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Journal of Volcanology and Geothermal Research 77 (1997) 267–283

Journal of volcanology
and geothermal research

Distal degassing of radon and carbon dioxide on Galeras volcano, Colombia

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Received 1 February 1996; accepted 16 October 1996

Abstract

Diffuse degassing at Galeras volcano, Colombia, was studied during three consecutive field seasons from 1993 to 1995. Measurements of ^{222}Rn and CO_2 were made at 30 stations which were distributed on the volcano and on regional faults intersecting the edifice. Time series data show a decline of radon soil gas of up to 50% prior to a M 2.8 earthquake on 12 August 1993 at stations located near the epicenter and on the volcano near the location of earthquake swarms which occurred in April 1993, November–December 1993 and March 1995. The onset of volcanic seismic activity ('tornillos') on 9 August 1994 was preceded by anomalous soil gas increases at six stations located on the flanks of the volcano. On the southwestern flank, radon increased from 51 to 130 pCi/l between 7 and 14 August, while on the northern flank, radon concentrations began to increase 19 days before the appearance of tornillos. In general, stations close to the crater showed the largest radon increases. Soil gas distributions and carbon isotope data suggest that diffuse degassing on the volcano is structurally controlled and that the abundance of CO_2 in soil gas on the edifice cannot be taken as an indicator for the presence of magmatic gases. Radon soil gas concentrations and the ^{222}Rn emanating ^{226}Ra concentration increase near faults, whereas CO_2 concentrations are more variable but commonly are higher on the volcano than near faults. $\delta^{13}\text{C}$ values in soil CO_2 vary between -8.5 and -23.2% , with $\delta^{13}\text{C}$ values more enriched than -15% found only in the vicinity of faults or sites prone to earthquake swarms. This suggests a magmatic origin of CO_2 soil gas only near faults and an almost impermeable edifice in unfractured areas. The observed correlations between seismic activity and soil degassing provide further evidence that soil gas studies, especially when correlated to other methods of volcano surveillance such as seismicity and deformation, may be useful in forecasting volcanic and seismic events.

Keywords: degassing; soil gas; radon; carbon dioxide; Galeras volcano; Colombia

1. Introduction

Galeras is a 4200-m-high stratovolcano, located at $1^\circ 14' \text{N}$ and $77^\circ 22' \text{W}$ in southern Colombia near the

Ecuadorian border. The Galeras volcanic complex is composed of several small calderas, cinder cones and a Holocene stratovolcano (Calvache et al., 1997). The area on or near the edifice of the volcano is highly populated. The city of Pasto, with a population of 350,000 people, is located on the eastern

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slopes of the volcano, and numerous small villages are situated near the Pan-American Highway or on the main road around the volcano. The climate at Galeras is equatorial and contains two dry seasons and two wet seasons. The rainy season is predominant in April–May and October–November, while the dry season occurs from June to August and from December to March (Calvache, 1990).

Galeras volcanic complex is situated in a tectonically active area of the northern Andes (Hall and Wood, 1985). The regional Romeral–Buesaco fault

system intersects the volcano along NE–SW axes, and the Pasto fault traverses the edifice on its south-eastern flank (Fig. 1). The Romeral–Buesaco fault system has been mapped by Murcia and Cepeda (1991). We have modified the trace of the fault system using air photo and soil gas analysis (Fig. 1). Due to the young volcanic rocks and dense vegetation cover on the volcano, the regional faults are often difficult to follow over much of the edifice.

Galeras reactivated in 1988. Since then, volcanic activity at Galeras has been characterized by four

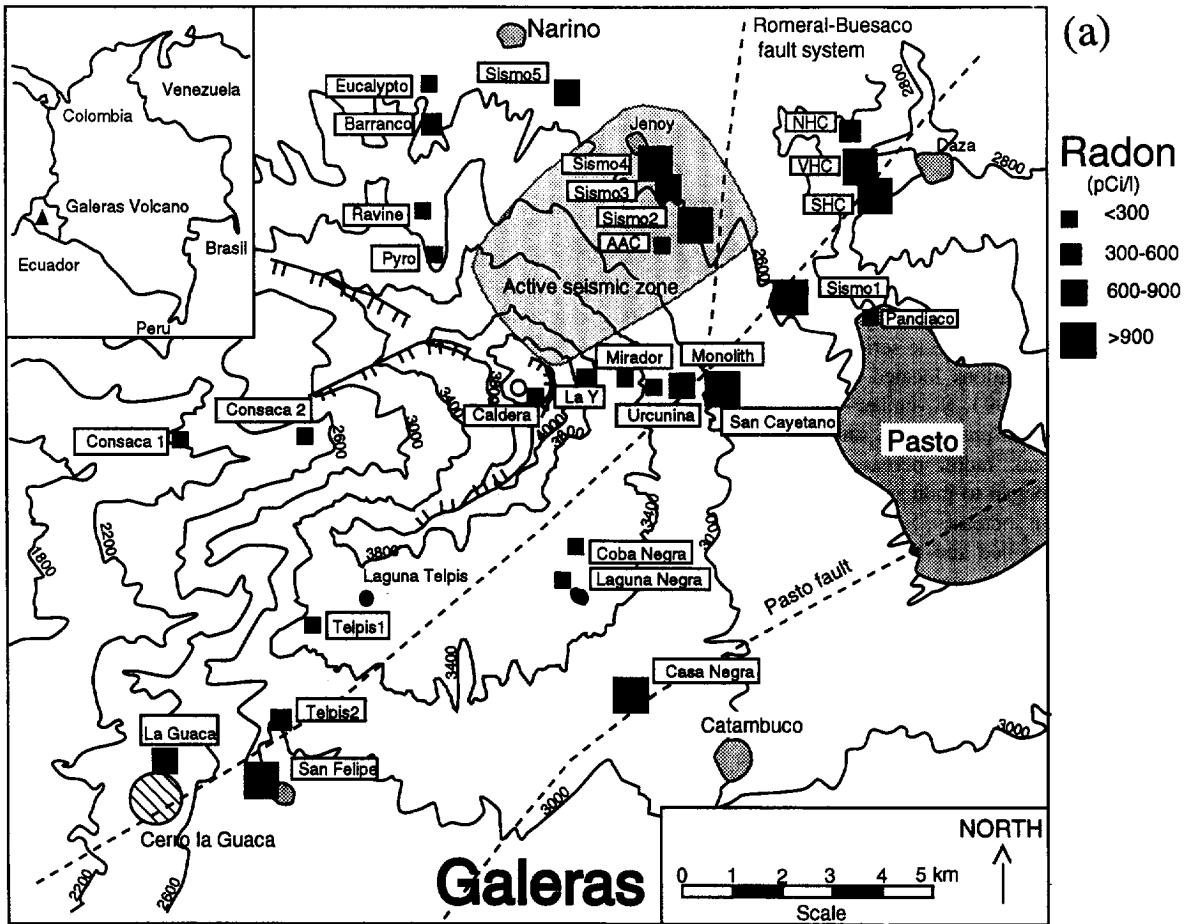


Fig. 1. Topographic map showing the location of Galeras volcano and the neighboring city of Pasto. The sampling stations are named and identified by filled symbols. The traces of the Pasto fault and the Romeral–Buesaco fault system are shown by the heavy dashed line. The lightly shaded area represents an area where earthquake swarms were located in 1993 and 1995. Caldera margins are indicated. (a) ■ represent the radon concentrations measured at the individual stations. (b) ▲ represent the magnitude of the radon emanating radium concentrations (RnERaC) of the soil at the individual stations. (c) ● represent the $\delta^{13}\text{C}$ ratios at the individual stations.

principal events (Stix et al., 1993; Cortés and Raigosa, 1997):

(1) In early May 1989, a series of semi-continuous vulcanian eruptions defined the first major activity of the current cycle.

(2) In October–November 1991, a dome was emplaced within the active crater.

(3) A series of six vulcanian eruptions occurred in 1992–1993, the first of which destroyed 90% of the dome. Five of six eruptions were preceded by a particular type of long-period seismic signal, characterized by a high-frequency onset and a slow, low-frequency decay coda. These have been called ‘screw’-type events or ‘tornillos’ (the Spanish word for ‘screw’) because the shape of the signal resem-

bles a screw (Narváez et al., 1997; Gómez and Torres, 1997). This type of signal has been observed on other active andesitic volcanoes, such as Tokachi-dake and Meakan-dake in Japan, and has been correlated with a pressure buildup in the magma conduit under the active crater (Gómez and Torres, 1997).

(4) Three high-frequency seismic crises, resulting from rock fracturing, occurred in April 1993, November–December 1993 and March 1995. Their sources were located about 1–5 km north and northeast of the crater (Fig. 1). The strongest earthquakes reached magnitudes between 4 and 5 and caused damage to houses near the village of Jenoy.

Although seismic activity, deformation and crater

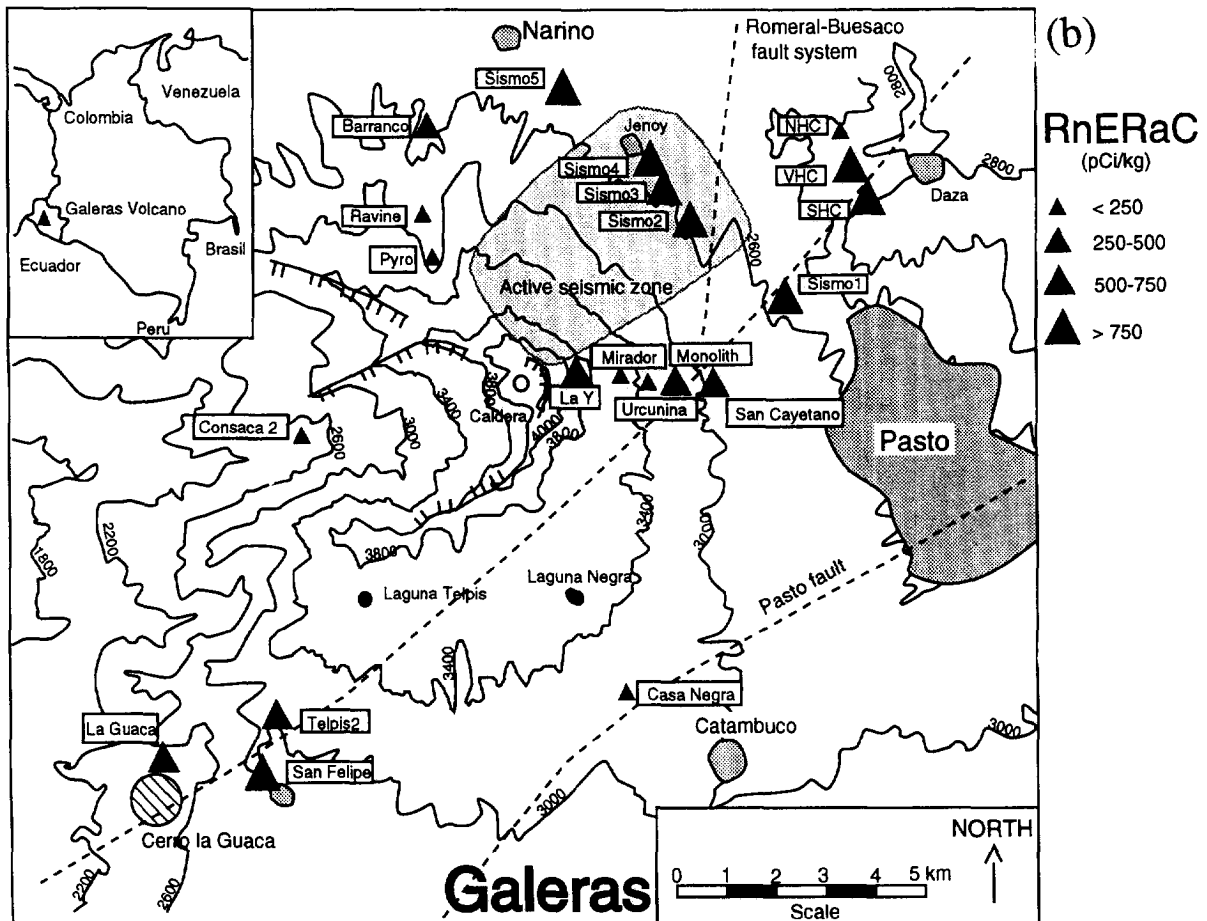


Fig. 1 (continued).

degassing are routinely monitored on Galeras and provide important new datasets that form the foundation for new eruption forecasting models, these traditional methods have encountered difficulties in forecasting the sudden eruptive events which have been observed at Galeras. This has prompted several alternative approaches, such as integrating gas flux and seismic data (Fischer et al., 1994) and attempting new remote sensing techniques to monitor crater gas (Stix et al., 1996, 1997). This article describes another approach in volcano monitoring, that of examining diffuse degassing on the flanks of Galeras and its utility in eruption forecasting. Such lateral emanations of gas can occur at a considerable distance from the crater and can be measured. These gases are essentially composed of CO₂ and rare gases such as

Rn and He (Baubron et al., 1991; Allard et al., 1991).

The purposes of this article are: (1) to evaluate soil gas distribution on the flanks of Galeras and on structural zones in the vicinity of the volcano; (2) to attempt to correlate the observed spatial and temporal patterns of soil gas to eruptive and seismic activity; and (3) to discuss the origin and the transport of these gases at Galeras. To achieve these objectives, we measured soil gas radon and CO₂ because: (1) the results can be compared to other volcanoes where similar measurements have been made; (2) it is comparatively simple to measure radon and CO₂; and (3) these gases are thought to respond to changes in volcanic activity and the stress-state of the volcano.

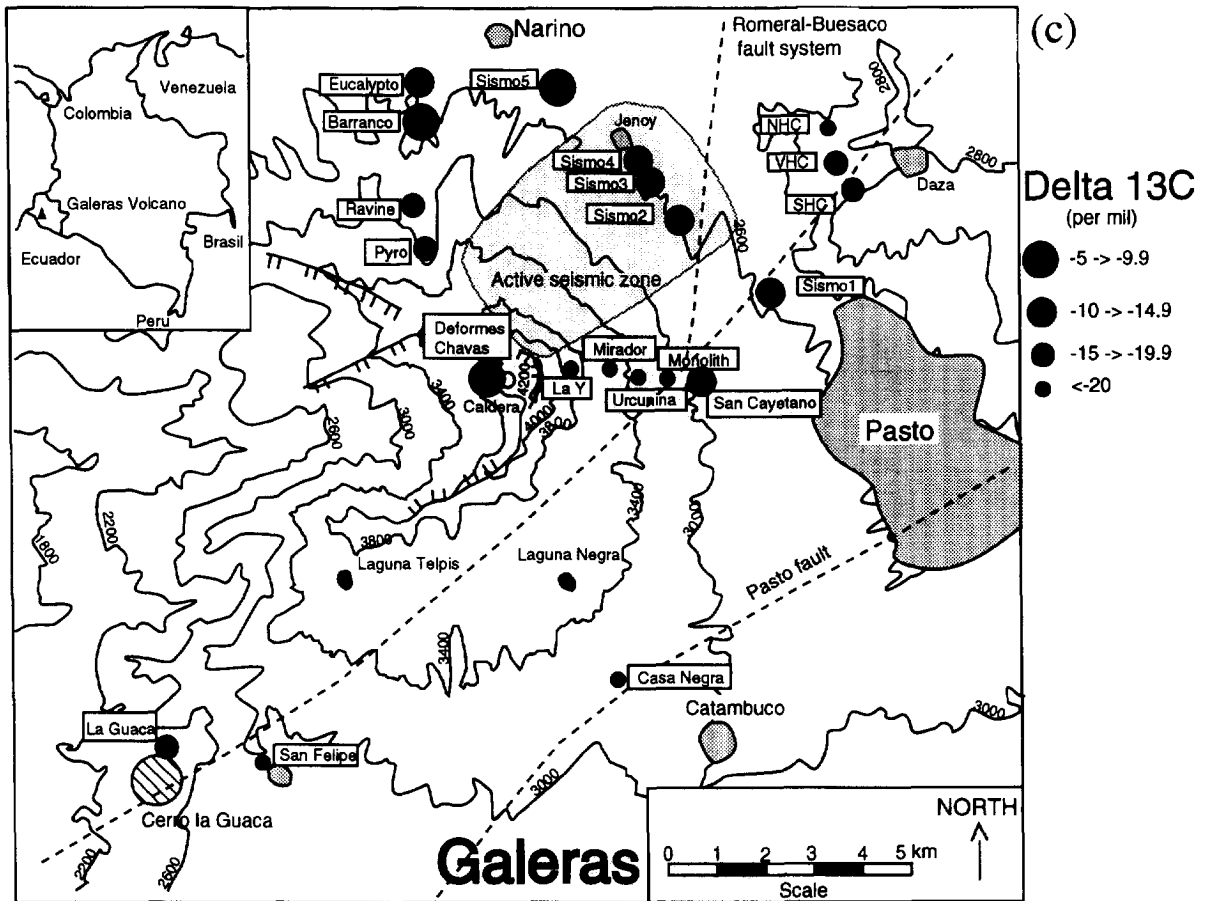


Fig. 1 (continued).

2. Previous studies of soil gases on faults and volcanoes

2.1. Soil gas variations

Variations in soil gas concentrations can be caused by any process or mechanism that changes the stress-state of the ground or modifies porosity and the volume of cracks and fissures, such as: (1) annual and diurnal variations (wind, rain, temperature, water content in soil; Shapiro et al., 1980; Schery et al., 1984; Owczarski et al., 1990; Schumann et al., 1992); (2) atmospheric pressure variations (Schery and Petschek, 1983); (3) deformation of the volcanic edifice (Thomas et al., 1986; Badalamenti et al., 1993); (4) volcanic and volcanic seismic activity (Baubron et al., 1990, 1991; Barberi and Carapezza, 1994); and (5) tectonic seismic activity (Mogro-Campero and Fleischer, 1977; King, 1980; Teng, 1980; Shapiro et al., 1980; Sugisaki et al., 1983; Anzà et al., 1993).

2.2. Radon

^{222}Rn is a naturally occurring radioactive noble gas with a half-life of 3.82 days which originates in the disintegration chain of ^{238}U where ^{226}Ra is its immediate parent isotope. Other naturally occurring isotopes of radon are ^{219}Rn and ^{220}Rn , both with very short half-lives (Ozima and Podosek, 1983). Radon gas can be emitted from any rock that contains uranium or its daughter isotope radium (Tilsley, 1992). Felsic rocks generally contain more uranium than more mafic rocks. Therefore, soils on felsic volcanoes can have higher radon contents than soils on mafic volcanoes.

2.3. CO_2

CO_2 is, after H_2O , generally the most abundant gas to emanate from a volcano. Its low solubility in silicate melts at low to moderate pressures favors its exsolution, and therefore CO_2 can be a good tracer for sub-surface magma degassing (Baubron et al., 1991). During diffuse degassing of magma, reactive gas species such as SO_2 are preferentially removed from the gas phase, and only inert gases and CO_2 reach the surface (Allard et al., 1991). CO_2 on a

dormant or active volcano may derive from a variety of sources, such as: (1) the mantle; (2) thermal metamorphism of carbonate rocks; (3) organic processes; and (4) mixing of gas from these different reservoirs (Irwin and Barnes, 1980).

2.4. Carbon isotopes

Carbon has two stable isotopes, ^{13}C and ^{12}C , with distributions of 1.11 and 98.89%, respectively (Faure, 1986). Generally, $\delta^{13}\text{C}$ is expressed relative to the $\delta^{13}\text{C}$ Pee Dee Belemnite (PDB) standard. Most biogenic carbon has $\delta^{13}\text{C}$ values ranging from -24 to -34‰ , whereas magmatic carbon varies from -2 to -8‰ and carbon from carbonate rocks is close to 0‰ (Faure, 1986). Fischer (1994) Fischer et al. (1997) found that $\delta^{13}\text{C}$ of CO_2 in summit crater fumaroles on Galeras varied between -10.4 and -4.6‰ . Sano et al. (1997) similarly found that $\delta^{13}\text{C}$ of CO_2 in summit crater fumaroles on Galeras varied between -5.7 and -7.6‰ , while that for the Pandiaco warm spring in Pasto varied between -8.7 and -9.2‰ .

3. Methodology

3.1. Station locations

Our sampling sites were chosen according to: (1) the geology; (2) the geographical location; and (3) the proximity to areas of enhanced seismic activity. The Eucalypto, Barranco, Ravine and Pyro stations located in the Barranco valley are close to where high-frequency earthquakes occurred in April and November–December 1993 and in March 1995 (Fig. 1). In addition, the five Sismo stations, installed in 1995, form a NW–SE-trending line across this zone of seismicity (Fig. 1).

The Guaca station was installed next to the La Guaca cinder cone on the southwestern flank of the volcano through which the Romeral–Buesaco fault system passes. The Aguas Agrias Calientes (AAC in Fig. 1) and Pandiaco stations were selected because of their proximity to hydrothermal warm springs. The stations on a direct line between Pasto and the summit of the volcano (San Cayetano, Monolith, Urcunina, Mirador, La Y) were selected to evaluate

changes with altitude and proximity to the crater. The Casa Negra, Laguna Negra and Coba Negra stations were chosen because this area also has been the center of seismic activity. The Telpis stations (San Felipe, Telpis2 and Telpis1) cover the southwestern flank of the volcano and were chosen for their geographic location (Fig. 1). The valley in which these three stations are located is one of the few places on the volcano where glacial deposits have not been eroded (Calvache, 1995). The Daza stations (NHC, VHC, SHC) are distributed across the Daza valley to evaluate degassing on and near the regional Romeral–Buesaco fault system before it intersects the volcano (Fig. 1).

3.2. Radon

^{222}Rn gas activity was measured using the E-PERM technique (Kotrappa et al., 1988) in which the radioactive decay of radon and its daughter isotopes decreases the surface potential of an electrostatic field on an electret detector. In order to minimize changes in gas concentrations due to meteorological conditions, measurements were made at a depth of about 75 cm in a PVC tube which was open at the bottom and sealed at the top. Duplicate measurements were taken for each measurement at every station to ensure reproducibility. Reproducibility of radon measurements, calculated from the duplicate electrets, generally was within 6%. Electrets were changed every 3–7 days and gave the average ^{222}Rn concentration in the tube during this period. An important advantage of the E-PERM method is the ability to obtain near real-time radon concentrations in the field.

3.3. Radon emanating $^{226}\text{Radium}$ concentration in the soil

In order to measure the ^{226}Ra emanating potential from the ground, soil samples were collected at a depth of 70–80 cm. In the lab, 20–60 g was placed in a petri dish and exposed to an E-PERM detector in a sealed 3.74-liter glass bottle for 10 to 15 days. The ^{222}Rn emanating ^{226}Ra concentration from the soil (RnERaC) is subsequently calculated and gives a measure of the soil's ability to produce radon gas. RnERaC measurements do not measure the chemical

concentration of the radon precursor ^{226}Ra , but rather the proportion of ^{226}Ra that is effectively emitting radon. Generally, the radon has to be produced near the edge of the soil grains and escape into the pore spaces to be able to reach the detectors.

3.4. CO_2

In 1993, CO_2 soil gas was sampled in evacuated glass tubes and later measured by gas chromatography in the laboratory. No pressure corrections were applied for this series of data, and thus values tend to underestimate the true CO_2 concentrations. In 1994 and 1995, CO_2 was measured directly in the field by a portable non-dispersive infrared analyzer, and altitude corrections were applied to all measurements.

3.5. $\delta^{13}\text{C}$ in CO_2

In 1995, carbon isotopes in CO_2 were measured from 21 sites which had been monitored for radon and CO_2 in 1993–1995. A 40–50-ml gas sample from 75 cm depth was collected via syringe and transferred into a stoppered, crimped 25-ml vial that had been pre-evacuated and fixed with saturated mercuric chloride solution to prevent any isotopic changes due to microbial activity. Isotopic analyses were performed by gas chromatograph–combustion–isotope ratio mass spectrometry (GC–C–IRMS) at the Stable Isotope Laboratory, University of Toronto. Carbon isotope ratios are expressed as per mil deviation from Pee Dee Belemnite (PDB). Accuracy and reproducibility are both better than 0.5‰.

4. Results

4.1. Soil gas distribution on Galeras and adjacent faults

Table 1 gives the average concentrations and isotopic values for the different stations. Stations located near the mapped Romeral–Buesaco fault system, such as VHC and SHC, have high radon concentrations (VHC, 860 ± 50 to 1020 ± 60 pCi/l for 1993; SHC, 570 ± 30 to 930 ± 50 pCi/l for 1993) whereas stations located several hundred meters

away, such as NHC, have considerably lower radon soil gas concentrations (260 ± 20 to 320 ± 20 pCi/l for 1993), indicating a decline of radon with distance from the fault. In the Daza valley, CO₂ concentrations also increase towards the fault but to a lesser

extent than radon. Since the regional Romeral–Buesaco fault system intersects the edifice, its degassing pattern also can be detected on the volcano. Other stations located near the Romeral–Buesaco fault zone, such as Guaca, Telpis 2 and San Cayetano,

Table 1
Range of soil gas concentrations, radon emanating radium concentrations of the soil (RnERaC) and $\delta^{13}\text{C}$ values at the different stations

Station	Field season	Altitude (m)	Radon			RnERaC (pCi/kg)	CO ₂			$\delta^{13}\text{C}$ 1995 data (‰)
			Minimum (pCi/l)	Maximum (pCi/l)	Average (pCi/l)		Minimum (%)	Maximum (%)	Average (%)	
Aguas Agrias	1993	2820	65	90	73		0.7	0.9	0.7	
Pandiaco	1993	2580	92	100	95		3.6	5.3	4.7	
Eucalypto	1994	2450	150	220	190		2.9	4.6	3.5	-13.4
Barranco	1993	2560	200	420	360		1.4	2.0	1.6	
Barranco	1994	2560	450	680	520	270	2.0	8.6	3.9	-8.7
Ravine	1994	2810	100	180	140	130	2.3	6.1	3.6	-18.3
Pyro	1994	2980	110	160	140	90	3.2	5.8	4.6	-19.4
Casa Negra	1994	3150	430	1260	1030	250	1.8	3.2	2.5	-22.4
Laguna Negra	1993	3420	83	120	100		5.5	7.4	6.4	
Laguna Negra	1994	3420	15	43	28		10.5	15.1	11.8	
Coba Negra	1994	3560	64	130	86		10.9	13.5	12.6	
Guaca	1993	2240	500	670	620		1.2	2.0	1.5	
Guaca	1994	2240	500	780	630	420	0.7	2.1	1.2	-17.9
San Felipe	1994	2800	630	1170	960	780	0.5	1.3	0.8	-18.7
Telpis 2	1993	3140	410	620	490					
Telpis 2	1994	3140	480	760	600	360	0.9	2.1	1.3	
Telpis 1	1993	3440	52	130	88		0.2	3.5	2.5	
Telpis 1	1994	3440	51	140	100		1.1	6.0	3.0	
SHC	1993	2820	570	930	780		0.3	1.1	0.8	
SHC	1994	2820	780	1380	890	560	1.4	4.8	2.9	-15.1
VHC	1993	2750	860	1020	920		1.2	1.7	1.5	
VHC	1994	2750	800	1410	1120	540	2.6	3.8	3.2	-18.3
NHC	1993	2820	260	320	300		0.2	0.9	0.5	
NHC	1994	2820	290	420	340	170	0.7	1.6	1.1	-20.2
Consaca 1	1994	2230	150	160	150		1.1	1.2	1.1	
Consaca 2	1994	2410	150	170	160	190	0.4	0.6	0.5	
San Cayetano	1994	2930	1070	1520	1320	680	1.6	3.9	2.5	-12.3
Monolith	1994	3210	590	1140	860	280	1.0	2.6	1.7	-21.1
Urcunina	1994	3370	44	170	90	90	1.7	2.7	2.5	-23.2
Mirador	1994	3650	54	150	110	120	1.1	3.1	2.1	-23.1
La Y	1994	3930	89	100	96	670	2.9	3.4	3.1	-22.7
Caldera	1994	3940	6	14	10		0.0	0.0	0.0	
Sismo 1	1995	2470	500	1320	1050	990	1.2	1.9	1.5	-14.2
Sismo 2	1995	2560	1200	1490	1380	1020	1.5	1.6	1.6	-11.4
Sismo 3	1995	2560	680	930	810	1430	6.6	9.7	7.8	-14.8
Sismo 4	1995	2525	670	1050	910	690	1.0	1.1	1.0	-14.2
Sismo 5	1995	2430	610	990	860	520	6.4	8.4	7.4	-8.5
Deformes	1995	4010							0.5	-8.7
Chavas	1995	4010							12.4	-7.9

Errors for measurements of radon concentrations and RnERaC (radon emanating radium concentrations of the soil) are within 6%.

Errors for CO₂ measurements are within 5% for the 1994 data and within 12% for the 1993 data.

$\delta^{13}\text{C}$ ratios have a precision of 0.5 per mil.

are characterized by high radon and relatively low CO₂ (Guaca, 500 ± 30 to 670 ± 40 pCi/l radon and 1.2 ± 0.1 to 2.0 ± 0.1% CO₂ for 1993; Telpis 2, 480 ± 30 to 760 ± 40 pCi/l radon and 0.9 ± 0.1 to 2.1 ± 0.1% CO₂ for 1994; San Cayetano, 1070 ± 60 to 1520 ± 80 pCi/l radon and 1.6 ± 0.1 to 3.9 ± 0.2% CO₂ for 1994); while their sister stations, such as Telpis 1 and Urcunina, which are removed from the fault, have low radon and more variable CO₂ concentrations (Telpis 1, 51 ± 3 to 140 ± 8 pCi/l radon and 1.1 ± 0.1 to 6.0 ± 0.3% CO₂ for 1994; Urcunina, 44 ± 2 to 170 ± 10 pCi/l radon and 1.7 ± 0.1 to 2.7 ± 0.2% CO₂ for 1994). The Casa Negra station located next to the Pasto fault also has high radon concentrations (430 ± 20 to 1260 ± 70 pCi/l radon and 1.8 ± 0.1 to 3.2 ± 0.2% CO₂ for 1994). Volcano stations that are not located in the vicinity of known faults generally have relatively low radon yet frequently high CO₂ values (e.g., Laguna Negra, 83 ± 5 to 120 ± 10 pCi/l radon and 5.5 ± 0.4 to 7.4 ± 0.5% CO₂ for 1993; Pyro, 110 ± 10 to 160 ± 10 pCi/l radon and 3.2 ± 0.2 to 5.8 ± 0.3% CO₂ for

1993). The highest CO₂ concentrations were measured at the Laguna Negra and Coba Negra stations in 1994 with CO₂ concentrations ranging between 10.5 ± 0.3 and 15.1 ± 0.5% CO₂. The Sismo stations are located on the northeastern flank of the volcano in an area where earthquake swarms occurred in 1993 and 1995. Soil gas measurements were taken in 1995 and showed high radon concentrations (e.g., Sismo 5, 740 ± 40 pCi/l and 7.4 ± 0.5% CO₂ for 1995; Sismo 2, 1380 ± 70 pCi/l and 1.6 ± 0.1% CO₂ for 1995).

Measurements of the ²²²Rn emanating ²²⁶Ra concentrations (RnERaC) varied over three orders of magnitude, from 90 pCi/kg at Pyro to 1430 pCi/kg at Sismo 3. Generally, the RnERaC was highest at stations that also had high radon concentrations, such as Sismo 1, Sismo 2, Sismo 3 and San Felipe, and was lowest at stations with low radon concentrations such as Pyro, Urcunina, Mirador and Ravine (Table 1).

Carbon isotope values for CO₂ also show significant spatial variations. On the active cone within the

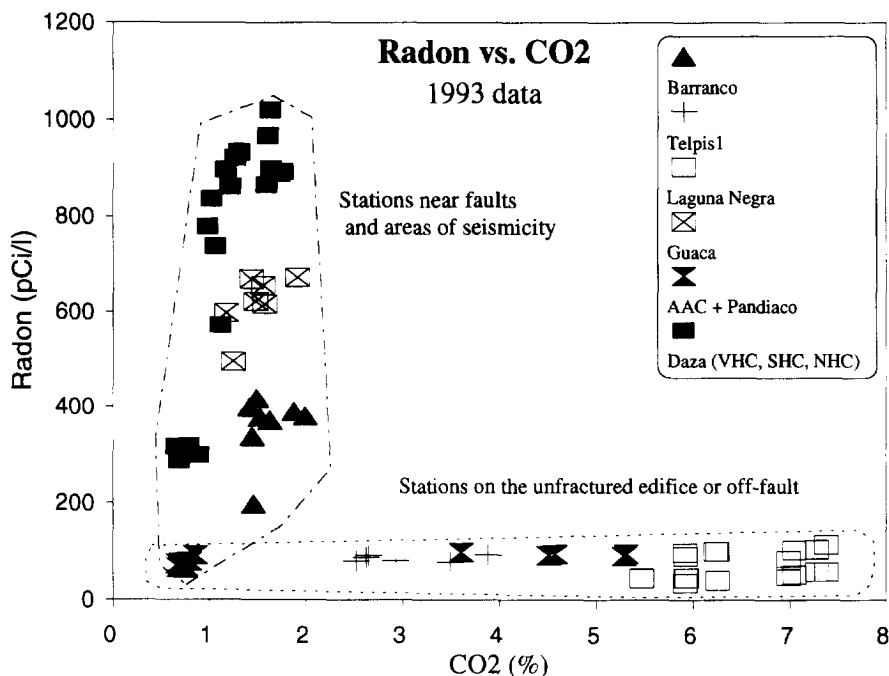


Fig. 2. Plot of radon vs. CO₂ (1993 data) for individual stations. Stations in the vicinity of faults and areas where earthquake swarms occurred show variable radon and relatively low CO₂ concentrations. Stations located on the unfractured edifice of the volcano or off-fault are defined by low and relatively stable radon and variable CO₂ concentrations.

caldera, soil gas stations located near Deformes and Chavas fumaroles have $\delta^{13}\text{C}$ values of -8.7 and -7.9‰ , respectively. By contrast, stations situated at high elevations outside the caldera have $\delta^{13}\text{C}$ generally lighter than -20‰ (e.g., La Y). The fault stations in the Daza valley vary from -15.1 to -20.2‰ , while the Sismo stations in the active northeast seismic zone range from -8.5 to -14.8‰ . The Barranco line varies from -8.7 to -22.4‰ , with values generally lighter at higher elevations. The Guaca and San Felipe stations have values of -17.9 and -18.7‰ , respectively.

Thus, soil gases on and in the vicinity of Galeras

can be subdivided into two different categories, those related to structural features such as faults and fissures, and those unrelated to faults located on the edifice of the volcano. Fig. 2 shows a clear bimodality caused by higher radon concentrations of stations near mapped faults and variable but often higher CO_2 concentrations found on the volcano.

4.2. Temporal variations

4.2.1. Seasonal trends

At Galeras, soil gas measurements were made between June and September, following the rainy

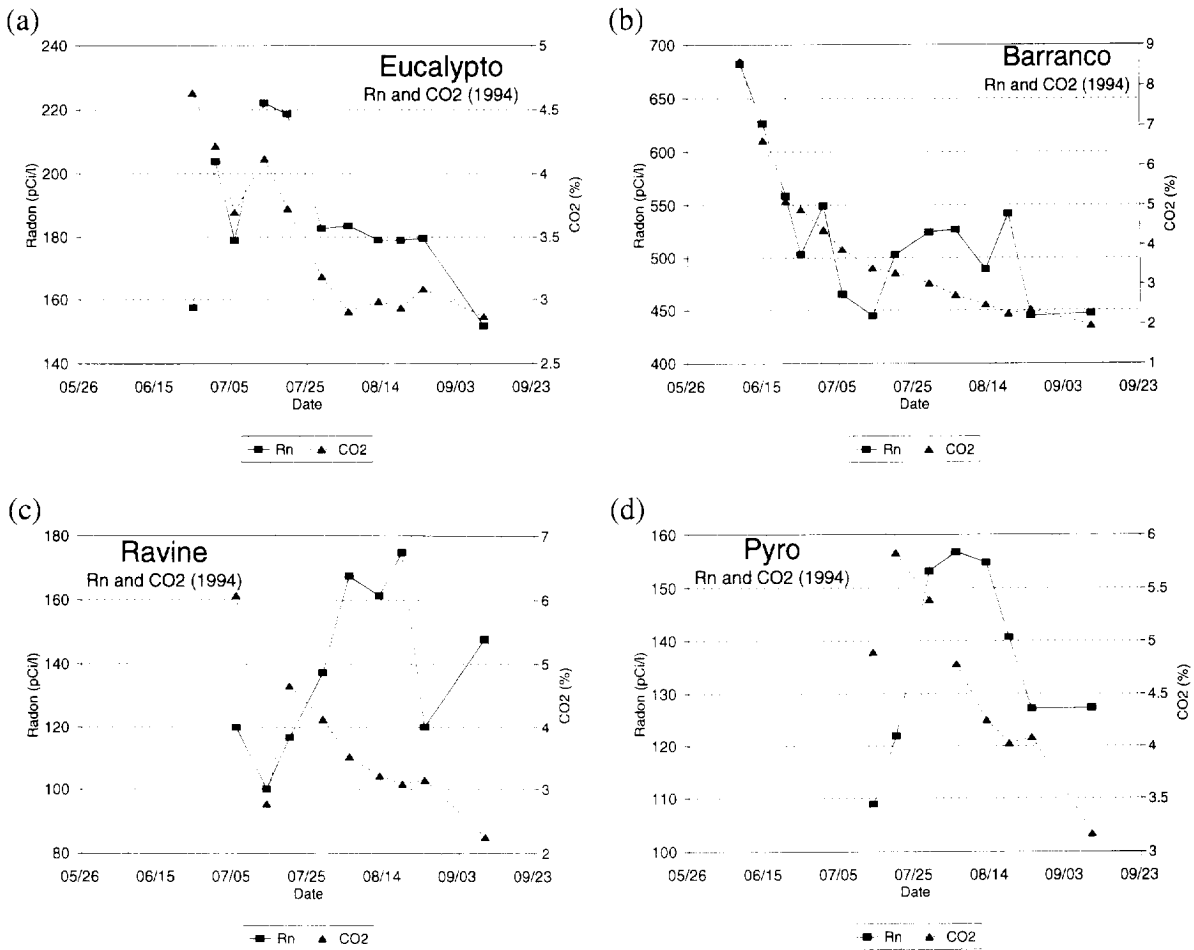


Fig. 3. Plot of CO_2 and radon at the four stations of the Barranco line (1994 data). The initial decrease of radon and CO_2 at the Barranco station (b) between 8 June and 14 July is interpreted as a seasonal trend. The increases in radon concentrations at the end of July for Barranco, Ravine and Pyro are interpreted as an anomalous response to volcanic seismic activity. By contrast, Eucalypto (a) shows no response.

season of April and May. During these months, the climate in Pasto was characterized by little precipitation. For the 1994 field season, measured precipitation in Pasto was negligible during this period. As Galeras has many microclimates, these data probably cannot be generalized for the entire edifice of the volcano. Stations that are located above 3400 m on the edifice of the volcano are frequently shrouded in clouds, such as Laguna Negra and Coba Negra. At these stations, no seasonal trend is discernible. On the flanks of the volcano below 3400 m, the ground dried, and the volume of water at springs decreased considerably. Time series data clearly mirror seasonal and climatic trends. At the Barranco station (2560 m), for example, the continuous decrease in both radon and CO₂ between 8 June and 14 July 1994 is very clear (Fig. 3b). CO₂ concentrations at this station decreased from 8.6 ± 0.4 to $3.4 \pm 0.2\%$, and radon decreased from 680 ± 40 to 450 ± 30 pCi/l during this period of time. Large amounts of precipitation have the effect of sealing the ground and allowing soil gas to accumulate, which explains the high soil gas concentrations in early June and the generally higher CO₂ concentrations on the volcano. As the ground dries, soil gas escapes to the atmosphere, thus lowering concentrations. Seasonal trends are also visible for several other stations, such as Telpis 1, Guaca, SHC and VHC.

4.2.2. 1993 response to seismic activity

Cerro La Guaca is a Quaternary cinder cone on the southwestern flank of the volcano (Fig. 1). The Guaca station is 14 km from the crater on the Romeral–Buesaco fault system (Fig. 1). A sudden dramatic decrease in radon soil gas was detected between 6 and 11 August 1993 at this station (Fig. 4a). This decrease coincided with a M 2.8 earthquake which occurred on 12 August 1993 under the La Guaca cinder cone (Diego Gómez, pers. commun., 1993). Radon concentrations at the Guaca station decreased from approximately 670 to less than 500 pCi/l between two consecutive measurements made five days apart. Since radon at this station showed consistently high values above 600 pCi/l prior to and after this event, the sudden decrease was considered anomalous. The CO₂ data show a constant decline from 1.9 ± 0.2 to $1.2 \pm 0.1\%$ prior to the event and a smaller increase from 1.2 ± 0.1 to $1.6 \pm$

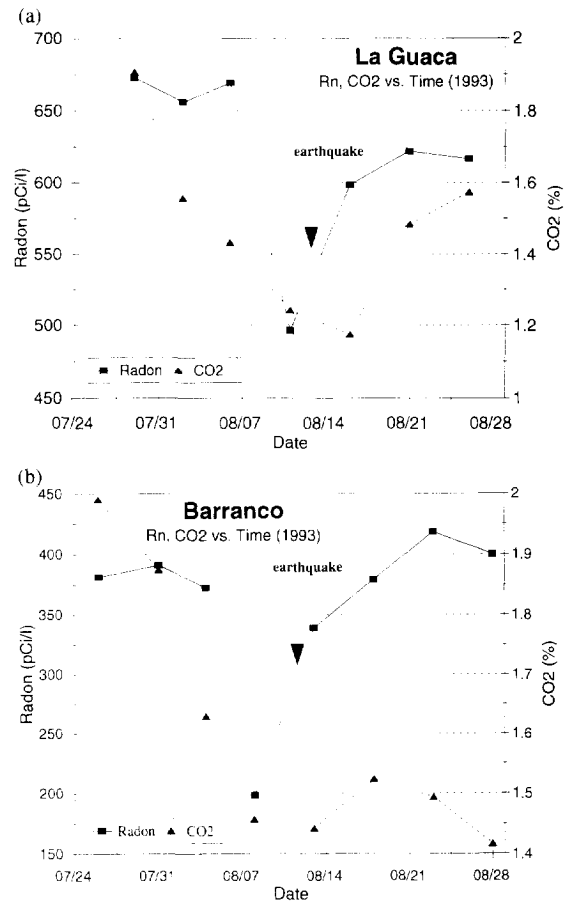


Fig. 4. (a) Plot of radon and CO₂ concentrations at the Guaca station. Note the dramatic decrease in radon prior to the M 2.8 earthquake on 12 August 1993. (b) Plot of radon and CO₂ concentrations at the Barranco station (1993). The sharp decrease in radon prior to the earthquake also occurs at this station.

0.1% following the event. The constant decline is suggestive of a seasonal trend, but the increase after the earthquake corresponds well with the radon data and may therefore be caused by the seismic event. During the same period of time, only the Barranco station showed a similar anomalous decrease that could not be correlated to seasonal changes (Fig. 4b). Radon activity at this station decreased from 370 ± 20 to 200 ± 10 pCi/l before the event and increased again to 340 ± 20 pCi/l after the event. The Barranco station is located in a steep-sided valley about 5 km north of the outer caldera wall near an area where earthquake swarms occurred in April and November–December 1993 and March 1995 (Fig. 1;

Gómez et al., 1993; GVN, 1993a,b; Cortés and Raigosa, 1997). Considering the distance and the different setting of the Barranco station, it is surprising that a tectonic event registered at the La Guaca station also would register in this area. The data suggest that there may be a structural link between the two areas.

4.2.3. 1994 response to tornillo seismic events

Time series data for 1994 were collected over a period of three months, from early June to late August. Volcanic activity during this time was defined by low fumarolic activity and generally little volcanic seismic activity for the first two months. However, on 9 August 1994, tornillo seismic events began to occur, with a total of 31 events recorded to 23 September, at which time a gas emission episode from the crater was noted, accompanied by tremor and followed by a swarm of long-period seismic events (Cortés and Raigosa, 1997). This sequence of events was similar to those observed during the 1992–1993 eruptive crises. Soil gas measurements at certain stations detected anomalous increases in radon before the tornillos reappeared in August. Of 22 stations sampled in 1994, eight could not be sampled on a continuous basis, eight showed no clear response, and six showed an anomalous increase prior to the occurrence of the tornillos. On the southwestern flank, the anomalous increase was most pronounced at the Telpis 1 station (Figs. 1 and 5a). Radon measurements show a clear seasonal trend from 13 June to 7 August 1994 with radon decreasing from 140 ± 10 to 51 ± 3 pCi/l, followed by a sudden increase to 130 ± 10 pCi/l between 7 and 14 August. CO_2 showed a small increase from 1.5 ± 0.1 to $1.9 \pm 0.1\%$ from 7 to 14 August. The subsequent decrease in soil gas concentrations between 22 and 27 August (radon decreased from 130 ± 10 to 72 ± 4 pCi/l, CO_2 decreased from 1.7 ± 0.1 to $1.1 \pm 0.1\%$) coincides well with the temporary decline of tornillo seismic activity during the same period of time (Fig. 5b). A more attenuated response to the tornillos occurred at the Telpis 2 station (radon increased from 520 ± 30 to 580 ± 30 pCi/l), whereas the San Felipe station did not show any clear response. Thus, it appears that the anomaly decreased with distance from the crater (Fig. 1). At the Guaca station, located

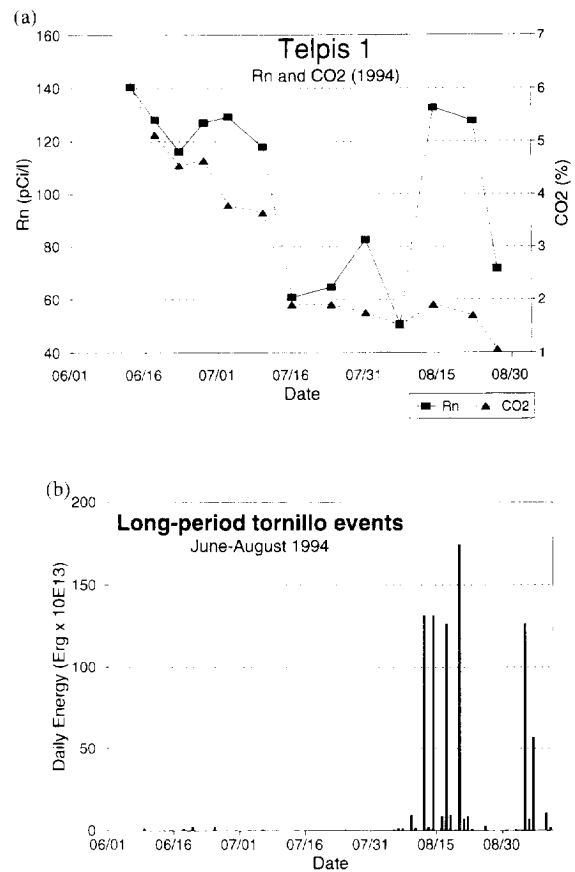


Fig. 5. (a) Plot of radon and CO_2 concentrations at the Telpis 1 station. Note the increase of radon concentrations prior to the occurrence of the tornillos. (b) Plot of long-period seismicity (tornillos) from June to August 1994 (data collected by the Observatorio Volcanológico de Pasto).

on the Romeral–Buesaco fault system, radon activity increased from 490 ± 30 to 700 ± 40 pCi/l between 7 and 14 August. Prior to the reappearance of the tornillos, a similar response was observed in the Barranco valley where the two highest stations closest to the crater (Pyro, Ravine) showed pronounced increases from 110 ± 10 to 160 ± 10 pCi/l and from 100 ± 10 to 170 ± 10 pCi/l, respectively, from 14 July to 5 August, while stations further removed from the caldera, such as Barranco, showed a more attenuated response (450 ± 20 to 530 ± 30 pCi/l over the same period) and Eucalypto, which did not show any response (Figs. 1 and 3a–d).

5. Discussion

Soil gas distributions at Galeras suggest four major trends: (1) stations in the vicinity of structural features and in areas where high-frequency earthquake swarms are located show degassing patterns distinct from stations located on the unfractured volcanic edifice; (2) near faults and areas of earthquake swarms, radon concentrations and RnERaC are comparatively high, and $\delta^{13}\text{C}$ values more enriched than -15‰ ; (3) diffuse degassing of magmatic gas inside the caldera is only significant at or near fumaroles; (4) along certain transects, CO_2 concentrations increase with altitude, radon concentrations decline, and $\delta^{13}\text{C}$ values become lighter.

5.1. Origin of radon and CO_2 at Galeras

$\delta^{13}\text{C}$ values in CO_2 from Galeras fumarole gases varied between -5.7 and -7.6‰ from 1988 to 1993 (Sano et al., 1997). These authors suggest that the fumarole CO_2 is composed of only 3–10% MORB-type mantle carbon and that the rest derives from limestone and sedimentary organic sources. $\delta^{13}\text{C}$ values in soil gas CO_2 from the Sismo stations varied between -8.5 and -14.8‰ , which suggests that the CO_2 in this area has similar deep sources as in fumarole gases, as well as an additional surficial biogenic component. Allard et al. (1991) have suggested that Mt. Etna is covered by a dome of magmatic CO_2 that emanates diffusely through the edifice of the volcano, being especially concentrated near faults and radial dykes. They also found that $\delta^{13}\text{C}$ increases at lower elevations due to a greater influence of marine carbonates and that recent lava flows generally have no gas anomalies. At Galeras, carbon isotope measurements show that $\delta^{13}\text{C}$ in CO_2 more enriched than -15‰ exists only near: (1) faults (e.g., VHC, SHC, San Cayetano, Guaca); (2) areas of seismic activity (e.g., Barranco, Sismo 2, Sismo 3); and (3) fumaroles. All other areas on the volcano have no significant deep CO_2 component. We therefore believe that a 'dome' of CO_2 does not cover the edifice of Galeras. This suggests that: (1) diffuse degassing of deep, magmatic gas on much of the edifice of Galeras is negligible due to the low permeability caused by the cover of young volcanic rocks; (2) deep roots of major faults can channel deep gases to the surface only if the faults have

surface expression; and (3) seismic activity has fractured the ground near Jenoy sufficiently to permit efficient transport of deep gas to the surface (e.g., the Sismo stations).

Although high radon activity is associated with faults and areas of seismic activity, the slow transport velocities and the short half-life of radon make it highly unlikely for deep radon to reach the surface. Instead, increased radon concentrations in these areas probably are due to (1) faster advective transport near the surface and (2) the greater availability of radon at shallow levels along faults and fissures. The high radon concentrations in most areas can be explained by the elevated radon emanating radium concentrations of the soil (RnERaC). When radon

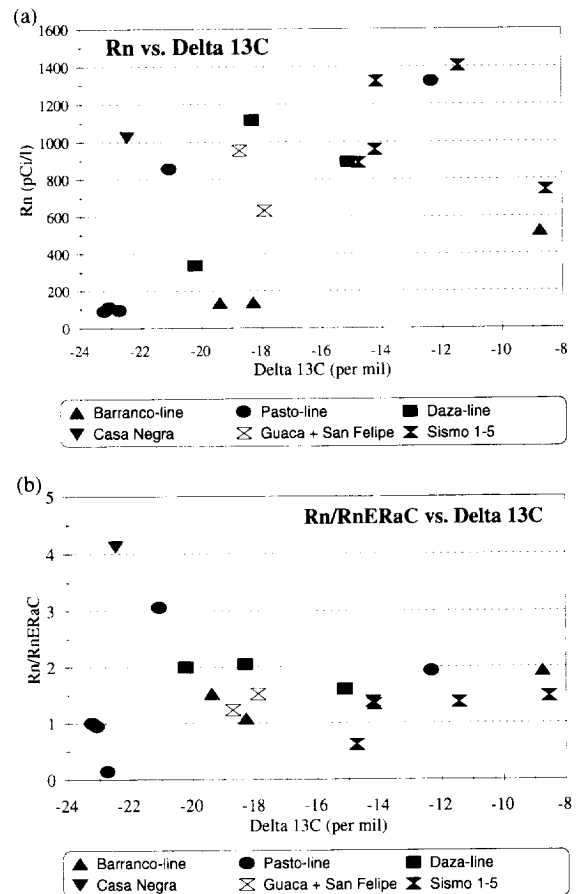


Fig. 6. (a) Plot of radon vs. $\delta^{13}\text{C}$. The linear relation is partly obscured by three outliers. (b) Plot of Rn/RnERaC vs. $\delta^{13}\text{C}$. If radon concentrations are normalized by the radon emanating potential of the soil (RnERaC), the correlation coefficient is 0.003.

concentrations are plotted against $\delta^{13}\text{C}$, the correlation coefficient is 0.3 because the relation is obscured by three outliers (Casa Negra, Barranco and Sismo 5, Fig. 6a). Neglecting these three stations, the correlation coefficient is 0.8. However, if radon concentrations are normalized by dividing them by the RnERaC, the correlation coefficient declines to 0.003 (Fig. 6b). This lack of correlation between normalized radon and $\delta^{13}\text{C}$ strongly suggests that soil gas radon is essentially surficial and that the high radon near faults can be explained, in most cases, by gases and aqueous solutions that ascend through faults and then deposit minerals rich in potassium and ^{222}Rn precursors near the surface (Nishimura and Katsura, 1990). In addition, the rocks in the vicinity of faults are often fractured with a larger surface area, allowing more radon to reach the surface than from unfractured rocks.

5.2. Soil degassing in the caldera

The Caldera station, located in the caldera moat at several hundred meters distance from the crater fumaroles, has very low soil gas concentrations (10 ± 6 pCi/l radon and 0.02% CO_2). Similar results have been observed in the crater of Poás volcano, Costa Rica, where extremely low soil gas values were measured on the dome (Charland et al., 1997). The La Y station, located at the same altitude but outside the caldera, has concentrations around 100 ± 10 pCi/l radon and $2.9 \pm 0.2\%$ CO_2 . This lack of soil gases in the caldera can be attributed to (1) subsurface sealing, which may be caused by an acid reflux zone from the hydrothermal system, or (2) enhanced breathing from wind effects (D. Thomas, pers. commun., 1996). As wind blows into the crater, pressure on the ground increases forcing air into the soil, resulting in a flux from atmosphere to soil. Indeed, the soil gas concentrations at the caldera station show atmospheric CO_2 levels. However, it is also possible that the ground inside the caldera is sealed due to the development of an impermeable clay layer associated with an acid reflux zone which acts as a barrier to magmatic gases. The lack of vegetation near the surface also results in very low levels of CO_2 in the ground.

In 1995, soil gases also were analyzed within 20 m of Deformes and Chavas fumaroles, both of which are located on the outer flanks of the active cone

(Fig. 1). Near Deformes, soil gas had a CO_2 content of 0.5% and a $\delta^{13}\text{C}$ of $-8.7 \pm 0.4\%$, while near Chavas, the soil gases contained 12% CO_2 with a $\delta^{13}\text{C}$ of $-7.9 \pm 0.4\%$. In the vicinity of the fumaroles, therefore, the CO_2 data indicate that the ground is fractured and sufficiently permeable to permit diffusion of magmatic gases to the surface.

5.3. Soil gas changes with altitude

Frequently, stations were arranged in linear arrays ascending towards the summit of Galeras. CO_2 concentrations generally increase towards the crater (1) if compared to other volcano stations located off-fault

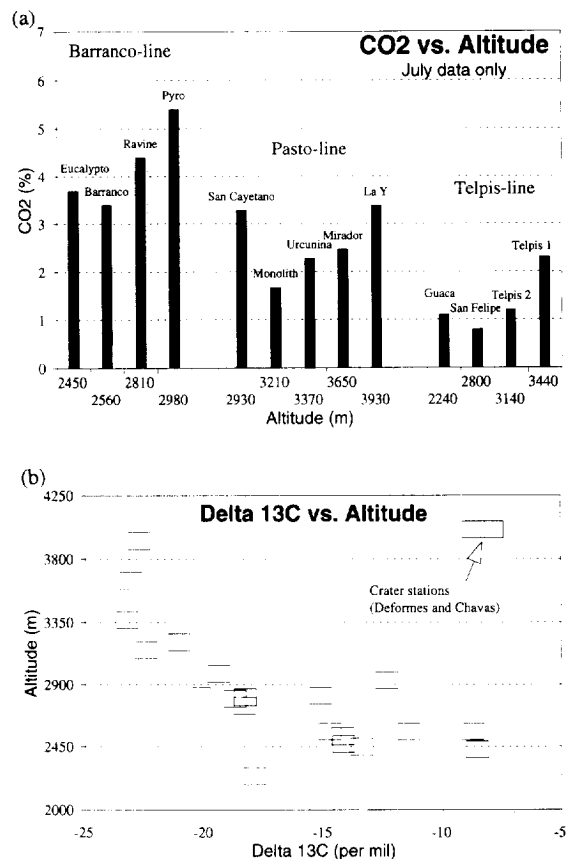


Fig. 7. (a) Plot showing CO_2 concentrations vs. altitude for the Barranco, Pasto and Telpis lines. The general increase of CO_2 towards the crater is obscured by the relatively high CO_2 concentrations at the San Cayetano and Guaca stations. (b) Plot of $\delta^{13}\text{C}$ vs. altitude for the individual stations. Although no trend is apparent for $\delta^{13}\text{C}$ ratios at lower elevations, the $\delta^{13}\text{C}$ values become lighter with increasing altitude. The size of the symbol encompasses the analytical error of $\pm 0.5\%$.

and (2) if measurements were done roughly at the same time to minimize seasonal influences. This general trend is observed on the Barranco, Pasto and Telpis lines, although the San Cayetano and Guaca stations, located near the Romeral–Buesaco fault system, tend to obscure this trend. (Figs. 1 and 7a). As these stations covered altitude differences of 500–1000 m, the increase of CO₂ may be caused by the higher humidity of the soil at stations higher on the volcano. The higher humidity reduces pore spaces and allows superficial CO₂ to accumulate. A general increase of CO₂ near the crater also has been observed on the Fossa cone on Vulcano Island (Baubron et al., 1990). Whereas high CO₂ near the crater on Volcano is associated with an elevated magmatic contribution, this correlation is not observed on Galeras. As CO₂ concentrations stay relatively constant or increase towards the summit, the $\delta^{13}\text{C}$ values frequently become lighter, suggesting a larger organic component at higher elevations due to the higher humidity and increased biogenic activity. The stable carbon isotopes indicate a significant input from a deep source near faults and areas of seismicity but not on the unfractured edifice of the volcano where values tend to become lighter with altitude (Fig. 7b). On most of the volcanic edifice, the faults are not discernible, since recent volcanic rocks such as lava flows cover the active faults. This cover also results in comparatively low radon concentrations compared to areas of active faulting. These observations suggest that (1) deep structural features do not reach the surface on much of the edifice due to the young volcanic cover and (2) diffuse degassing of the volcano through the unfractured edifice is negligible. Apparently, Galeras does not allow much diffuse degassing through its flanks.

5.4. Barranco and the Sismo stations

The Sismo stations are located on the northeastern flank of the volcano in and near an area where swarms of high-frequency seismicity have been observed in 1993 and 1995 (Fig. 1). The comparatively heavy isotopic signature of the soil gases, the high radon concentrations and the presence of earthquake swarms near the Barranco and Sismo stations together suggest (1) an area of active faulting, or (2) the intrusion of magma in this area. In both cases,

the resultant fracturing would explain the seismicity, the high radon concentrations and the comparatively heavy carbon isotope values.

Active faulting in this area would channel deep CO₂ to the surface. The heavy carbon isotope signature in CO₂ (reaching -8.5‰ at Sismo 5) suggests that these faults act as important channelways through which CO₂ is transported from deep levels. The deep CO₂ may be a mixture of magmatic, crustal and/or organic gas (Sano et al., 1997).

The isotopic signature of CO₂ from soil gas stations on the northern and northeastern flanks is also consistent with a magmatic source. Magma in the central conduit of Galeras was frozen and acted as a plug since dome emplacement in October–November 1991. If the three earthquake swarms of April 1993, November–December 1993 and March 1995 were caused by intrusion of magma under the northeastern flank of the volcano, then magma was repeatedly injected from deeper levels into this area. The heavy isotopic signature of CO₂ suggests that gases escaped through the northeastern flank and therefore may not have contributed to the pressure build-up in the central conduit after June 1993. In this context, it should be noted that tornillo seismic activity, indicating pressurization, did occur between July and November of 1993 but was not followed by an eruption. The tornillo activity ended temporarily after the earthquake swarms of November–December 1993. Fracturing, magma injection and degassing beneath the northeastern flank may have reduced pressure on the central conduit sufficiently to avoid an eruption.

5.5. Relationships among soil gases, seismicity and structure

In 1993, the soil gas response to the *M* 2.8 earthquake located beneath the La Guaca cinder cone may have resulted from the stress-induced dilation along the fault prior to the earthquake, a condition which caused a decrease in the soil pressure gradient and a consequent drop in radon soil gas prior to the event. The increase in soil gas concentrations after the event may indicate renewal of the former pressure gradient, thus transporting more gas to the surface. A similar decline also was registered at the Barranco station and raises the question why soil

gases in this northern area were affected by the seismic event when no important changes were registered at stations located closer to the La Guaca cinder cone (such as the Laguna Negra and the Telpis stations). Although we cannot answer this question satisfactorily at present, the possible interaction between the Romeral–Buesaco fault system and the volcano should be considered. It is possible that the Barranco area is linked structurally with the La Guaca area.

The observed soil gas response to the tornillos of August–September 1994 may have been caused by several processes:

(1) Pressure increases along faults and fissures in the edifice changed the pressure gradient of gas and thus channeled more radon to the surface.

(2) A pressurized magma chamber and dyke system generated stress and minor deformation along faults and fissures in the edifice, which could cause small variations in pore spaces. In areas where pore spaces were compressed, gas was pushed to the surface, and increases in soil gas concentrations were observed. Soil gas radon always has a more pronounced response than CO₂ because the measured concentrations are the average of the entire exposure period, and the effect is thus cumulative.

(3) Radon usually has a pronounced soil gas gradient; if gas is pushed to the surface, more radon reaches the detectors. As pressure in the magma chamber increased, gas was channeled into fractures and fissures, which changed the pressure gradient towards the surface. Increases in radon at the Guaca station, located on the Romeral–Buesaco fault system, also suggest that the volcano has an influence on soil degassing on the fault. It is unclear whether expansion in the magma chamber simply channeled more gas to the surface or whether the fault was actually compressed.

6. Conclusions

The observed response to tectonic and seismic events at Galeras suggests that soil gases can be useful in better understanding volcanic behavior. As soil gas concentrations increase prior to the occurrence of tornillos, the gases can be used as an initial warning sign of the pressurization of the magma

chamber, in conjunction with other data such as fumarole gas geochemistry and SO₂ fluxes measured by COSPEC.

Important conclusions of this work are the following:

(1) On Galeras, soil gas radon is, in all likelihood, not of magmatic origin. Its short half-life and relatively slow transport speed render a magmatic origin of radon soil gas unlikely. The high RnERaC of the soil itself can explain most elevated radon concentrations.

(2) Deep degassing on the edifice of Galeras is structurally controlled. Carbon isotopes in CO₂ from 21 stations on the edifice and on regional faults indicate that $\delta^{13}\text{C}$ values heavier than -15‰ exist only near faults and near areas of earthquake swarms.

(3) Soil gas variations can be correlated to climatic and seismic events. Prior to seismic events, sudden soil gas variations of up to 50% from previous levels were observed. By contrast, seasonal trends registered as constant, long-term decreases or increases. Volcanic seismic events, associated with the pressurization of the magma chamber, also can be correlated to soil gas variations. Soil gas radon concentrations increased significantly at certain sites up to three weeks before the onset of the seismicity.

(4) Soil gas response to seismic events is detectable at both volcano and fault stations, a fact which suggests that tectonic events can affect volcanic behavior at Galeras. In addition, a pressure buildup in the volcano registers at fault stations as an increased soil gas emanation, which suggests that the faults are compressed and exhale more soil gas. Thus, volcanic events also appear to affect tectonic activity in the area.

Acknowledgements

We especially thank the staff of the Observatorio Vulcanológico de Pasto, Colombia, for their support and assistance during the course of this work. Diego Gómez and Roberto Torres made the seismic data available and assisted in the interpretation. Libaniel Casa Ospina and Bruno Martinelli greatly assisted in organizational matters. Dave Haneson (Biomation), Dr. Paul Kotrappa and Lorin Stieff (Rad-Elec) helped answer our questions regarding E-PERMS. Mike

Dalva and Tim Moore of McGill University assisted with the CO₂ methodology and analysis of the 1993 data. We would also like to thank Neil Arner of the Stable Isotope Laboratory, University of Toronto, for analytical support with the isotopic analyses. We appreciate the helpful comments and suggestions from Don Thomas and Chuck Connor who reviewed the manuscript and greatly improved it. This work was supported by grants to J. S. from the Natural Sciences and Engineering Research Council of Canada, Fonds pour La Formation de Chercheurs et l'Aide à la Recherche (Québec), and the Université de Montréal.

References

- Allard, P., Carbonnelle, J., Dajlevic, D., Le Bronec, J., Morel, P., Robe, M.C., Maurenas, J.M., Faivre-Pierret, R., Martin, D., Sabroux, J.C. and Zettwoog, P., 1991. Eruptive and diffuse emissions of CO₂ from Mount Etna. *Nature*, 351: 387–391.
- Anzà, S., Bandalamenti, B., Giammanco, S., Gurrieri, S., Nuccio, P.M. and Valenza, M., 1993. Preliminary study on emanation of CO₂ from soils in some areas of Mount Etna (Sicily). *Acta Vulcanol.*, 3: 189–193.
- Badalamenti, B., Di Gangi, F., Guerrieri, S. and Valenza, M., 1993. Continuous monitoring (temperature, CO₂ in soil gases and reducing capacity). *Acta Vulcanol.*, 3: 269–271.
- Barberi, F. and Carapezza, M.L., 1994. Helium and CO₂ soil gas emission from Santorini (Greece). *Bull. Volcanol.*, 56: 335–342.
- Baubron, J.C., Allard, P. and Toutain, J.P., 1990. Diffuse volcanic emissions of carbon dioxide from Vulcano Island, Italy. *Nature*, 344: 51–53.
- Baubron, J.-C., Allard, P., Sabroux, J.-C., Tedesco, D. and Toutain, J.-P., 1991. Soil gas emanations as precursory indicators of volcanic eruptions. *J. Geol. Soc. London*, 148: 571–576.
- Calvache V., M.L., 1990. Geology and volcanology of the recent evolution of Galeras Volcano, Colombia. M.Sc. Thesis, Louisiana State Univ., Baton Rouge, LA, 148 pp.
- Calvache V., M.L., 1995. The geological evolution of Galeras Volcanic Complex. Ph.D. Thesis, Arizona State Univ., Tempe, AZ, 180 pp.
- Calvache V., M.L., Cortés, G.P. and Williams, S.N., 1997. Stratigraphy and chronology of the Galeras volcanic complex, Colombia. In: J. Stix, M.L. Calvache V. and S.N. Williams (Editors), Galeras Volcano, Colombia: Interdisciplinary Study of a Decade Volcano. *J. Volcanol. Geotherm. Res.*, 77: 5–19 (this volume).
- Charland, A., Stix, J., Barquero, J., Fernandez, E., Williams-Jones, G., Sherwood Lollar, B. and Barboza, V., 1997. Controls on diffuse degassing of radon and CO₂ at Poás volcano, Costa Rica. *Bull. Volcanol.* (in review).
- Cortés J., G.P. and Raigosa, A., J., 1997. A synthesis of the recent activity of Galeras volcano, Colombia: seven years of continuous surveillance, 1989–1995. In: J. Stix, M.L. Calvache V. and S.N. Williams (Editors), Galeras Volcano, Colombia: Interdisciplinary Study of a Decade Volcano. *J. Volcanol. Geotherm. Res.*, 77: 101–114 (this volume).
- Faure, G., 1986. Principles of Isotope Geochemistry. Wiley, New York, NY, 589 pp.
- Fischer, T., 1994. The geochemistry of fumarole gases at Galeras Volcano, Colombia. M.Sc. Thesis, Arizona State Univ., Tempe, AZ, 103 pp.
- Fischer, T.P., Morrissey, M., Calvache V., M.L., Gomez, D., Torres, R., Stix, J. and Williams S.N., 1994. SO₂ flux and long-period seismicity at Galeras volcano, Colombia. *Nature*, 335–337.
- Fischer, T.P., Arehart, G.B., Counce, D., Sturchio, N.C., Williams, S.N. and Stix, J., 1997. The chemical and isotopic composition of fumarolic gases and spring discharges from Galeras volcano, Colombia. In: J. Stix, M.L. Calvache V. and S.N. Williams (Editors), Galeras Volcano, Colombia: Interdisciplinary Study of a Decade Volcano. *J. Volcanol. Geotherm. Res.*, 77: 229–253 (this volume).
- Hall, M.L. and Wood, C.A., 1985. Volcano-tectonic segmentation of the northern Andes. *Geology*, 13: 203–207.
- Gómez M., D.M. and Torres C., R.A., 1997. Unusual low-frequency volcanic seismic events with slowly decaying coda waves observed at Galeras and other volcanoes. In: J. Stix, M.L. Calvache V. and S.N. Williams (Editors), Galeras Volcano, Colombia: Interdisciplinary Study of a Decade Volcano. *J. Volcanol. Geotherm. Res.*, 77: 173–193 (this volume).
- Gómez M., D.M., Torres C., R.A. and Cortés J., G.P., 1993. Volcan Galeras—El episodio sísmico de alta frecuencia de abril de 1993. INGEOMINAS, Intern. Rep., 17 pp.
- GVN, 1993a. Galeras volcano, Colombia. *GVN Bull.*, 18(11): 12.
- GVN, 1993b. Galeras volcano, Colombia. *GVN Bull.*, 18(12): 4.
- Irwin, P.W. and Barnes, I., 1980. Tectonic relations of carbon dioxide discharge and earthquakes. *J. Geophys. Res.*, 85: 3115–3121.
- King, C.Y., 1980. Episodic radon changes in subsurface soil gas along active faults and possible relation to earthquakes. *J. Geophys. Res.*, 83: 3065–3078.
- Kotrappa, P., Dempsey, J.C., Hickey, J.R. and Stieff, L.R., 1988. An electret passive environmental ²²²Rn monitor based on ionization measurements. *Health Phys.*, 54(4): 47–56.
- Mogro-Campero, A. and Fleischer, R.L., 1977. Subterrestrial fluid convection: a hypothesis for long-distance migration of radon within the earth. *Earth Planet. Sci. Lett.*, 34: 321–325.
- Murcia, A. and Cepeda, H., 1991. Memoria de la plancha 429—Pasto. INGEOMINAS, Bogotá, p. 18.
- Narváez M., L., Torres C., R.A., Gómez M., D.M., Cortés J., G.P., Cepeda V., H. and Stix, J., 1997. 'Tornillo'-type seismic signals at Galeras volcano, Colombia, 1992–1993. In: J. Stix, M.L. Calvache V. and S.N. Williams (Editors), Galeras Volcano, Colombia: Interdisciplinary Study of a Decade Volcano. *J. Volcanol. Geotherm. Res.*, 77: 159–171 (this volume).
- Nishimura, S. and Katsura, I., 1990. Radon in soil gas: applications in exploration and earthquake prediction. In: E.M. Durrance, E.M. Galimov, M.E. Hinkle, G.M. Reimer, R. Sugosaki

- and S.S. Augustithis (Editors), *Geochemistry of Gaseous Elements and Compounds*. Theophrastus Publications S.A., Athens, Greece, pp. 497–533.
- Owczarski, P.C., Holford, D.J., Freeman, H.D. and Gee, G.W., 1990. Effects of changing water content and atmospheric pressure on radon flux from surfaces of five soil types. *Geophys. Res. Lett.*, 17: 817–820.
- Ozima, M. and Podosek, F.A., 1983. *Noble Gas Geochemistry*. Cambridge Univ. Press, Cambridge, Australia, 367 pp.
- Sano, Y., Gamo, T. and Williams, S.N., 1997. Secular variations of helium and carbon isotopes at Galeras volcano, Colombia. In: J. Stix, M.L. Calvache V. and S.N. Williams (Editors), *Galeras Volcano, Colombia: Interdisciplinary Study of a Decade Volcano*. *J. Volcanol. Geotherm. Res.*, 77: 255–265 (this volume).
- Schery, S.D. and Petschek, A.G., 1983. Exhalation of radon and thoron: the question of the effect of thermal gradients in the soil. *Earth Planet. Sci. Lett.*, 64: 56–60.
- Schery, S.D., Gaeddert, D.H. and Wilkening, M.H., 1984. Factors affecting the exhalation of radon from a gravelly loam. *J. Geophys. Res.*, 89: 7299–7309.
- Schumann, R.R., Owen, D.E. and Asher-Bolinder, S., 1992. Effects of weather and soil characteristics on temporal variations in soil gas concentrations. In: A.E. Gates and L.C.S. Gundersen (Editors), *Geologic Controls on Radon*. *Geol. Soc. Am., Spec. Pap.*, 271: 65–72.
- Shapiro, M.H., Melvin, J.D., Tombrello, T.A. and Whitcomb, J.H., 1980. Automated radon monitoring at a hard rock site in the southern California transverse ranges. *J. Geophys. Res.*, 85: 3058–3064.
- Stix, J., Zapata G., J.A., Calvache V., M.L., Cortés J., G.P., Fischer, T.P., Gómez M., D.M., Narváez M., L., Ordoñez V., M., Ortega E., A., Torres C., R.A. and Williams, S.N., 1993. A model of degassing at Galeras volcano, Colombia, 1988–1993. *Geology*, 21: 963–967.
- Stix, J., Morrow, W.H., Nicholls, R. and Charland, A., 1996. Infrared remote sensing of CO and COS gas emitted by Galeras volcano, Colombia, 8–10 January 1993. *Can. J. Remote Sens.*, 22: 297–304.
- Stix, J., Torres C., R.A., Narváez M., L., Cortés J., G.P., Raigosa A., J., Gómez M., D.M. and Castonguay, R., 1997. A model of vulcanian eruptions at Galeras volcano, Colombia. In: J. Stix, M.L. Calvache V. and S.N. Williams (Editors), *Galeras Volcano, Colombia: Interdisciplinary Study of a Decade Volcano*. *J. Volcanol. Geotherm. Res.*, 77: 285–303 (this volume).
- Sugisaki, R., Ido, M., Takeda, H., Isobe, Y., Hayashi, Y., Nakamura, N., Satake, H., Mizutani, Y., 1983. Origin of hydrogen and carbon dioxide in fault gases and its relation to fault activity. *J. Geol.*, 91: 239–258.
- Teng, T.-L., 1980. Some recent studies on groundwater radon content as an earthquake precursor. *J. Geophys. Res.*, 85: 3089–3099.
- Tilsley, J.E., 1992. Radon: sources, hazards and control. *Geosci. Can.*, 19: 163–167.
- Thomas, D.M., Cuff, K.E. and Cox, M.E., 1986. The association between ground gas radon variations and geologic activity in Hawaii. *J. Geophys. Res.*, 91: 12,186–12,198.