010) showed that repeated samplings of soil gases over large areas during long periods of time did not

Table 1
Basic statistics for the soil radon and soil thoron activity data (both raw and Log_{10}-transformed) from the study area.

	N total	Mean	Stand. dev.	Skewness	Minimum	Median	Maximum
Results for the raw data							
Radon	227	10,100	11,000	1.82	267	6230	52,000
Thoron	227	14,600	12,000	1.24	31.3	12,900	64,600
Results for the log_{10}-transformed data							
Radon	227	3.75	0.51	−0.26	2.42	3.79	4.72
Thoron	227	3.95	0.54	−1.49	1.49	4.11	4.81