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Preliminary radon measurements at Villarrica volcano, Chile

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ABSTRACT

We report data from a radon survey conducted at Villarrica volcano. Measurements have been obtained at selected sites by E-PERM® electrets and two automatic stations utilizing DOSEman detectors (SARAD Gmbh). Mean values for Villarrica are 1600 (±1150) Bq/m^3 are similar to values recorded at Cerro Negro and Arenal in Central America. Moderately higher emissions, at measurement sites, were recorded on the NNW sector of the volcano and the summit, ranging from 1800 to 2400 Bq/m^3. These measurements indicate that this area could potentially be a zone of flank weakness. In addition, the highest radon activities, up to 4600 Bq/m^3, were measured at a station located near the intersection of the Liquiñe-Ofqui Fault Zone with the Gastre Fault Zone.

To date, the Villarrica radon measurements reported here are, together with those collected at Galeras (Colombia), the sole radon data reported from South American volcanoes. This research may contribute to improving future geochemical monitoring and volcano surveillance.

1. Introduction

The measurement of radon emissions from active volcanoes represents an additional tool to detect variations in volcanic activity and forecast eruptions. In-soil radon measurements at active volcanoes can also provide useful information on the occurrence and the magnitude of diffuse degassing along their flanks. Volcanic areas are generally affected by the release of gases along faults, fractures and fumaroles (cf. Chiodini et al., 1996; Giammanco et al., 2007). However, some volcanoes, generally characterized by persistent out-gassing from active vents (i.e., open conduit volcanoes), may show very low emissions at proximal and distal areas (Williams-Jones et al., 2000; Varley and Armienta, 2001), and gases are essentially concentrated within the plume itself (due to the high permeability that develops at the conduit–wallrock interface when the magma is approaching the vent, cf. Cigolini et al., 1984).

Radon is a noble, chemically inert gas, constantly generated in rocks, soils and crustal materials. It is principally represented by the isotope ^{222}Rn (with a half life of 3.82 days) and it easily enters the rock pores and migrates to significant distances from the site of origin before its decay. Measuring the variations of radon, induced only by physical factors since it is not a reactive element, can provide valuable information on volcanic degassing as well as on the dynamics of fluid transport processes (cf. Heiligmann et al., 1997; Trique et al., 1999; Cartagena et al., 2004).

Variations in radon concentration have been observed before and during the onset of regional seismic events with magnitude 4 or higher (Scholtz et al., 1973; Fleischer and Mogro-Campero, 1985; Igarashi et al., 1995; Planinić et al., 2004; Pulinets et al., 2009; Cigolini, 2010).

Chirkov (1975) was the first scientist to report an increasing trend followed by an anomalous peak in radon concentration prior to the 1971 eruption at Karimsky volcano, Kamchatka. In later years, radon anomalies related to changes in volcanic activity and the onset of volcanic eruptions, have been extensively reported (Cox, 1980, 1983; Thomas et al., 1986; Segovia and Mena, 1999). In particular, the latter authors concentrated their work on four explosive American stratovolcanoes (El Chichón and Popocatépetl in Mexico, Poás in Costa Rica, and Cerro Negro in Nicaragua): they showed a positive correlation between the increase in radon activity (related to the initial stages of volcanic eruptions) and the Volcanic Explosivity Index (VEI) of single eruptions. According to their findings, the ratio: peak Rn-values/mean quiescence R_n-values, may be as high as 22.6 for eruptions with VEI $= 5$ (such as the eruption that occurred at El Chichón, on March 28, 1982). For minor eruptions observed at the cited Central America Volcanoes (with VEI < 2), the above ratios ranged from 4 to 4.8.

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More recently, Cigolini et al. (2001) used a network for radon monitoring at Mount Vesuvius to differentiate signals produced by regional earthquakes from those derived from the local volcanic seismicity. Burton et al. (2004), on the basis of radon measurements, were able to infer the geometry of a hidden fault at Mount Etna during a period of marked flank seismicity (October 2002). Cigolini et al. (2007) detected earthquake–volcano interactions at Stromboli volcano: radon anomalies occurred with a time-delay with respect to the onset of major regional seismic events. Radon anomalies regarded as precursors of volcanic eruptions have been reported by several authors (e.g., Connors et al., 1996; Alparone et al., 2005; Cigolini et al., 2005). However, degassing in volcanic areas (diffuse and/or concentrated) may be particularly efficient and its monitoring is crucial in volcano surveillance (e.g., Allard et al., 1991; Carapezza et al., 2004; Viveiros et al., 2008). In addition, systematic radon measurements have been carried out at several active volcanoes in Central America (Varley and Armienta, 2001; Williams-Jones et al., 2000) and Southern America (Heiligmann et al., 1997). Radon transport to the surface occurs along faults or fractures, and it is controlled by bulk porosity and permeability. It essentially migrates by convection and advection at a larger scale, but at the site-scale diffusion may be considerably effective (cf. Dueñas et al., 1997). Moreover, the radon gas is passively carried by water and carbon dioxide (e.g., Gauthier and Condomines, 1999). The role of environmental parameters has been shown to be critical in modulating in-soil radon concentrations (e.g., Mogro-Campero and Fleischer, 1977; Pinault and Baubron, 1996; Zimmer and Erzinger, 2003; Pérez et al., 2007; Laiolo et al., 2012). Similarly, the effects of environmental parameters on CO_2 degassing have been reported by Viveiros et al. (2008) and Carapezza et al. (2008).

Automatic alpha particles detectors and real-time radon measurements considerably improve field surveys (cf. Siniscalchi et al., 2010) and monitoring strategies (cf. Neri et al., 2006; Cigolini et al., 2009). Nowadays, radon data can be automatically transferred and elaborated, enabling us to filter the effects of environmental parameters on radon degassing (cf. Laiolo et al., 2012). This allows us to refine volcano surveillance and alert procedures.

The main purpose of this paper is to present the results of a radon survey at Villarrica volcano by using different methods and techniques. We provide measurements on local emissions also outlining their spatial variations that seem to be related to specific structural and volcanological conditions. In addition, we compare our results with soil radon measurements acquired at other Central and Southern American volcanoes.

2. Villarrica volcano

Villarrica is an ice-capped composite volcano located in Central Chile (39.42°S, 71.95°W; 2847 m in altitude), near the town and lake of the same name (Fig. 1). The base area of the cone reaches 110 km^2 whereas the glacier at its summit extends for about 30 km^2 (Rivera et al., 2008). Climbing this volcano is challenging due to variations in climate and the presence of several crevasses hidden below the snow cover (Fig. 2). Villarrica volcano lies in the Southern Central Volcanic Zone (Lara and Clavero, 2004; Ortiz et al., 2003) and grows onto an NW–SE volcano-tectonic segment that includes the edifices of Quetrupillán and Lanín (proceeding eastward toward the structural axis of the orogen). This alignment runs parallel to the Gastre Fault Zone (Bohm et al., 2002) that is, in turn, affecting basement rocks and is located approximately 5 km North of Villarrica (Fig. 1). This fault zone displaces the Liquiñe-Ofqui Fault Zone (LOFZ) that runs parallel to the structural axis of this portion of the orogen (Melnick et al., 2002). The early Villarrica edifice grew inside a minor caldera, approximately 2 km wide that was formed 3500 years ago within a larger caldera ($\sim$6 km in diameter) during the early Pleistocene (Moreno et al., 1994a; Clavero and Moreno, 2004). Older lavas were essentially basalts to basaltic andesites and their composition has not changed substantially over time. However, domes and tephra of dacitic composition have been reported in basal deposits related to the major caldera (Moreno, 1993; Moreno et al., 1994b; Clavero and Moreno, 1994; Witter et al., 2004; Hickey-Vargas et al., 2004). Several parasitic cones and fissure vents may be observed along its flanks. Plinian ignimbrites and pyroclastic flows were emplaced during the Holocene and may reached distances of about 20 km (Silva Parejas et al., 2010; Lohmar et al., 2007). Similarly, lava flows (up to 18 km in length) were erupted from the summit vents and flank fissures and could easily reach the base of the cone. Historical eruptions have been recorded since 1558 and consist of strombolian-type eruptions with mild to moderate explosivity occasionally accompanied by lava effusions. Lahars may generate during eruptive periods and could be dangerous: they caused more than 100 fatalities during the twentieth century alone (Naranjo and Moreno, 1991).

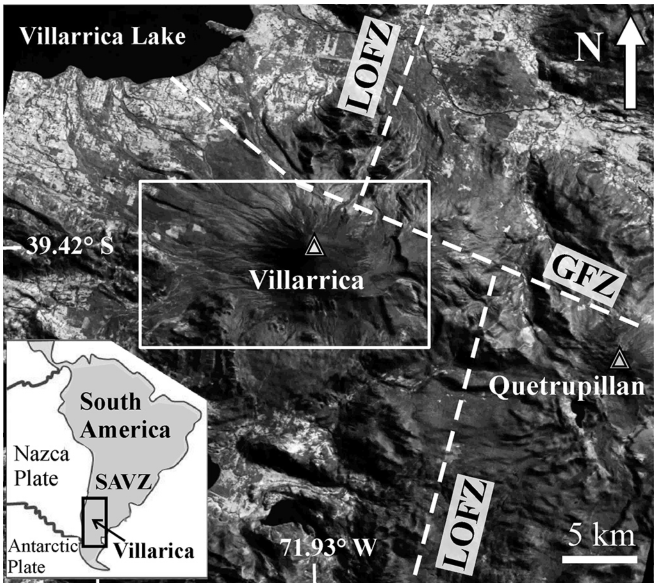

Fig. 1. Location map of Villarrica volcano and surrounding area. Dotted white lines represent the main recognized regional structures: LOFZ – Liquiñe-Ofqui Fault Zone; GFZ – Gastre Fault Zone (modified after Volland et al., 2007; Lohmar et al., 2007). Inset shows the location of Villarrica volcano within the Southern Andean Volcanic Zone (SAVZ). The rectangle represents the limits of the area investigated in this work.

The regional tectonic setting has been described by López-Escobar et al. (1995), Lavenu and Cembrano (1999), and Ortiz et al. (2003). The Central Southern Volcanic Zone (CSVZ) of the Southern Andes runs NNE for approximately 1000 km along the so-called Liquiñe-Ofqui Fault Zone (with a dextral strike-slip motion) (Cembrano and Herve, 1993; Lavenu and Cembrano, 1994; López-Escobar and Moreno, 1994). Its northern sector is offset by the Gastre Fault Zone, trending N60W and running parallel to the Villarrica-Quetrupillán-Lanín alignment (Moreno, 1974; Cembrano and Moreno, 1994; Ortiz et al., 2003). It is well known that most of the eruptions of the Villarrica are triggered by regional earthquakes located above fracture zone or to the north of it (Petit-Breuilh, 1994). This cause-effect link was first reported for several Chilean volcanoes (Casertano, 1963; Barrientos and Acevedo, 1992; Barrientos, 1994) but its occurrence has been recently investigated in different volcano-tectonic domains (Hill et al., 2002; Cigolini et al., 2007; Delle Donne et al., 2010).

Since 1558, several eruptions of Hawaiian, strombolian, and/or violent strombolian type with explosivity index VEI < 3, have