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The effects of environmental parameters on diffuse degassing at Stromboli volcano: Insights from joint monitoring of soil CO_2 flux and radon activity

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A B S T R A C T

Soil CO_2 flux and ^{222}Rn activity measurements may positively contribute to the geochemical monitoring of active volcanoes. The influence of several environmental parameters on the gas signals has been substantially demonstrated. Therefore, the implementation of tools capable of removing (or minimising) the contribution of the atmospheric effects from the acquired time series is a challenge in volcano surveillance. Here, we present 4 years-long continuous monitoring (from April 2007 to September 2011) of radon activity and soil CO_2 flux collected on the NE flank of Stromboli volcano. Both gases record higher emissions during fall–winter (up to 2700 Bq * m^{-3} for radon and 750 g m^{-2} day^{-1} for CO_2) than during spring–summer seasons. Short-time variations on ^{222}Rn activity are modulated by changes in soil humidity (rainfall), and changes in soil CO_2 flux that may be ascribed to variations in wind speed and direction. The spectral analyses reveal diurnal and semi-diurnal cycles on both gases, outlining that atmospheric variations are capable to modify the gas release rate from the soil. The long-term soil CO_2 flux shows a slow decreasing trend, not visible in ^{222}Rn activity, suggesting a possible difference in the source depth of the of the gases, CO_2 being deeper and likely related to degassing at depth of the magma batch involved in the February–April 2007 effusive eruption. To minimise the effect of the environmental parameters on the ^{222}Rn concentrations and soil CO_2 fluxes, two different statistical treatments were applied: the Multiple Linear Regression (MLR) and the Principal Component Regression (PCR). These approaches allow to quantify the weight of each environmental factor on the two gas species and show a strong influence of some parameters on the gas transfer processes through soils. The residual values of radon and CO_2 flux, i.e. the values obtained after correction for the environmental influence, were then compared with the eruptive episodes that occurred at Stromboli during the analysed time span (2007–2011) but no clear correlations emerge between soil gas release and volcanic activity. This is probably due to *i*) the distal location of the monitoring stations with respect to the active craters and to *ii*) the fact that during the investigated period no major eruptive phenomena (paroxysmal explosion, flank eruption) occurred. Comparison of MLR and PCR methods in time-series analysis indicates that MLR can be more easily applied to real time data processing in monitoring of open conduit active volcanoes (like Stromboli) where the transition to an eruptive phase may occur in relatively short times.

1. Introduction

Real-time monitoring of gas release (output and composition) at active volcanoes is useful to forecast changes in volcanic activity. Active volcanoes are characterised by persistent huge gas emissions from craters, fumaroles and also diffusively from soils (Allard et al., 1991; Burton et al., 2013; Inguaggiato et al., 2013) and systematic gas monitoring may help to detect precursory signals of incoming eruptions (e.g., Aiuppa et al., 2009; Padrón et al., 2013). In recent years, this approach was applied at several volcanoes to record geochemical changes during volcanic activity and to investigate their role before, during and after major eruptive episodes (including flank instabilities; e.g., Carapezza et al., 2004, 2009; Alparone et al., 2005; Cigolini et al., 2005). Another open and debated issue is the role of degassing prior the onset of earthquakes (Toutain and Baubron, 1999; Salazar et al., 2001) and during earthquake–volcano interactions including seismic–volcanic unrest (Cigolini et al., 2007; Padilla et al., 2014).

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Carbon dioxide, after water, is the most abundant volatile dissolved in magmas and, because of its relatively low solubility in magmatic liquids, it is essentially released at higher depths and before other gas species (Pan et al., 1991, Papale et al., 2006). Notably, measurements of soil CO_2 fluxes or CO_2 concentrations in volcanic plumes, are critical for detecting degassing processes related to changes in the plumbing system of the volcano.

Radon is a noble gas, a daughter decay product of ^{226}Ra and belongs to the ^{238}U decay chain. Due to its short half-life ($t_{1/2} = 3.82$ days), ^{222}Rn can be used as a tracer of both diffuse and localised degassing since it can substantially be measured everywhere. Radon concentrations may be moderate during diffuse degassing, but during fracture opening they may reach extremely high values (higher than 10^6 Bq/m^3, as measured in Stromboli crater area; Cigolini et al., 2013). Its ascent toward the surface is strictly ruled by the mobility of other gas phases, such as CO_2 and H_2O defined as "carrier gases" (Gauthier and Condomines, 1999). The jointed measurements of soil CO_2 flux and ^{222}Rn activity have been used in search of possible volcanic activity and seismic precursors (Makario Londoño, 2009), as well as to track fluid migration and outgassing along active faults, fractures or fumaroles (Baubron et al., 2002; Faber et al., 2003; Zimmer and Erzinger, 2003). Particularly, in volcanic areas, the combined surveys of ^{222}Rn, ^{220}Rn and CO_2 measurements allow to investigate the role developed by different sources or factors (i.e. rock fracturing, fumaroles or magma) on the degassing rate. (Giammanco et al., 2007; Siniscalchi et al., 2010). Moreover, this method has shown its efficiency to track the evolution of a volcanic unrest phase (Padilla et al., 2013).

Continuous and automatic measurements substantially increase the possibility to identify precursory signals, since the data are easily collected, transferred and processed in near real-time (Brusca et al., 2004; Viveiros et al., 2008; Cigolini et al., 2009; Carapezza et al., 2009). Environmental parameters are critical in modulating gas release from soils, including radon and CO_2 (Pinault and Baubron, 1996; Carapezza and Granieri, 2004; Pérez et al., 2007; Cigolini et al., 2009) and their effects must be considered during continuous geochemical monitoring.

In this respect, a promising challenge is to establish a fully-automated data processing able to minimise the effects of environmental factors on the acquired data. In this way, data obtained by the geochemical monitoring networks can be easily transferred to the authority responsible of volcano surveillance. The statistical treatment or the spectral analysis of the data are the mostly used methods to recognise and remove the contribution of the atmospheric factors (e.g., Carapezza et al., 2009; Laiolo et al., 2012; Rinaldi et al., 2012; Silva et al., 2015; Viveiros et al., 2008, 2014). Particularly, the spectral analysis may be positively applied to recognise diurnal to seasonal cycles and to investigate the processes ruling the release of gases from soils (Rinaldi et al., 2012; Martin-Luis et al., 2015).

Radon concentrations can be diluted by major fluxes of CO_2 and water vapour (e.g., Giammanco et al., 2007; Siniscalchi et al., 2010). Recently, Girault et al. (2014) and Girault and Perrier (2014) have shown, at the Syabru-Bensi hydrothermal system (Central Nepal), that radon is generated from a shallow source (a rock thickness of 100 m is sufficient to account for the observed radon discharge) and incorporated into upraising CO_2. In active volcanoes radon can be carried to the surface from great depths along major faults. Cigolini et al. (2013) have shown that high radon emissions can be related to the ascent of CO_2-bearing hot fluids along the fractures (200–300 m deep) surrounding the crater rim of Stromboli volcano (at about 700–720 m a.s.l.) and well correlate with the estimated depth of the source region of VLP events (e.g., (Chouet et al., 1997; Marchetti and Ripepe, 2005). Previous investigations have shown that CO_2 fluxes and ^{222}Rn concentrations at Stromboli are within the range of those measured in other open-conduit active volcanoes (Cigolini et al., 2013; Inguaggiato et al., 2013).

In this paper, we present 4 years of continuous monitoring of ^{222}Rn activity and soil CO_2 flux collected by two automatic stations located on the north-eastern upper flank of Stromboli Island (Fig. 1). The measurement sites have been chosen in the light of previous surveys: anomalous radon values were recorded in this site during periods of sustained volcanic activity and before, during and after the paroxysmal explosion of March 15, 2007 (Cigolini et al., 2013). Similarly, systematic measurements of soil CO_2 flux revealed anomalous degassing areas on the volcano slopes and this site has been identified as a potential target for continuous monitoring (Carapezza et al., 2009).

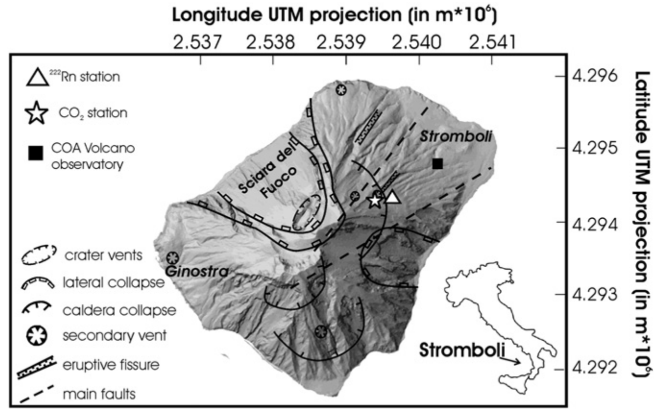

Fig. 1. Digital elevation model of Stromboli Island (from Baldi et al., 2005) with major faults and collapsed sectors (simplified from Finizola et al., 2002 and Tibaldi et al., 2009). Locations of the Volcano Observatory (COA) and of the radon and CO_2 flux stations are reported.

2. Stromboli volcano

Stromboli is the north-easternmost island of the Aeolian archipelago and reaches an elevation of 924 m a.s.l. (Fig. 1). It is a composite strato-volcano consisting of lava flows alternated with abundant tephra deposits. The emerged part of the volcanic edifice was built in the last 100 ky (Francalanci et al., 1989; Hornig-Kjarsgaard. et al., 1993). The morphology of the island results from periods of extrusive growth alternated to lateral collapses, in turn related to dyke intrusions, magma upwelling and regional tectonics (Tibaldi, 2003, 2004; Corazzato et al., 2008). The volcano is well known for its typical persistent explosive activity called Strombolian, that started approximately 2 ky ago (Rosi et al., 2000; Arrighi et al., 2004). Strombolian activity is characterised by continuous degassing with the emission, on average every 15–20 min, of juvenile material (glowing scoriae, lapilli and ash) ejected from the active vents located within the crater terrace at ~700 m. a.s.l. This mild explosive activity is episodically interrupted by lava flows, major and paroxysmal explosions (Barberi et al., 1993, 2009) that can be accompanied by flank failure and collapses, which may also generate tsunamis, like in 1930 and recently in December 2002 (Tinti et al., 2006). Paroxysmal events, such as the ones occurred on April 5, 2003 and March 15, 2007, are the most violent volcanic explosions of Stromboli and are characterised by the ejection of the so-called "golden pumices" (nearly aphyric, phenocrysts <10 vol%, highly vesicular >50 vol%, low viscosity K-basaltic pumiceous materials; Métrich et al., 2005, 2010). These ejecta are generally mixed with degassed scorias (the latter also ejected during the typically mild Strombolian activity) and with ballistic solid blocks. The CO_2 and H_2O contents measured in primitive melt inclusions, found within forsteritic olivines of the golden pumices, indicate that these materials represent the undegassed magma residing in the deeper part of the Stromboli plumbing system (Bertagnini et al., 2003; Francalanci et al., 2004; Métrich et al., 2005; Cigolini et al., 2008, 2014).

Soon after the 2002–2003 effusive event, a great improvement of the monitoring system was undertaken under the coordination of the Italian Civil Protection Department. This advance on ground-based monitoring allowed the scientific community to acquire a great amount of geophysical, geochemical and geodetic data during the most recent effusive episodes, as well as during the span of time characterised by low to high explosive activity (cf. Barberi et al., 2009; Ripepe et al.,