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RADON AND CO$_2$ EMISSIONS IN DIFFERENT GEOLOGICAL ENVIRONMENTS AS A TOOL FOR MONITORING VOLCANIC AND SEISMIC ACTIVITY IN CENTRAL PART OF COLOMBIA

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RESUMEN

Se realizaron mediciones de emisiones de gas ^{222}Rn (radon) y CO$_2$ en suelo, durante varios años en tres diferentes ambientes geológicos en la parte central de Colombia: Volcán Nevado del Ruiz (VNR), una zona volcánica activa; Eje Cafetero (EC), una zona tectónicamente activa; y el Volcán Cerro Machín (VCM), una zona volcánica que está iniciando un proceso de reactivación. Esto con miras a comparar los niveles de emisión y hacer seguimiento a la actividad sísmica y volcánica. Se instalaron tres redes con un total de 16 estaciones. El VNR mostró los valores más altos de emisión de radón, seguida por el VCM y finalmente el EC. Se detectaron cambios temporales en radón y CO$_2$ para el EC y VCM, asociados con actividad sísmica. Aunque el VNR mostró los mayores valores de emisión de radón, presentó estabilidad en su actividad durante el período estudiado, algo que podría indicar un efecto retardado a posteriori en su actividad, lo que implicaría mayor actividad volcánica en un tiempo posterior, dado que el VNR aún se encuentra en un estado activo. El VCM presentó cambios temporales, que podrían estar asociados al incremento paulatino de su actividad.
Se calculó la relación ^{222}Rn/CO$_2$ para varias estaciones. La relación fue similar para las tres zonas, y los cambios temporales en esta relación se asocian a sismicidad en las tres zonas NRV, EC y VCM. Las mediciones periódicas de radón y CO$_2$ son una buena herramienta para la vigilancia volcánica y sísmica en esta región. Es importante contar con una línea base para entender mejor el fenómeno. Por lo tanto, es necesario continuar con el programa de mediciones regulares en esta región.

Palabras clave: Gas Radón, CO$_2$, sismicidad, volcán, actividad volcánica, pronóstico.

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ABSTRACT

^{222}Rn (radon) and CO$_2$ emissions in soil has been measured during a lapse time of several years in three different geological environments at the central part of Colombia, namely Nevado del Ruiz Volcano (NRV), an active volcanic area, Coffee Axes (CA), an active tectonic zone, and Cerro Machín Volcano (CMV), a zone starting a volcanic reactivation process, in order to compare levels of emissions and to monitoring volcanic and seismic activity. Three networks were deployed, with a total of 16 stations. NRV zone showed the highest values of radon emission, followed by CMV and finally CA. Temporal changes of radon and CO$_2$ emissions were detected for CA and CMV, related with seismic activity. Although NRV showed stability during the studied period, in agreement with steady tendency in radon emissions, high levels of radon emission were detected. This could be related with the level of activity of NRV, which is still in an active stage, and probably there is a delay effect on its activity, implying a future increase in its activity. For CMV, some temporal changes were detected too, associated probably with the increase in activity of this volcano. ^{222}Rn/CO$_2$ ratios were calculated for several stations. Ratios were similar for the three zones, and temporal changes in that ratio were associated with seismicity at NRV, AC and CMV. Regular measurements of radon and CO$_2$ emissions is a good tool for monitoring volcanic and seismic activity in this region. A base line of data is an important initial step to understand the phenomena; therefore, it is necessary to continue with the program of regular measurements in this region.

Key words: Radon gas, CO$_2$, seismicity, volcano, volcanic activity, prognostic

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INTRODUCTION

^{222}Rn emissions have been used for the prognostic of seismic activity, and recently as a tool for prognostic of volcanic activity (Williams et al, 2000; Italiano et al, 1998; Bräuer et al, 2003; Lewicki et al, 2003; Reddy et al, 2004). It is well known that the Radon gas is sensitive to stress changes inside crust. It is believed that radon is a tracer of CO_2 degassing in volcanic and tectonic active regions, where CO_2 is more abundant (Burton et al, 2004). Some volcanoes have shown important changes in ^{222}Rn emission before eruption (Cigolini et al, 2005). On the other hand, faulting process involves ^{222}Rn release before rupture process (Wakita, 1996).

^{222}Rn periodical measurements have been implemented in several Volcanological and seismological observatories around the world, in order to monitoring volcanic and tectonic activity. At the central part of Colombia, there are several regions with complex geological features. It is the case of the volcanic chain known as the Cerro Machín – Cerro Bravo volcanic Complex, where several active volcanoes are present, such as Nevado del Ruiz Volcano (NRV) and Nevado del Tolima. NRV, is well-known for the catastrophic eruption of November 13th 1985, where more than 20.000 people died. NRV is an active volcano with permanent fumaroles and seismic activity. Cerro Machín volcano (CMV) is a volcano that recently is showing signals of reactivation, after 800 years of quiescence. Seismic activity and changes in geochemical parameters have been detected in last 5 years. The Axes Coffee (AC) is a region tectonically active with major earthquakes occurring periodically (1979, ML=6.3; 1995, ML=6.0; 1999, ML=6.3). It is located in a subduction zone, with important superficial tectonic activity due to many faults crossing the region. The Volcanological and Seismological Observatory of INGEOMINAS (Colombia Geological Survey) in Manizales city, has established a permanent network for monitoring ^{222}Rn y CO_2 in soil, to monitoring the volcanic and seismic activity of this region in the central part of Colombia.

During several years, the ^{222}Rn network has been working continuously, with periodical measurements. The purpose of this work is to analyze those data, and compare the ^{222}Rn emissions in this three different geological environments in the central part of Colombia.

METHOD

The ^{222}Rn stations were deployed using PVC tubes, buried 1.5m in soil, and an E-PERM passive monitor system, composed of an Electret and a chamber (Kotrappa et al, 1988; Kotrappa et al, 1990) was installed inside the tube. Then the tube was sealed with a cup and covered with silicone to protect the station. Replacement of E-PERM system were done regularly. For the CO_2 stations, an alumina tube of 1.5m with an adapted medical venoclisis system at the top is buried in soil, and used to trap CO_2 inside the hose, avoiding the escape of the gas. When sample was taken, the hose was open and gas was evacuated by using a pump, which vacuums the hose. Places to deploy stations were carefully selected, avoiding those with no humus, in order to use it as a seal. Each ^{222}Rn and CO_2 stations were installed in the same place, in order to compare data. FIGURE 1 shows an example of the deployment of an station configuration system.

^{222}Rn emissions were calculated by using Kotrappa et al (1988) and Kotrappa et al (1990) procedure. A SPERM-1 reader was used to measure the voltage decay into the E-PERM system (Electret). Error of readings are in the range of 7% according factory sheet. Another possible sources of error are the E-PERM system (chamber volume and Electret thickness) factory parameters (<5%) and gamma radiation at measurement point. Therefore, we assume a total error less than 10% for each measurement. Corrections for gamma radiation, altitude, and calibration factors were applied to the data prior to calculate ^{222}Rn concentration. After all corrections, ^{222}Rn concentration is calculated by the following equation:

$$^{222}RnC = \frac{(Vi - Vf)}{(T * CF)} - BGR$$

Where:

^{222}RnC is the concentration of radon in pCi L^{-1},

Vi and Vf are the initial and final voltages in volts respectively,

T is the exposure time in days,

CF is the calibration factor (given by factory chart) in pCi L^{-1},

BGR is the Rn concentration equivalent of natural gamma radiation background in pCi L^{-1}

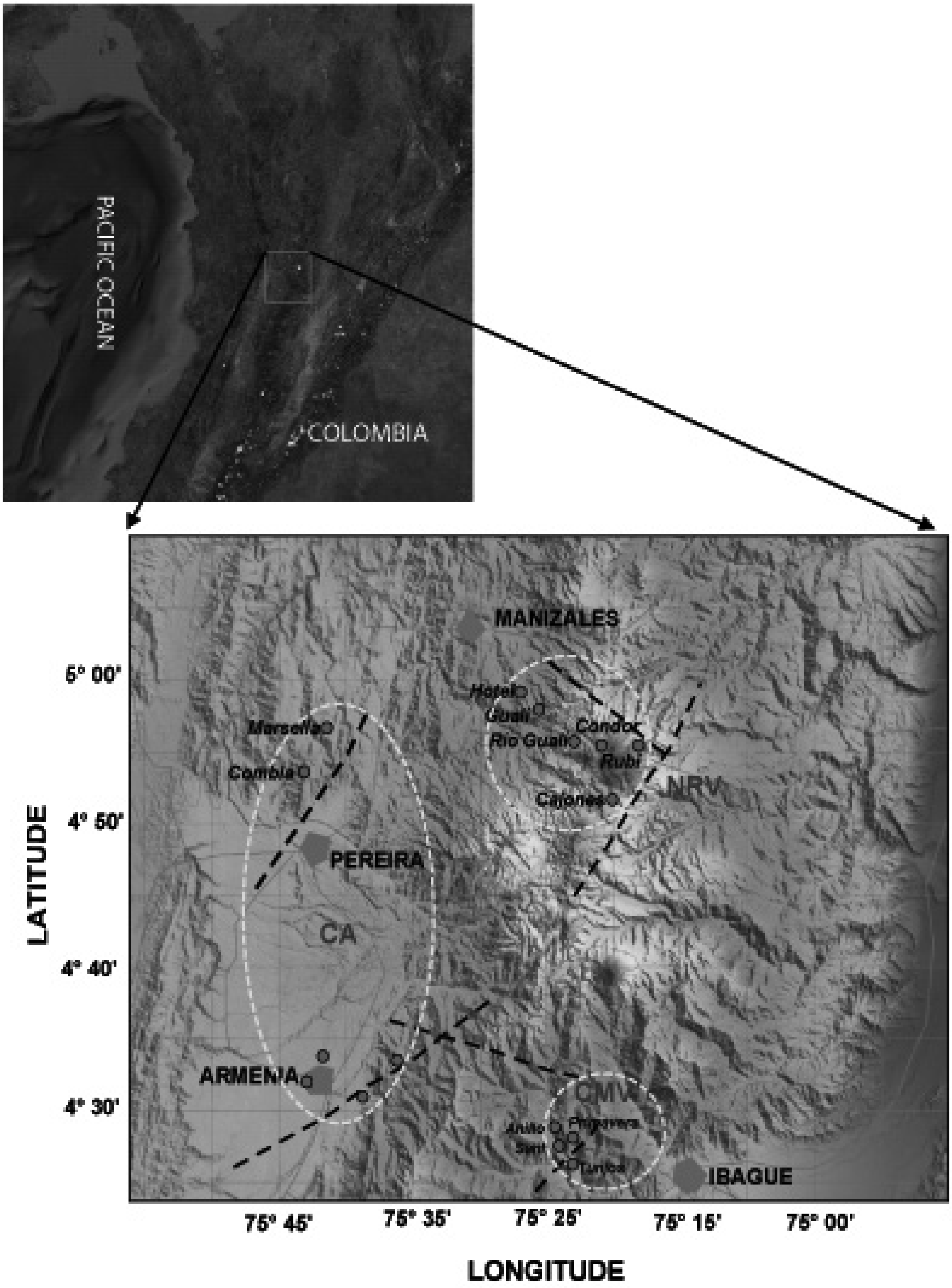


FIGURE 1. Location of Radon and CO_2 stations (red circles) used in this study (NRV=Nevado del Ruiz volcano, CMV=Cerro Machín volcano). Main cities (gray polygons) and roads (brown thick lines) are indicated. Some level contours (thin gray lines) are included too.

The CO2 soil emission samples were obtained taking the CO_2 trapped in, by a syringe and storaged in a vacutainer tube of 10mL. Then, samples were analyzed in a gas Chromatograph Philips PU-4410, with detection level of 0.01% of CO_2.

DATA AND PROCESSING

A network was established to measure periodically ^{222}Rn (hereafter radon) and CO_2 emissions in soil. 14 stations were installed into three different geological environments; an active volcano with recent eruption corresponding to Nevado del Ruiz Volcano (NRV), a volcano in quiescence period, starting to reactivate, corresponding to Cerro Machín Volcano (CMV), and finally, a tectonically active region, corresponding to Coffee Axes (CA) at the central part of Colombia. FIGURE 2 shows the location of the network.

Data were collected regularly, every 10 days approximately, although sometimes data were taken more spaced in time due to different situations (weather conditions, logistical problems, among others). After radon and CO_2 calculations, data were processed for each station. The NRV network was installed since 2003 up to date, CMV network was installed since 2006 and AC network was installed since 2006-2007. Data were grouped by areas, and statistics analysis were done.

Earthquakes recorded by the seismic network of the INGEOMINAS, Volcanological Observatory of Manizales, were used to compare with radon data. High quality local earthquakes and volcano-tectonic earthquakes were selected for the analysis. FIGURE 2 shows the epicenters of selected earthquakes.

RESULTS

FIGURE 4 shows the time series for each station at each Network. Temporal changes can be observed in NRV, CMV and CA networks, probably associated with seismic activity (see later). Figure 5 shows same results as Figure 4, but in a cumulative fashion. In this figure, is possible to observe that levels of radon emissions for each geological setting are different. NRV showed the higher values, followed by CMV, and finally by CA.

In order to compare seismicity and radon and CO_2 emissions, earthquakes with local magnitudes larger than 2, were selected. In addition, for NRV and CMV areas, only those earthquakes with epicentral distance shorter than 5Km were selected. For AC, earthquakes with epicentral distance shorter than 20Km were selected (FIGURES 4, 5 and 6).

At NRV, there are few increasing in radon emissions during the studied period. This is in agreement with the activity of this volcano, which has been stable during last 10 years, but as it was mentioned before, NRV is an active volcano showing high values of radon emission.

CMV is a volcano with relatively low activity, starting a reactivation process, probably since 2005, after more than 800 years of quiescence. Some increases in radon emission at CMV, were associated with the occurrence of earthquakes, especially those registered on December 28th 2008 (M_L=3.7), and November 9th 2008 (M_L=4.3). This results suggest that, radon emissions are useful for monitoring increasing in volcano-tectonic activity at volcanic regions. Some temporal increases in CO_2 were observed prior to radon increase. This fact seems to be related with the assumption that radon traces de CO_2 degassing, and that CO_2 degassing carries from deeper sources by diffusivity the radon to upper places near the surface (Burton et al, 2005).

CA is an active tectonic regions, with many faulting processes occurring today, as it was mentioned previously. Some increases in radon emissions were associated with occurrence of earthquakes in this region, but in general, few strong earthquakes have been recorded in last years in this region, in agreement with the results of radon and CO_2 emissions.

The $^{222}Rn/CO_2$ ratio was calculated for selected stations with available data (FIGURE 6). Temporal changes in $^{222}Rn/CO_2$ ratio related with seismicity were detected in some stations AC, At NRV and CMV. At AC the temporal changes were observed more clearly than at NRV and CMV. This is noteworthy, since it can indicate that, for seismic activity related with tectonic activity, the $^{222}Rn/ CO_2$ ratio is a very good tool for monitoring occurrence of seismic events. The tendency of the $^{222}Rn/CO_2$ ratio curve and the occurrence of earthquakes is rather similar, indicating some physical mechanism that is activated before or after the earthquakes, which affects the physic-chemical conditions of the media.

On the other hand, radon vs CO_2 emissions were plotted for all stations in order to observe if there were any tendency. FIGURE 7 shows the results. For NRV area, almost all stations showed similar distribution for radon and CO_2; higher values of radon corresponded to GUALI and HOTEL stations, which are located near a fault that crosses near the active crater of NRV, while CAJONES showed the lowest values, and it is located far away to the southern part of the volcano. This could indicate that NRV has zones with different porosity levels. Probably The northwest zone is more porous than southern zone, where many lava flows are present.

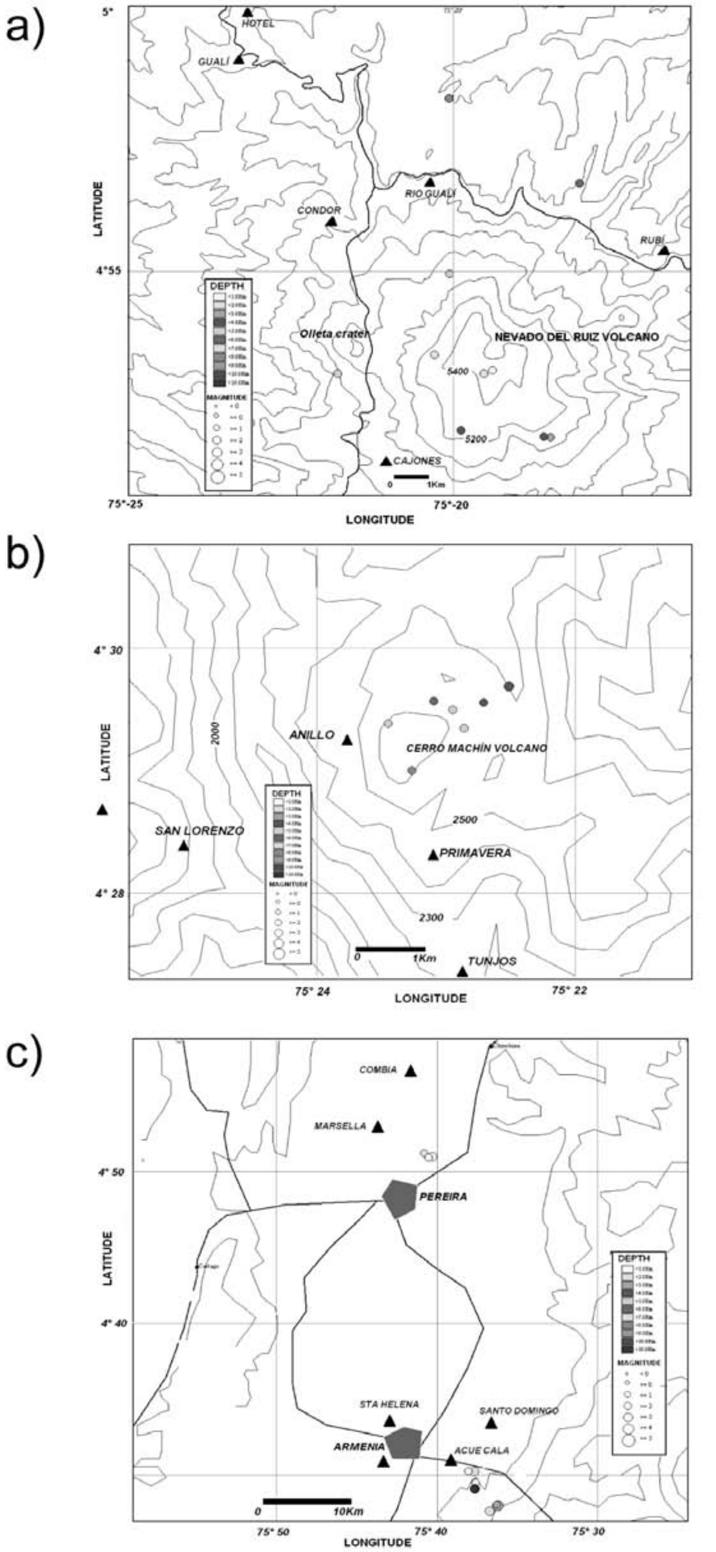


FIGURE 2. Earthquakes (solid colored circles) used for comparison with radon and CO_2 emissions. a) NRV; b) CMV; c) CA. Solid triangles represent radon station. Some topographic curves are plotted.

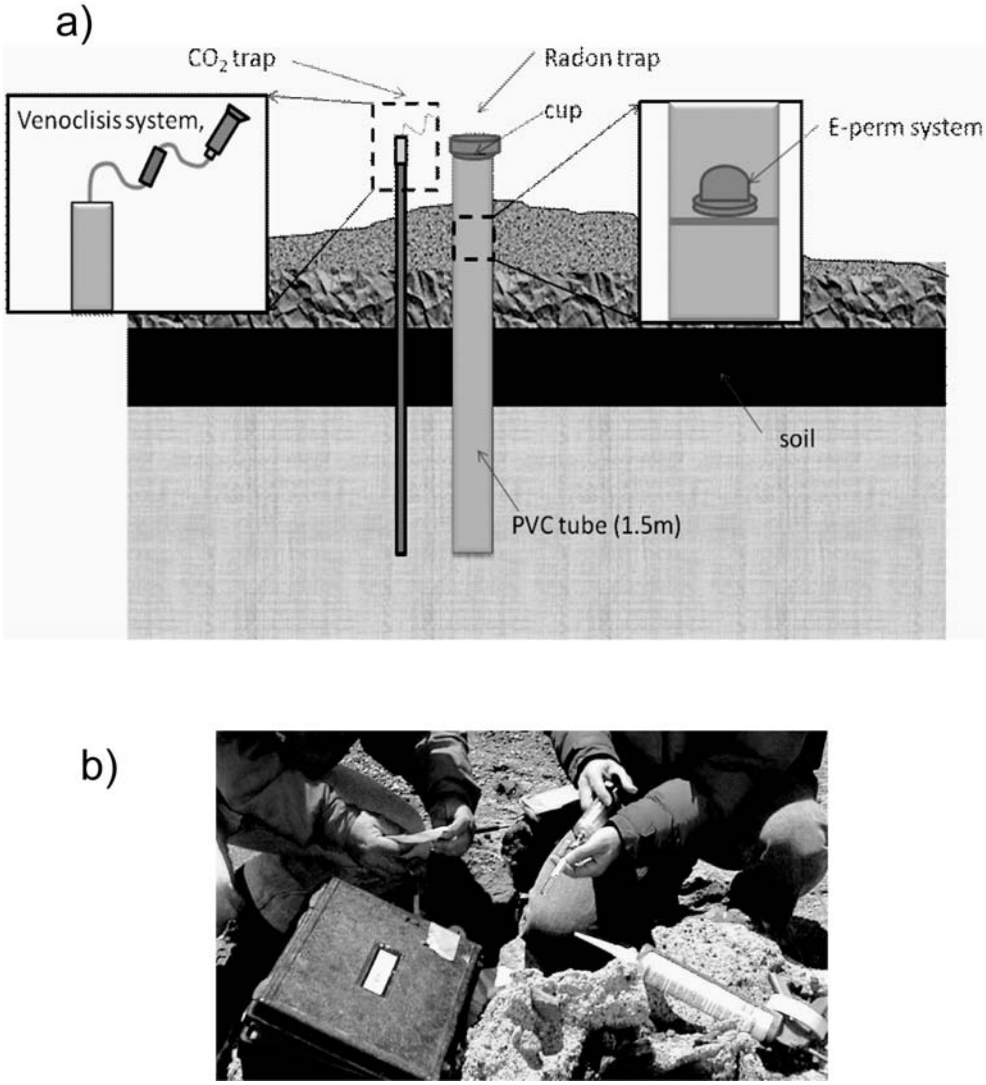


FIGURE 3. a) Example of radon and CO_2 in soil station deployment, used in this study. b) collecting data.

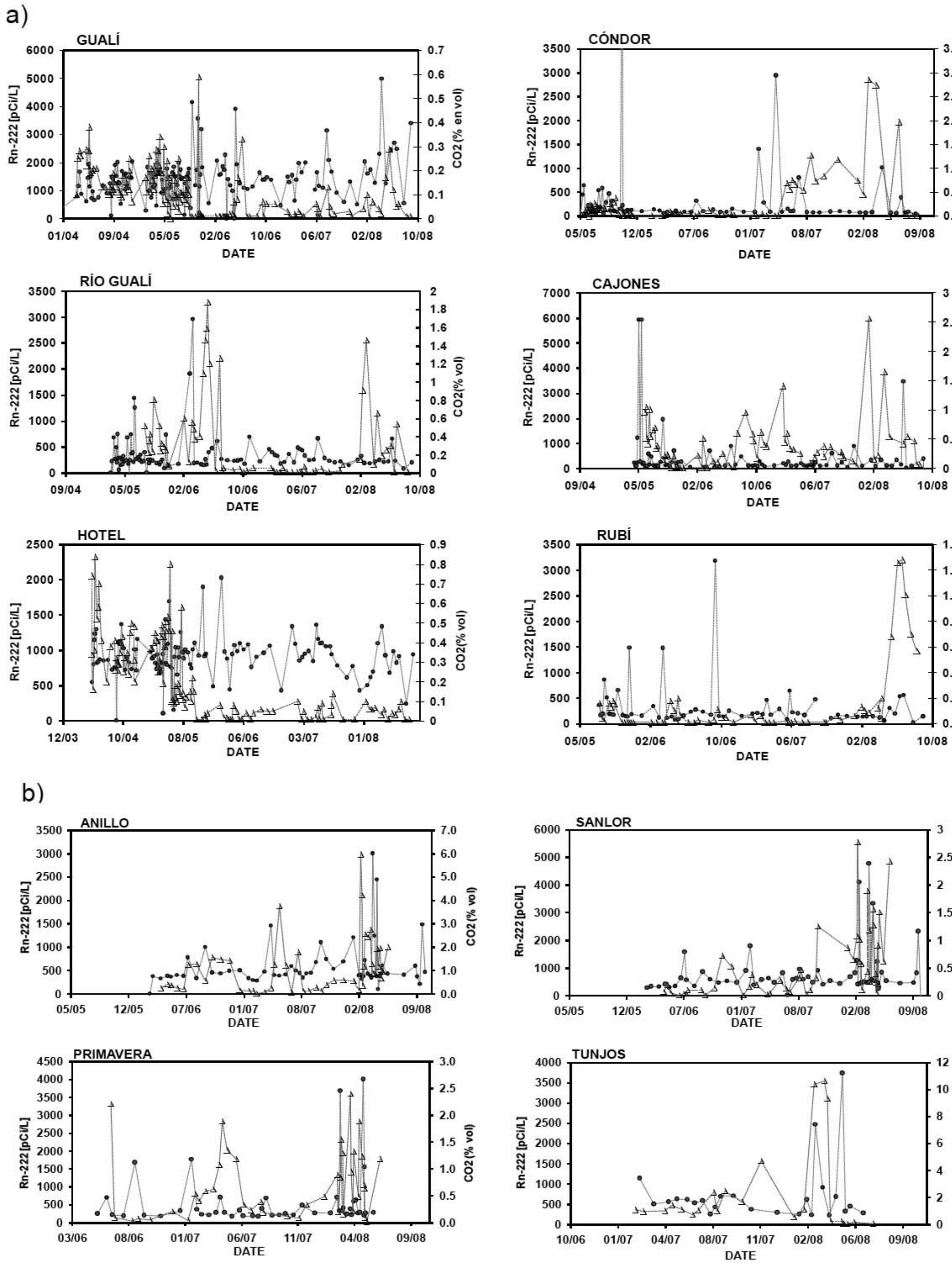
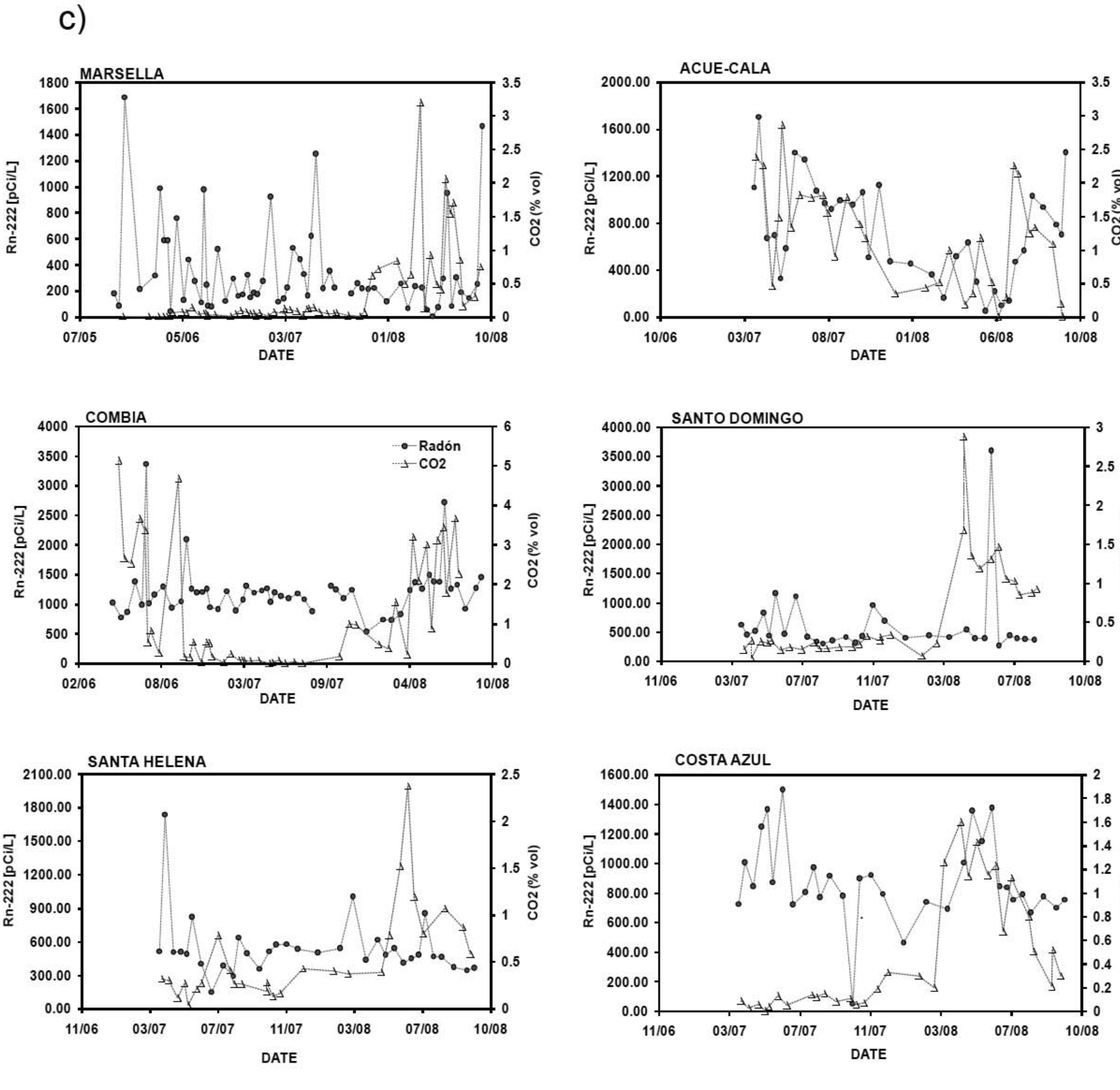


FIGURE 4. Radon (circles) and CO_2 (triangles) emissions at each station used in this study. A) Nevado del Ruiz Volcano area (NRV); b) Cerro Machín Volcano area (CMV); c) Coffee Axes area (CA).



CONT. FIGURE 4. Radon (circles) and CO_2 (triangles) emissions at each station used in this study. A) Nevado del Ruiz Volcano area (NRV); b) Cerro Machín Volcano area (CMV); c) Coffee Axes area (CA).

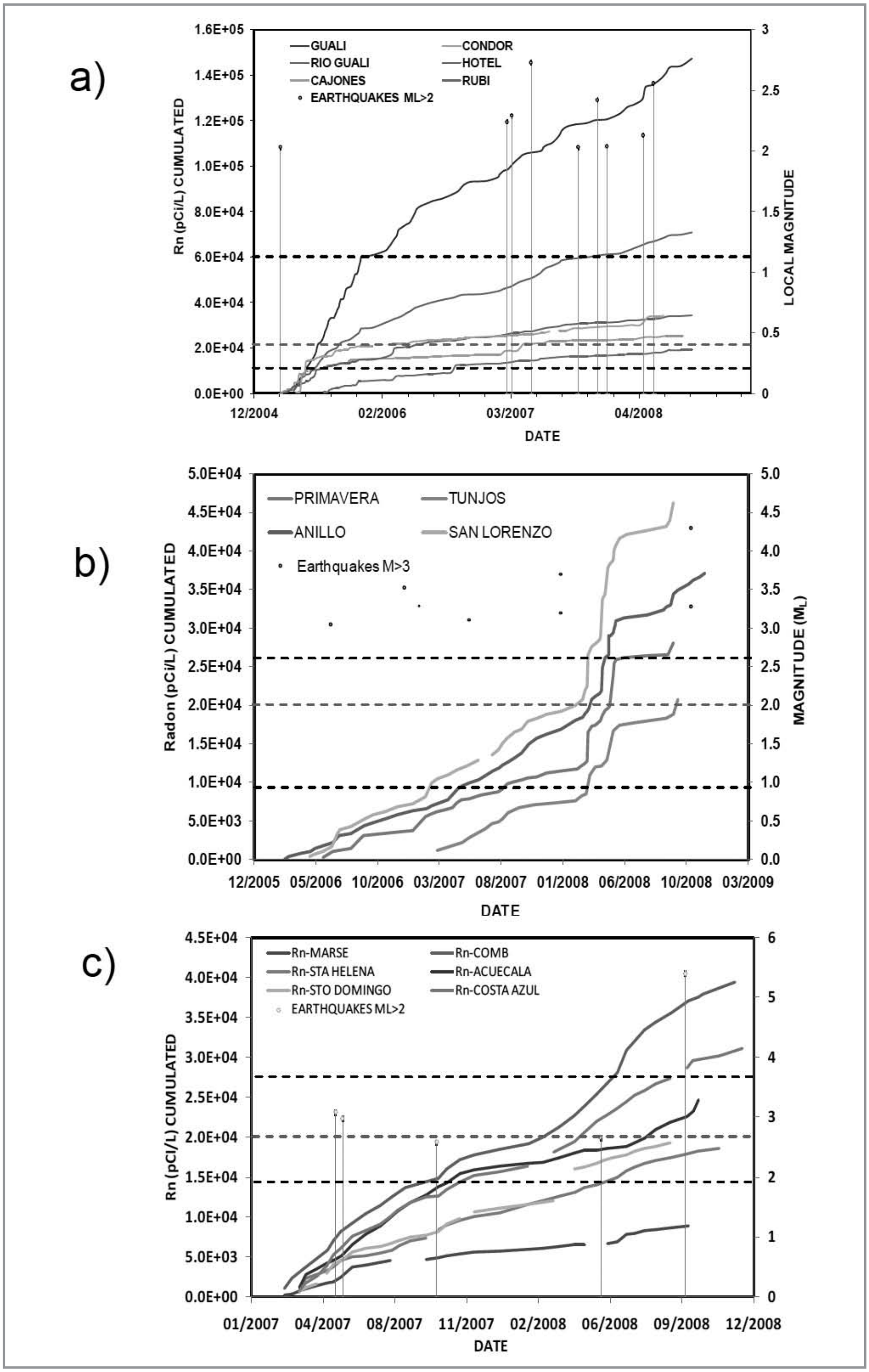


FIGURE 5. Cumulated radon emissions at different areas with time. Horizontal dotted lines represent the place with the main change in slope of the curve, associated with the normal and high levels of radon emission for each area. Red dotted horizontal line corresponds to $2x10^4$ pCI/L for comparison. Vertical dotted lines represent earthquakes. Notice that NRV (a) is the area with higher radon emissions, followed by CMV (b), and then CA (c), (see FIGURE 7).

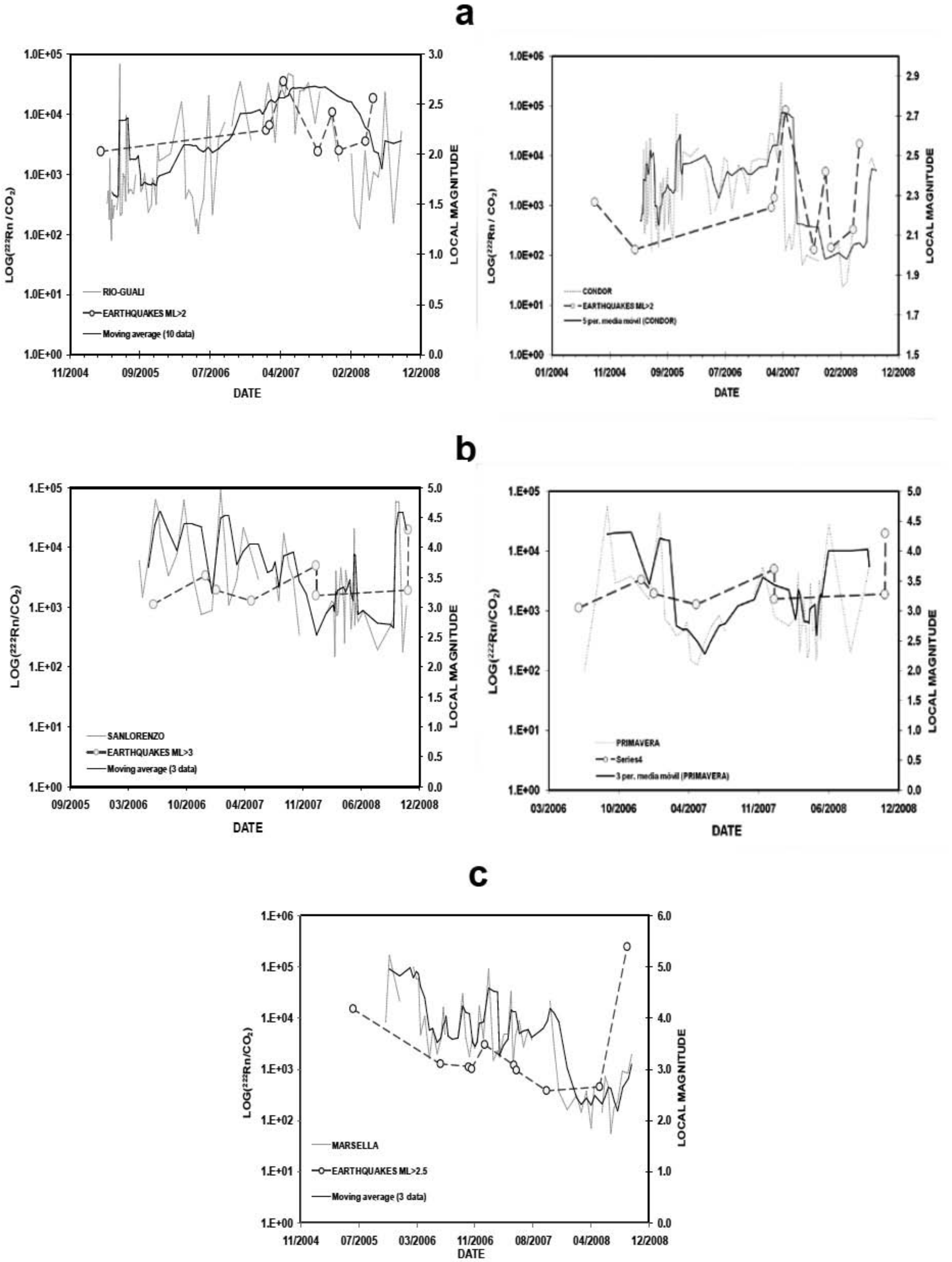


FIGURE 6. Relationship of ^{222}radon/CO_2 ratio and occurrence of earthquakes at different areas studied. Earthquakes with local magnitude >2 were plotted (yellow circles). a) NRV; b) CMV; c) CA.

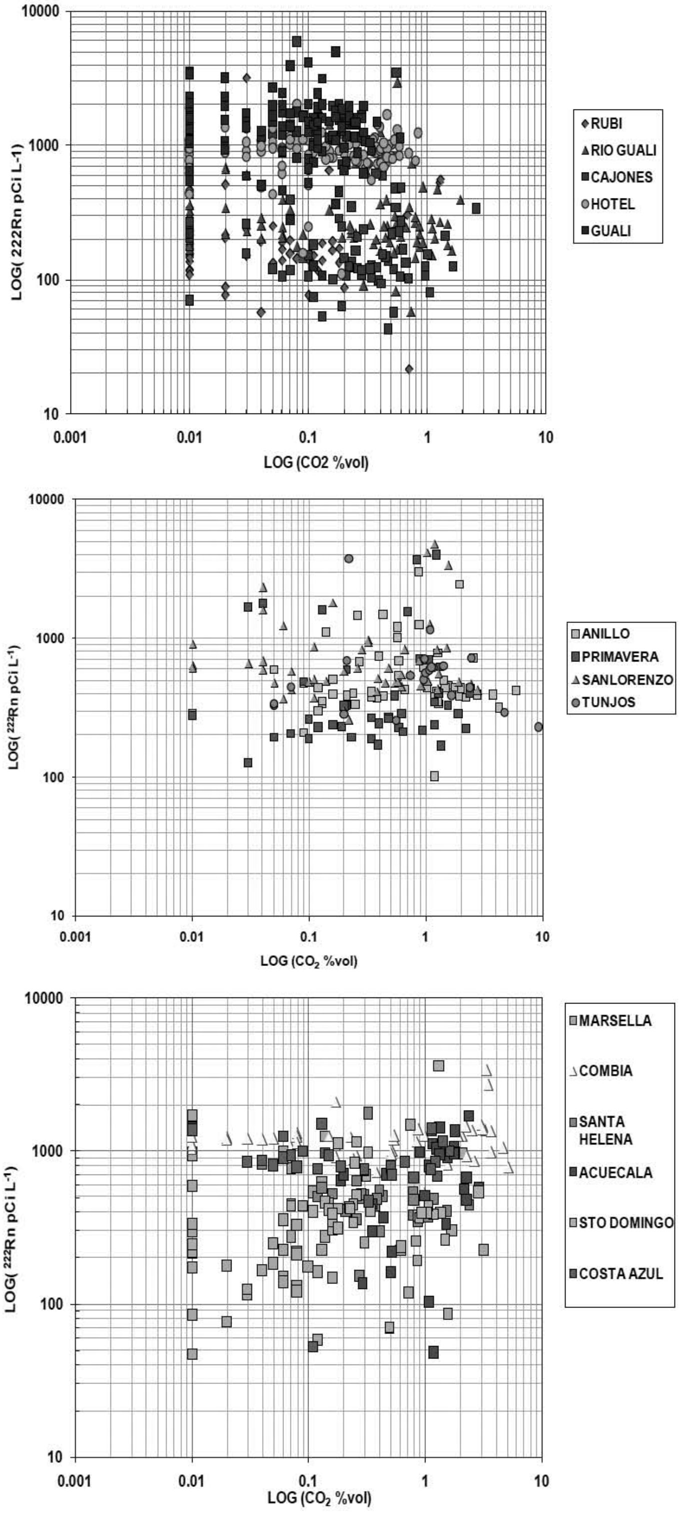


FIGURE 7. Comparison of radon emissions and CO$_2$ emissions at different areas. a) NRV; b) CMV; c) CA.

For CMV, almost all stations showed similar values of radon emission, but there were higher values of CO_2 than NRV (FIGURE 7b). This could be related with the relatively high CO_2 emissions from hot springs, and fumaroles detected at CMV. NRV has lower values of CO_2 in hot springs and fumaroles than CMV (Giggenbach et al., 1990).

AC is the zone with lowest values of radon emissions, as it was pointed out above, but it showed the higher values of CO_2, that is, there are more individual measurements of CO_2, with higher values than NRV and CMV (FIGURE 7c).

DISCUSSION AND CONCLUDING REMARKS

At volcanic and tectonic active regions, the periodical measurements of radon and CO_2 emissions in soil, seems to be a good tool for monitoring volcanic and seismic activity. The levels of radon emission seem to be different for each region. This could be related with the different geological setting for each studied station.

At NRV region, there are several faults crossing the volcano, as well as several volcanic focus. Moreover, the volcanic activity is permanent, but it has been stable for the last 10 years. This implies that radon emission levels should be relatively high but with a regular tendency. This was observed at NRV, in agreement with its level of activity. Only one station showed very high values of radon (GUALI station). This station (FIGURE 3a and 4a) is very close to a fault. Probably those high values are due to faulting activity related; at some extend, with the volcanic activity. On the other hand, radon/CO_2 ratio at RIO GUALÍ station showed a clear tendency to increase from 2006 to early 2008 (FIGURE 5a), when it started to decrease. This could imply changes in inner conditions of the volcano.

CMV, from last five years, is showing an increase in activity, mainly in seismicity and geochemistry. In the last years, several earthquakes have been felt by people living near the volcano. A gradual Increasing in magnitude of the earthquakes has been observed. Several peaks of radon and CO2 emissions seem to be related with the increase In seismic activity (FIGURES 3b, 4b and 5b). A change in the slope of the cumulative curve of radon emissions, on December 2007, was detected in all the stations at CMV. This fact, could represent a change in volcanic activity, evidenced by ulterior changes in geochemical variables such us conductivity, pH, and cations concentration, and also the occurrence of an earthquake with local magnitude of 4.3, in 9 November 2008. It is possible that, in the near future other important changes can be observed in the activity of CMV. Therefore, is important to continue with the monitoring of radon and CO_2 emissions at this volcano.

The AC region has been quite stable since 1999, when strong earthquakes with local magnitude 6.1 stroke the region. Recently, an earthquake with local magnitude of 5.3 was recorded, coincident with a later increasing in radon emission in the nearest station to the epicenter (MARSELLA, FIGURE 3c). The steady tendency of the radon emissions in the studied period, is in agreement with the tectonic stability of the region.

Levels of radon/CO_2 ratios were very similar for the three zones; this could indicate that diffusivity of radon is associated with CO_2 degassing. On the other hand, several increases in CO_2 degassing were detected almost simultaneously with increasing in radon emissions, which could be associated with transport of radon after CO_2 degassing (Burton et al, 2004).

The source of radon is an important matter when interpretation is done. Measurements of radon can be influenced by several sources of error, such as atmospheric changes, soil uranium-bearing, soil permeability, among others. This conditions make difficult to distinguish what is the cause of temporal changes in radon. Studies of isotopes of Radon, CO_2 and He in soil have been used to try to determine the source and, at some extend, the depth of the source of radon (Baubron et al, 2002; Giammanco et al, 2007; Chiodini et al, 2008). Even with available data such as those mentioned before, it is hard to define exactly the source and depth of radon anomalies, due to combination of several factors acting simultaneously. On the other hand, the expensiveness of these analysis make them of unpractical use for routinely monitoring of volcanic and seismic activity. One easiest way to abolish the main errors affecting the interpretation of radon data and its associated source, is deploying a dense network of radon stations surrounding the physical phenomena (volcano or tectonic fault) to investigate. If only remarkable changes recorded in all , or almost all the stations are considered for study, it is highly probable that those changes are due to the physical phenomenon (volcano, faulting), independent of the presence of other local factors affecting the measurement, since the anomaly is recorded in all the stations simultaneously, suggesting that it is due to a large phenomenon, instead to a local condition (soil, atmospheric changes, etc). Isolated changes in a few stations should not be considered.

In this case, it is more probable that local conditions affect the measurement. A study using this approach is carrying on at Cerro Machín volcano.

As a conclusion, radon emissions levels help to monitoring tectonic or volcanic active regions. A base line of measurements is an essential step to know the behavior of those phenomena since point of view of geochemical changes. The way to measure radon and CO_2 is important, since errors can be included in measurement. Also, periodicity is an important variable, since long term measurements can hide, instantaneous temporal changes.

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