



ELSEVIER

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

SCIENCE @ DIRECT®

Journal of Volcanology and Geothermal Research 138 (2004) 325–344

Journal of volcanology  
and geothermal research

[www.elsevier.com/locate/jvolgeores](http://www.elsevier.com/locate/jvolgeores)

## SO<sub>2</sub> emissions to the atmosphere from active volcanoes in Guatemala and El Salvador, 1999–2002

Lizzette A. Rodríguez<sup>a,\*</sup>, I. Matthew Watson<sup>a</sup>, William I. Rose<sup>a</sup>, Yvonne K. Branan<sup>a</sup>,  
Gregg J.S. Bluth<sup>a</sup>, Gustavo Chigna<sup>b</sup>, Otoniel Matías<sup>b</sup>, Demetrio Escobar<sup>c</sup>,  
Simon A. Carn<sup>d</sup>, Tobias P. Fischer<sup>e</sup>

<sup>a</sup>*Geological Engineering and Sciences, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, USA*

<sup>b</sup>*INSIVUMEH, 7a Avenida 14-57 Zona 13, Ciudad de Guatemala, Guatemala, Central America*

<sup>c</sup>*Servicio Nacional de Estudios Territoriales, km 5.5 Carretera a Nueva San Salvador, Avenida Las Mercedes,  
San Salvador, El Salvador, Central America*

<sup>d</sup>*Joint Center for Earth Systems Technology (NASA/UMBC), University of Maryland Baltimore County, MD 21250, United States*

<sup>e</sup>*Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, United States*

Received 17 July 2003; accepted 28 July 2004

### Abstract

Ground-based and aircraft correlation spectrometer (COSPEC) measurements at the principal active volcanoes in Guatemala (Pacaya, Santiaguito, Fuego, and Tacaná) and El Salvador (Santa Ana and San Miguel) were carried out at intervals during the period 1999–2002, as part of an attempt to measure baseline SO<sub>2</sub> emissions of potentially dangerous volcanoes and to better understand their eruption mechanisms. We discuss some of the uncertainties involved in interpreting intermittent gas data, together with possible improvements. Other problems pertaining to current monitoring of SO<sub>2</sub> and implications for future studies are also discussed.

Santa Ana volcano is proposed to be a venting hydrothermal system, while Santiaguito, Fuego, Pacaya, and San Miguel all exhibit open-vent characteristics. Data for Tacaná volcano are presented, but are not enough to make descriptions of its characteristics and activity. Pacaya is emitting high fluxes of SO<sub>2</sub> (>1000 tonnes/day), while the other vents are much lower emitters (20–300 tonnes/day in general). SO<sub>2</sub> emissions at Pacaya suggest a large circulating and convecting high level chamber. The most recent emission rates at Fuego were measured during its current active phase (since January 2002).

Average SO<sub>2</sub> emission rates during 1999–2002 are: 1350 tonnes/day for Pacaya, 340 tonnes/day for Fuego, 120 tonnes/day for Santiaguito, 260 tonnes/day for San Miguel, 140 tonnes/day for Santa Ana, and 30 tonnes/day for Tacaná. These volcanoes account for about 6% to 12% of the estimated annual global volcanic output of SO<sub>2</sub>.

© 2004 Elsevier B.V. All rights reserved.

*Keywords:* sulfur dioxide; COSPEC; gas monitoring; Guatemala; El Salvador; degassing

\* Corresponding author. Tel.: +1 906 487 2826; fax: +1 906 487 3371.

E-mail address: [larodrig@mtu.edu](mailto:larodrig@mtu.edu) (L.A. Rodríguez).

## 1. Introduction and objectives

Gas monitoring is an important tool used by volcanologists to understand volcanic processes and monitor eruptions. Volcanoes produce several gas species, of which water vapor, carbon dioxide, and sulfur dioxide are the most prevalent. Sulfur dioxide can cause significant damage to the local environment and the population's health, as well as perturb the climate and the atmosphere through the action of sulfate aerosol (Lacis et al., 1992). Direct sampling of volcanic gases has proven to be a very dangerous task, which is one of the reasons why volcanologists are more and more reliant upon remote sensing tools.

SO<sub>2</sub> is commonly measured remotely to determine emission rates, which can better our understanding of eruptive processes (Andres et al., 1993). Increases in SO<sub>2</sub> emission rates may indicate that magma is rising to lower confining pressures and that cracks have formed in the carapace covering the magma chamber (Stoiber et al., 1983). It can also be attributed to a constant and increasing supply of exsolving sulfur from depth, combined with an increasing magma discharge rate at the surface (Edmonds et al., 2003b). At the other hand, decreases suggest lower permeability of the upper conduit due to cooling and 'sealing' by the precipitation of hydrothermal minerals and the closure of fracture and bubble networks, and withdrawal of magma to lower levels and higher confining pressures (Stoiber et al., 1983; Edmonds et al., 2003b). An SO<sub>2</sub> time series, therefore, provides information about the dynamics and chemistry of magma (Edmonds et al., 2003a), including conduit permeability and driving pressures, the role of the hydrothermal system and changes in magma flux both at depth and to the surface (Edmonds et al., 2003b).

The volcanoes of Central America, many of them which are consistently active, are associated with a subduction zone, where the Cocos Plate subducts beneath the Caribbean Plate at a rate of around 7–9 cm per year (DeMets, 2001; Mann et al., 1990). This zone extends from Guatemala in the north to southern Costa Rica. Ground-based and airborne correlation spectrometer (COSPEC) measurements were carried out at the principal active volcanoes

(Fig. 1) in Guatemala (Pacaya, Santiaguito, Fuego, and Tacaná) and El Salvador (Santa Ana and San Miguel) during the 4-year period of 1999 to 2002 (March 1999–September 2002). Field measurement campaigns were conducted in March 1999, February to April 2001, November 2001, and January and September 2002, at Pacaya; in January to February 2001, January 2002 and April 2002 at Santiaguito; in May, September, and November 2001 and January to August 2002 at Fuego; in November 2001 at Tacaná; in February and May 2001, and January 2002 at Santa Ana; and in January 2002 at San Miguel. Andres et al. (1993) described the results of 20 years of SO<sub>2</sub> emission rate studies (1972–1991) from Pacaya, Santiaguito, and Fuego volcanoes. In this paper, we update their work, summarizing the results from the period 1999–2002, with the primary objective of estimating baseline SO<sub>2</sub> emissions of potentially dangerous volcanoes and of comparing trends in emission rates with the activity at each volcano. We also discuss some of the uncertainties involved in interpreting intermittent gas data, as well as focusing on some of the problems pertaining to current monitoring of SO<sub>2</sub> and implications for future studies.

*Pacaya* volcano (14°22' N, 90°36' W, 2552 m) is located on the southern rim of the Pleistocene Amatitlán caldera, about 23 km south of the international airport in Guatemala City, capital of Guatemala. Pacaya has been active since 1965, with activity consisting of frequent strombolian eruptions with intermittent lava flow extrusion on the flanks of MacKenney cone, punctuated by occasional larger explosive eruptions (GVN Bulletin, 1996). An eruption on 20 May 1998 disrupted airport operations for 3 days due to ash fallout (GVN Bulletin, 1998). This activity resumed on 2 January 1999 (GVN Bulletin, 1999a). A violent eruption took place on 16 January 2000, with tephra injections (~30 cm of tephra fell in the area south of the vent) and lava flows (GVN Bulletin, 1999d). On the evening of 29 February 2000, a second major eruption began. The ash column rose 2 km and lava fountained up to ~700 m above the summit (GVN Bulletin, 2000). A lava lake was observed at the crater from August 2000 until May 2002.

*Santiaguito* dome (14°44' N, 91°34' W, 2520 m) began growing in 1922 inside the 0.7×1.0-km crater

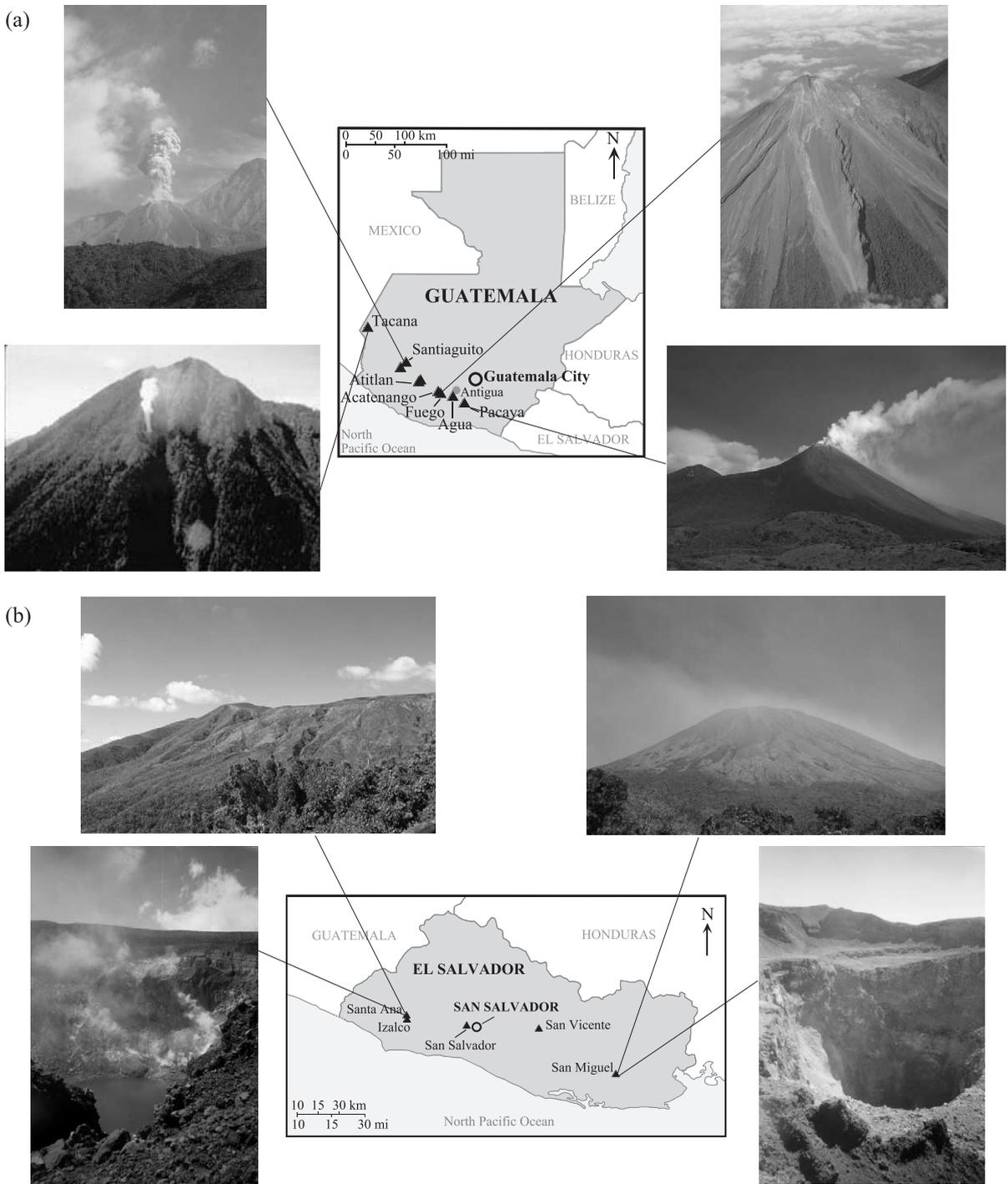


Fig. 1. Maps of (a) Guatemala and (b) El Salvador, with the location of the volcanoes studied (photo of Fuego volcano was taken by Danilo Juarros on 19 March 2002, and that of Tacaná was obtained from <http://www.proteccioncivil.chiapas.gob.mx/volcanes/Volcanes.htm>).

left by the 1902 eruption of Santa María volcano (Rose, 1972a), Guatemala. Growth of the dacite dome has proceeded episodically from four westward-younging vents (El Caliente, La Mitad, El Monje, and El Brujo) (Anderson et al., 1995), accompanied by very frequent explosions, lava extrusion, pyroclastic flows, and lahars (Sanchez Bennett et al., 1992). The vertical ash explosions have been proposed to be phreatomagmatic and therefore possibly influenced by the infiltration of groundwater (Sanchez Bennett et al., 1992). Santiaguito has high-temperature fumaroles that have served as sites for volcanic gas studies (Stoiber et al., 1971), gas condensates (Stoiber and Rose, 1970), and fumarolic incrustations (Stoiber and Rose, 1974). Since 1970, activity has shifted back to the main Caliente vent (Barmin et al., 2002; Harris et al., 2003). Activity in the last 4 years has been characterized by regular (around  $2 \text{ h}^{-1}$  and around 1 km high) ash emissions from the main vent, the eruption of a block lava flow, frequent ( $\sim 1 \text{ min}^{-1}$ ) incandescent rock falls from the flow and vent area (Harris et al., 2004), and lahars, which deposit fine sediments on the river valleys south–southwest of the vent (i.e. Río Nima I and Río Nima II) (GVN Bulletin, 1999b, 2002b).

Fuego volcano ( $14^{\circ}28' \text{ N}$ ,  $90^{\circ} \text{ W}$ , 3763 m) is one of three large stratovolcanoes (Fuego, Acatenango, and Agua) overlooking Guatemala's former capital of Antigua. Growth of the modern Fuego volcano started about 8500 years ago, continuing the southward migration of volcanism that began at Acatenango (Chesner and Rose, 1984). On October 1974, Fuego had its largest eruption since 1932, which produced heavy ashfall (Rose et al., 1978). In late May 1999, there was an eruption characterized by pyroclastic flows. This activity was followed by moderate strombolian eruptions until September 1999 (GVN Bulletin, 1999c). Activity in January 2000 comprised occasional ash venting (frequencies varied from less than 1 per hour to over 12 per hour) and small explosions, suggesting an open vent regime (GVN Bulletin, 2000). The current eruptive episode started on 4 January 2002, with degassing and weak to moderate steam explosions. The crater left from the May 1999 eruption (200 m diameter and 250–300 m depth) was filled partly by this activity. On January 23, a lava flow extended 300–500 m down the eastern flank and strombolian

explosions occurred every 20–45 s. Activity increased slightly on February 9, with moderate-sized explosions and a lengthening and widening of the lava flow to around 1000 and 400–500 m, respectively. Activity after February continued at the same level, with periods of high and low seismicity and weak to moderate explosions. The lava flow continued to descend during April 2002 down Barranca Las Lajas, Barranca Honda, and the western flank of the volcano, with continuous collapses of its front (Rüdiger Escobar (Coordinadora Nacional para la Reducción de Desastres, Guatemala), pers. commun., May 2002). Strombolian activity became more energetic on July 16, 2002, accompanied by a high-frequency tremor.

Tacaná volcano ( $15^{\circ} \text{ N}$ ,  $9^{\circ}27' \text{ W}$ , 4110 m) is a stratovolcano located on the Mexico–Guatemala border. Tacaná rises 1800 m above deeply dissected plutonic and metamorphic terrain. The elongated summit region is dominated by a series of lava domes intruded along a northeast trend. Historical activity has been restricted to mild phreatic eruptions, but the prehistoric record indicates more powerful explosive activity, including pyroclastic flow production (De La Cruz Martínez and Hernández Zuniga, 1986; Rose and Mercado, 1986). Its current activity is characterized by low-temperature fumarolic gas emissions. Analysis of fumaroles in April 1987 indicated that the largest fumarole had a temperature of  $89.3^{\circ} \text{ C}$  (SEAN Bulletin, 1987).

Santa Ana volcano ( $13^{\circ}51' \text{ N}$ ,  $89^{\circ}38' \text{ W}$ , 2365 m), El Salvador, is a stratovolcano immediately west of Coatepeque caldera. It was the source of the Pleistocene or early Holocene debris avalanche that formed the Acajutla Peninsula. Since the 16th Century, activity has consisted mainly of small-to-moderate explosive eruptions from both summit and flank vents. Within its summit (0.5 km diameter), there is an acid lake (pH $\sim$ 1), with a fumarole field on the crater wall adjacent to it. The lake was created by the 1904 eruption of Santa Ana (Pullinger, 1998). The hazards from Santa Ana include phreatic and phreatomagmatic summit eruptions, which can occur without observed precursory activity and are caused by the overpressurization of the volcanic gases produced by the fumaroles (Pullinger, 1998; GVN Bulletin, 2001).

San Miguel volcano ( $13^{\circ}26' \text{ N}$ ,  $88^{\circ}16' \text{ W}$ , 2130 m), El Salvador, is a basaltic volcano capped by a

broad deep crater (~1950–2000 m). San Miguel has erupted around 30 times since 1699, all events classified with a VEI of 1 or 2. Many of the earlier eruptions occurred at flank vents, but since 1867 all have taken place at the summit (Simkin and Siebert, 1994). The volcano erupts basalt and basaltic andesite and usually has a faint plume being emitted from its summit crater. It has had active fumaroles in the summit region at least since 1964. Since 1970, weak explosions have taken place four times, the last in January 2002. On 16 January 2002, a gas-and-steam plume rose with a mushroom-like profile a few hundred meters above the summit crater of San Miguel. During the field campaign documented here on 28–29 January 2002, the plume was observed to rise around 100 m above the crater rim. Long-period earthquakes, volcanic tremor, and explosion events were recorded at San Miguel in late January and February 2002 (GVN Bulletin, 2002a).

## 2. Methodology

### 2.1. COSPEC

The instrument most commonly used to detect and quantify SO<sub>2</sub> emission rates from volcanoes has been the COSPEC (Millan, 1980; Stoiber et al., 1983), which takes advantage of the selective absorption of ultraviolet radiation between 300 and 330 nm. The COSPEC measures SO<sub>2</sub> as a burden that is expressed in units of concentration multiplied by pathlength (ppm m) (Stoiber et al., 1983; Andres et al., 1993; Williams-Jones et al., in press a). The average concentration pathlength is then multiplied by the width and the velocity of the plume, in order to determine the emission rate, which is the mass of SO<sub>2</sub> emitted per unit of time (typically metric tonnes per day or kilograms per second). The signal is calibrated internally using cells that have a known SO<sub>2</sub> burden. The limit of detection of the COSPEC technique is in the range 5–10 ppm m, and it will be higher during conditions of rain or opaque clouds, which affect the intensity of light (Edmonds et al., 2003a).

A COSPEC V (Barringer Research, Toronto) was used to measure the SO<sub>2</sub> emission rates from active volcanoes in Guatemala and El Salvador. A daily average of the SO<sub>2</sub> emission rate was calculated for

each volcano. In the past, most averages were produced by combining results obtained using different techniques. In this study, the COSPEC results obtained through each of the different field methods (stationary, vehicular and airborne) were plotted, averaged, and analyzed separately.

### 2.2. Error analysis

#### 2.2.1. Sources of error

The COSPEC is subject to several sources of error, which include: uncertainty in the plume speed, scattering and absorption of ultraviolet light by other plume constituents (e.g. the presence of ash will cause overestimation due to scattering-UV radiation is partially blocked by ash increasing the apparent measured SO<sub>2</sub> by raising the effective background levels), and errors in calculating plume geometry (Millan, 1980; Stoiber et al., 1983).

Because the conditions and access to each volcano is different, the COSPEC methodology varied from one volcano to another. Three main techniques were used in the field: stationary, vehicular, and airborne. However, depending on the position of the plume both vertical (when the plume was traveling to the sides of the volcano) and horizontal (above the vent) scans were made during stationary measurements. The confidence in each technique depends on several factors, including the volcano under study, the instrument orientation and the field of view (determined by plume geometry) (Sutton et al., 2001). In general, throughout this research we have established the following order in decreasing confidence: airborne, vehicular, and stationary. Airborne techniques are the most reliable because the direction and velocity of the plume can be constrained more accurately. Along with vehicular techniques, they help avoid some of the errors of stationary measurements, such as: long pathlengths, inconsistent background conditions, oblique viewing angles, and plume geometry (Stoiber et al., 1983; Shannon et al., 2001; Williams-Jones et al., in press a). During stationary measurements of a wide, close plume, an “edge effect” can sometimes be seen, which is caused by scattering and results in a “smearing” of the plume’s edges (Millan and Hoff, 1978; Shannon et al., 2001). Shannon et al. (2001) used models to correct for the errors related to plume geometry, and concluded that they are only a part of

the discrepancy observed between airborne/vehicular and stationary measurements, and further models need to be constructed.

Plume speed (wind speed) was mostly measured using a hand-held anemometer at ground level. This is the biggest source of error, as it is an underestimate of the wind speed at plume height. In the case of the most recent measurements made at Santa Ana, the plume speed was measured by timing the movement of a portion of the plume over a known distance. Edmonds et al. (2003a) determined that the measured speed is most likely to be an underestimate of the true plume speed by around 30%, based on comparisons with estimates of wind speed in the helicopter at plume height (Stoiber et al., 1983; Young et al., 1998a; Edmonds et al., 2003b).

The plume width and azimuth are calculated from the scan angle and the plume height. The errors in plume geometry are mainly caused by ill-defined angular relationships between the instrument and the plume, which are related to the accurate determination of the instrument's position and the distance to the plume. The angles were measured using a compass and clinometer. Plume heights are essential to constrain the measurements during vertical scans (Edmonds et al., 2003a), which was the main method used in the determination of SO<sub>2</sub> emission rates during 1999–2002. The difficulty with this stationary scanning method is that a larger, higher plume will appear the same as a smaller, lower plume. An accurate estimate of plume height is therefore essential to minimize this error. At the other hand, during horizontal traverses, plume height is not essential, as two plumes with the same mass at different heights will produce equal SO<sub>2</sub> plume cross sections (Edmonds et al., 2003a).

#### 2.2.2. Volcano conditions and techniques employed

The conditions prevalent at each volcano studied are used to determine the COSPEC technique that will be employed. Although airborne techniques could be used to make traverses at all the volcanoes in this study, airborne traverses have not been common because of their high cost. Based on the conditions, we determined an order of increasingly suitable geometry for stationary work: Pacaya, San Miguel, Santa Ana, Santiaguito, and Fuego. At Fuego volcano, the errors related to plume geometry and speed are minimized, due to easy access to downwind plume

areas and the fact that wind speed measurements can be made at an appropriate plume height in order to estimate plume speeds. The narrow, high plume also permits more accurate calibration of the COSPEC output. The conditions at Pacaya volcano, at the other hand, are suitable for all COSPEC techniques. Most measurements are made through vehicular traverses, as a road (El Patrocinio) cuts through lava flows to the southwest of the vent and is oriented perpendicular to the prevalent plume direction. However, when the plume is traveling in other directions, stationary (both vertical and horizontal) traverses are made. Based on our data from Pacaya volcano in 2002, it was observed that the rates measured through vehicular methods were considerably higher than those measured by scanning from fixed positions. Similar discrepancies have been observed at Kilauea volcano, Hawaii (Andres et al., 1987; Sutton et al., 2001). The level of confidence on the vehicular traverses made at Pacaya is sometimes lower because of the ambiguity of the segment assignments on the road used to make the traverses (El Patrocinio). The angles and length of the segments are not always recorded and this considerably affects the output obtained.

#### 2.2.3. Uncertainty and spread of data

Using the mean and standard deviation data from Tables 3–6, a plot of the uncertainty of the COSPEC data for each volcano was created (Fig. 2). We were only able to use a small percent of the data for each volcano (based on the days in which measurements were made): 0% for Tacaná, 21% for Fuego, 25% for Santiaguito, 26% for Pacaya, 86% for Santa Ana, and 100% for San Miguel, as raw data were not available for every day. Based on the increasing spread of the data relative to the mean, we determined an order of increasing confidence in the results from the five volcanoes: Santa Ana, San Miguel, Pacaya, Fuego, and Santiaguito.

#### 2.2.4. Error analysis

A number of authors have discussed the errors involved in COSPEC measurements through the years. In this study, we use estimates from previous error analyses (Stoiber et al., 1983; Williams-Jones et al., in press a; Edmonds et al., 2003a,b), and add a discussion of errors on the techniques employed at the volcanoes studied. Stoiber et al. (1983) and Williams-

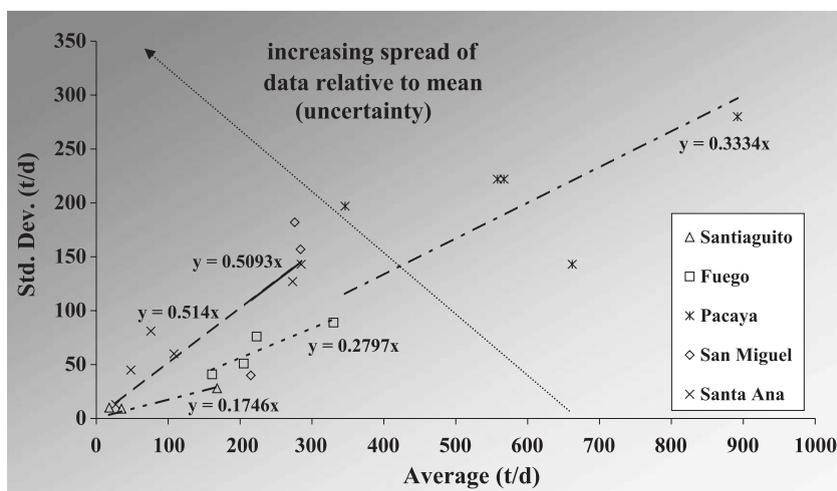


Fig. 2. Spread of data relative to the average.

Jones et al. (in press a) calculated the errors to range between ±13% and ±42%. These incorporate both instrumental and methodology errors. Using the means and standard deviations from Tables 3–6, we calculated the errors, *E*, related to the various techniques employed at each volcano, using

$$E = \frac{\sum (\text{AVERAGE (S.D.)})/n}{\sum (\text{AVERAGE (mean)})/n} \times 100\% \quad (1)$$

where *n* is the number of days in which the technique was used at each volcano. As mentioned previously, we were only able to use a small percent of the data for each volcano, as raw data were not available for every day.

2.2.4.1. Errors. The errors calculated for this analysis can be seen in Table 1, and they have been applied to

the plots from each volcano (Figs. 3–5) accordingly. The total error in the COSPEC measurements is calculated as the square root of the sum of the squares of the individual errors, for positive and negative errors, as follows.

Instrumental errors:

Calibration cells concentrations – COLSPEC V :

$$339.2 \text{ ppm} = -2\%$$

(based on Williams-Jones et al., in press a)

Chart record reading error :

$$\pm 0.5 \text{ mm} (0.5 \text{ mm} = 6 \text{ ppm})$$

For an average deflection of 100 ppm  $m = \pm 6\%$  (based on Stoiber et al., 1983)

Table 1  
Total error in the COSPEC measurements

Technique	Santiaguito	Fuego	Pacaya	San Miguel	Santa Ana	Tacana
Stationary vertical	-23%, +37%	-31%, +43%	-24%, +38%	-67%, +73%	-64%, +70%	-
Stationary horizontal	-	-27%, +40%	-45%, +54%	-40%, +50%	-	-
Vehicular	-	-	-47%, +55%	-	-47%, +56%	-
Airborne	-	-29%, +41%	-33%, +44%	-	-	31%, +43%

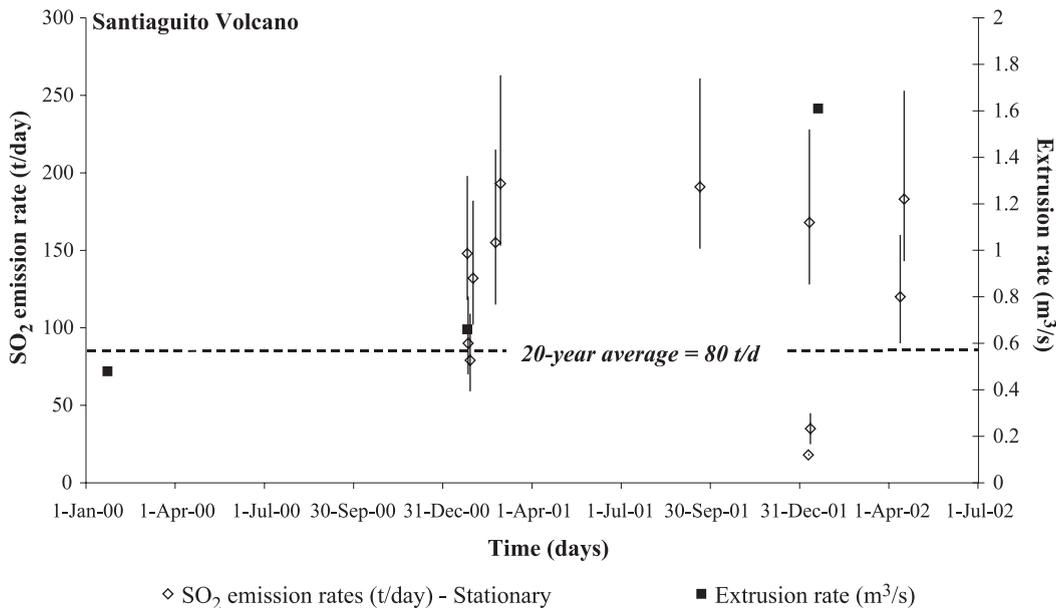
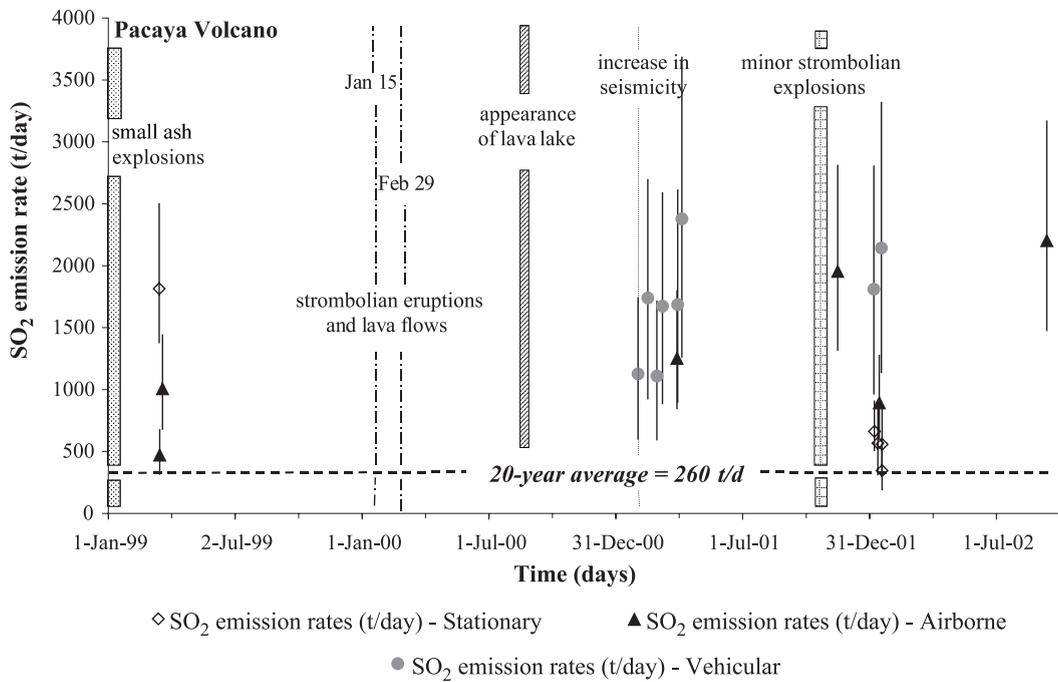


Fig. 4. SO<sub>2</sub> emission rates from Santiaguito dome, Guatemala (2001–2002). Error bars are based on the results from the error analysis (Table 1). The 20-year average (1972–1992) emission rate, calculated by Andres et al. (1993), is shown, together with the extrusion rates from 2000–2002 (Harris et al., 2004). SO<sub>2</sub> emission rate data from Table 4.

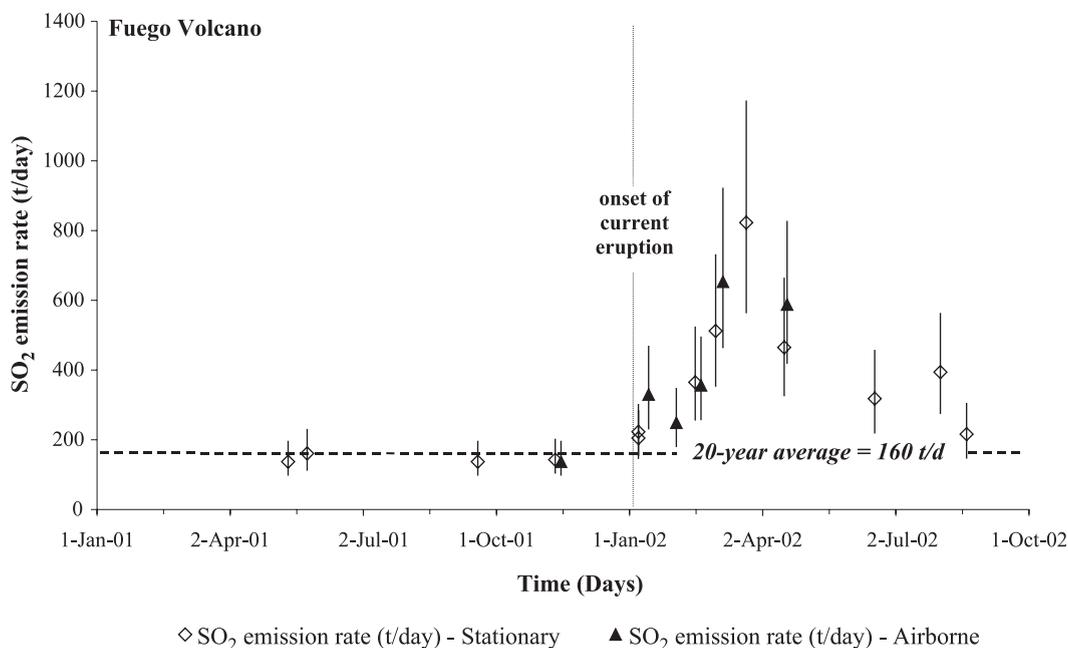


Fig. 5. SO<sub>2</sub> emission rates from Fuego volcano, Guatemala (2001–2002). Error bars are based on the results from the error analysis (Table 1). The 20-year average (1972–1992), calculated by Andres et al. (1993), is shown. The start of the current eruption, on January 4, 2002, is identified. SO<sub>2</sub> emission rate data from Table 5.

Technique errors: Errors related to the techniques used at each volcano (Table 2)

Variable vehicle/aircraft speed =  $\pm 5\%$   
(based on Williams-Jones et al., in press a)

Wind speed errors:  $-5\%$ ,  $+30\%$  (based on Edmonds et al., 2003a)

Distance determination error (related to calculation of plume width and direction):  $\pm 5\%$  (used) to  $\pm 10\%$  (worst case scenario) (based on Stoiber et al., 1983).

### 3. Results

The SO<sub>2</sub> emission rates, measured by COSPEC for Pacaya, Santiaguito, and Fuego volcanoes are listed in Tables 3–5, and plotted in Figs. 3–5. Those for Tacaná, Santa Ana, and San Miguel volcanoes are listed in Table 6. The data are plotted against time, and the results obtained from different methods can be distinguished. The number of measurements made on any 1 day will depend on the technique used, because, for example, in the time that one car traverse is made, about 30 stationary measurements can be made if the conditions are favorable. The

Table 2  
Errors related to the techniques used at each volcano

Volcano	Stationary vertical	Stationary horizontal	Vehicular	Airborne
Santiaguito	$\pm 21\%$	–	–	–
Fuego	$\pm 30\%$	$\pm 25\%$	–	$\pm 27\%$
Pacaya	$\pm 22\%$	$\pm 44\%$	$\pm 46\%^*$	$\pm 31\%$
San Miguel	$\pm 66\%$	$\pm 39\%$	–	–
Santa Ana	$\pm 63\%$	–	$\pm 46\%$	–
Tacana	–	–	–	$\pm 29\%^{**}$

\* Using error from Santa Ana's vehicular traverses.

\*\* Using average of errors from airborne traverses at Fuego and Pacaya.

Table 3  
SO<sub>2</sub> emission rates from Pacaya volcano, Guatemala

Date	Technique	# of Meas	Ave (tonnes/day)	Min (tonnes/day)	Max (tonnes/day)	S.D. (tonnes/day)	Activity
15 Mar 1999	Stationary <sup>V</sup>	16	1820	–	–	–	fuming
16 Mar 1999	Airborne	n.r.d.a.	470	–	–	–	fuming
20 Mar 1999	Airborne	n.r.d.a.	1010	–	–	–	fuming
1 Feb 2001	Vehicular	1	1130	–	–	–	fuming
15 Feb 2001	Vehicular	1	1740	–	–	–	fuming
28 Feb 2001	Vehicular	1	1110	–	–	–	fuming
8 Mar 2001	Vehicular	1	1670	–	–	–	fuming
29 Mar 2001	Airborne	n.r.d.a.	1250	–	–	–	fuming
30 Mar 2001	Vehicular	1	1690	–	–	–	fuming
5 Apr 2001	Vehicular	1	2380	–	–	–	fuming
15 Nov 2001	Airborne	n.r.d.a.	1950	–	–	–	fuming
6 Jan 2002	Vehicular	1	1810	–	–	–	fuming
7 Jan 2002	Stationary <sup>V</sup>	29	660	440	980	140	fuming
12 Jan 2002	Stationary <sup>H</sup>	14	570	120	880	220	fuming
14 Jan 2002	Airborne	3	890	680	1210	280	fuming
17 Jan 2002	Vehicular	1	2140	–	–	–	fuming
18 Jan 2002	Stationary <sup>H</sup>	10	560	230	970	220	fuming
18 Jan 2002	Stationary <sup>H</sup>	2	350	210	480	200	fuming
12 Sep 2002	Airborne	n.r.d.a.	2200	–	–	–	fuming

n.r.d.a.: no raw data available.

Stationary<sup>V</sup>: vertical scans.

Stationary<sup>H</sup>: horizontal scans.

average SO<sub>2</sub> emission rate reported for each time frame (days) is an unweighted average. The minimum, maximum, and standard deviation of the daily measurements are included on the tables where appropriate (i.e. for stationary and multiple vehicular measurements). The prevalent eruptive activity occurring during the time of the measurements is summarized in Tables 3–6.

### 3.1. Pacaya

Pacaya volcano is an open vent system, and, at least during the study period, it was the highest SO<sub>2</sub> emitter of the six volcanoes studied (Table 3 and Fig. 3). Andres et al. (1993) reported an average emission rate of 260 tonnes/day for Pacaya for the 20-year period before 1992. COSPEC measurements were

Table 4  
SO<sub>2</sub> emission rates from Santiaguillo volcano, Guatemala

Date	Technique	# of Meas	Ave (tonnes/day)	Min (tonnes/day)	Max (tonnes/day)	S.D. (tonnes/day)	Activity
25 Jan 2001	Stationary <sup>V</sup>	9	150	–	–	–	fuming/v.a.e.
26 Jan 2001	Stationary <sup>V</sup>	n.r.d.a.	90	–	–	–	fuming/v.a.e.
28 Jan 2001	Stationary <sup>V</sup>	6	80	–	–	–	fuming/v.a.e.
31 Jan 2001	Stationary <sup>V</sup>	20	130	–	–	–	fuming/v.a.e.
23 Feb 2001	Stationary <sup>V</sup>	20	160	–	–	–	fuming/v.a.e.
28 Feb 2001	Stationary <sup>V</sup>	n.r.d.a.	190	–	–	–	fuming/v.a.e.
20 Sep 2001	Stationary <sup>V</sup>	17	190	–	–	–	fuming/v.a.e.
9 Jan 2002	Stationary <sup>V</sup>	10	20	10	30	10	fuming/v.a.e.
10 Jan 2002	Stationary <sup>V</sup>	30	170	120	220	30	fuming/v.a.e.
11 Jan 2002	Stationary <sup>V</sup>	24	40	20	60	10	fuming/v.a.e.
13 Apr 2002	Stationary <sup>V</sup>	n.r.d.a.	120	–	–	–	fuming/v.a.e.
17 Apr 2002	Stationary <sup>V</sup>	n.r.d.a.	180	–	–	–	fuming/v.a.e.

n.r.d.a.: no raw data available.

v.a.e.: vertical ash eruption.

Stationary<sup>V</sup>: vertical scans.

Table 5  
SO<sub>2</sub> emission rates from Fuego volcano, Guatemala

Date	Technique	# of Meas	Ave (tonnes/day)	Min (tonnes/day)	Max (tonnes/day)	S.D. (tonnes/day)	Activity
12 May 2001	Stationary <sup>V</sup>	21	140	–	–	–	fuming
25 May 2001	Stationary <sup>V</sup>	24	160	90	270	40	fuming
19 Sep 2001	Stationary <sup>V</sup>	14	140	–	–	–	fuming
11 Nov 2001	Stationary <sup>V</sup>	n.r.d.a.	140	–	–	–	fuming
15 Nov 2001	Airborne	n.r.d.a.	140	–	–	–	fuming
7 Jan 2002	Stationary <sup>V</sup>	20	220	120	350	80	stromb
7 Jan 2002	Stationary <sup>H</sup>	14	200	130	350	50	stromb
14 Jan 2002	Airborne	4	330	220	440	90	stromb
2 Feb 2002	Airborne	n.r.d.a.	250	–	–	–	stromb
15 Feb 2002	Stationary <sup>V</sup>	19	360	–	–	–	stromb
19 Feb 2002	Airborne	14	360	–	–	–	stromb
1 Mar 2002	Stationary <sup>V</sup>	11	510	–	–	–	stromb
6 Mar 2002	Airborne	14	650	–	–	–	stromb
22 Mar 2002	Stationary <sup>V</sup>	14	820	–	–	–	stromb
17 Apr 2002	Stationary <sup>V</sup>	n.r.d.a.	460	–	–	–	stromb
19 Apr 2002	Airborne	n.r.d.a.	590	–	–	–	stromb
18 Jun 2002	Stationary <sup>V</sup>	n.r.d.a.	320	–	–	–	stromb
2 Aug 2002	Stationary <sup>V</sup>	n.r.d.a.	390	–	–	–	vulc
20 Aug 2002	Stationary <sup>V</sup>	n.r.d.a.	220	–	–	–	stromb

n.r.d.a.: no raw data available.

stromb: strombolian.

Stationary<sup>V</sup>: vertical scans.

vulc: vulcanian.

Stationary<sup>H</sup>: horizontal scans.

made in 1999, 2001, and 2002, and mostly during the first months of the year (January to April). More SO<sub>2</sub> measurements have been carried out at Pacaya than

the other volcanoes considered here during 1999–2002, because of its continuous activity and close proximity to Guatemala City, where INSIVUMEH is

Table 6  
SO<sub>2</sub> emission rates from Tacaná, Santa Ana, and San Miguel volcanoes

Date	Technique	# of Meas	Ave (tonnes/day)	Min (tonnes/day)	Max (tonnes/day)	S.D. (tonnes/day)	Activity
<i>Tacaná</i>							
14 Nov 2001	Airborne	n.r.d.a.	30	–	–	–	fuming
<i>Santa Ana</i>							
8 Feb 2001	Stationary <sup>V</sup>	13	110	30	260	60	fuming
9 Feb 2001	Stationary <sup>V</sup>	42	280	100	950	140	fuming
9 Feb 2001	Vehicular	3	270	190	420	130	fuming
9 May 2001	Stationary <sup>V</sup>	n.r.d.a.	170	–	–	–	fuming
24 Jan 2002	Stationary <sup>V</sup>	8	80	10	220	80	fuming
25 Jan 2002	Stationary <sup>V</sup>	4	30	10	40	10	fuming
26 Jan 2002	Stationary <sup>V</sup>	14	50	20	180	40	fuming
<i>San Miguel</i>							
28 Jan 2002	Stationary <sup>V</sup>	28	280	40	690	180	fuming
28 Jan 2002	Stationary <sup>H</sup>	20	220	140	290	40	fuming
29 Jan 2002	Stationary <sup>H</sup>	25	280	50	600	160	fuming

n.r.d.a.: no raw data available.

Stationary<sup>V</sup>: vertical scans.

Stationary<sup>H</sup>: horizontal scans

based. The 4-year average SO<sub>2</sub> emission rate for Pacaya is 1350 tonnes/day. SO<sub>2</sub> emission rates were high (>1000 tonnes/day) following an eruptive period in 1998–1999. No measurements were made during the year 2000. In February 2001, the SO<sub>2</sub> emission rate was greater than 1000 tonnes/day (Table 3), and these high emission rates have been sustained to the end of 2002. Pacaya shows continuous degassing, but “puffing” from the vent occurs with periods of a few seconds. These was visually observed during the 2002 field campaign and confirmed through temperature measurements conducted using an infrared radiometer (A. Harris, University of Hawaii at Manoa, pers. commun., 2003).

The range in daily SO<sub>2</sub> emissions at Pacaya was high, especially during the beginning of 2002. SO<sub>2</sub> emission rates of 350 to 2140 tonnes/day have been recorded during 1 day. This suggests that averaging is not necessarily representative of the true emission from Pacaya. It was also observed that the rates measured through vehicular methods were considerably higher than those measured through stationary occupations.

Due to the changes in plume azimuth at Pacaya, not all the stationary measurements were made through vertical scans, and very low SO<sub>2</sub> emission rates were sometimes obtained (i.e. January 12 and 18, 2002). Only one set of measurements was done using a fixed wing aircraft to carry out a horizontal traverse in January 2002 (January 14), which was used to generate a more accurate plume speed and direction. This measurement, 890 tonnes/day, is regarded as the most accurate SO<sub>2</sub> emission rate (associated with the lowest errors) during January 2002. The plume at Pacaya extends for several tens of kilometers from the vent and is usually narrow and well-defined, making it relatively easy to make measurements of SO<sub>2</sub> emissions using the COSPEC. The measurements undertaken on 12 September 2002 indicated an increase in SO<sub>2</sub> emission rate, to 2200 tonnes/day.

### 3.2. Santiaguito

Santiaguito dome is an open vent system and a relatively low SO<sub>2</sub> emitter (Table 4 and Fig. 4). The 20-year SO<sub>2</sub> average for Santiaguito, calculated by Andres et al. (1993), was 80 tonnes/day, which is lower than most of the emission rates measured on

2001 and 2002. COSPEC measurements were made in 2001 and 2002, with an average SO<sub>2</sub> emission rate of 120 tonnes/day.

Stationary SO<sub>2</sub> emission rate measurements made 9–11 January 2002 show a wide variability. On 9 and 11 January, SO<sub>2</sub> emission rates were determined to be between 20 and 40 tonnes/day, whilst on 10 January the average SO<sub>2</sub> emission rate was 170 tonnes/day. No significant changes in volcanic activity were noted during this period. On 9 January 2002, the SO<sub>2</sub> emission rate was below detection. However, we have included the measurements for completeness of the data set. The measurements at Santiaguito represent 2 to 3 h of monitoring each day, with a maximum of 30 measurements in an hour. COSPEC measurements carried out on 13 and 17 April 2002 yielded emission rates of 120 and 180 tonnes/day, respectively.

### 3.3. Fuego

During 2001, the average SO<sub>2</sub> emission rate at Fuego, calculated on the basis of the measurements presented here, was 140 tonnes/day. The 20-year SO<sub>2</sub> average for Fuego, calculated by Andres et al. (1993), was 160 tonnes/day. The onset of a new eruption on 4 January 2002 corresponded with our field season in Guatemala, and we were able to conduct measurements on the volcano in the initial stages. Measurements of SO<sub>2</sub> emissions at Fuego (Table 5 and Fig. 5) conducted on 6 and 14 January 2002 showed a higher SO<sub>2</sub> emission rate than that measured in 2001. SO<sub>2</sub> emission rate then increased from January through to the end of March 2002 and then began to decrease once again in April 2002. No COSPEC measurements were made during May 2002. The SO<sub>2</sub> emission rates during the month of August ranged between 200 and 400 tonnes/day.

### 3.4. Tacaná volcano

SO<sub>2</sub> emission rates were measured at Tacaná once during 1999–2002, on 14 November 1999, when SO<sub>2</sub> emission rates were 30 tonnes/day (Table 6).

### 3.5. Santa Ana

SO<sub>2</sub> emission rates at Santa Ana (Table 6) have been measured only in 2001 and 2002 (since 1999),

with lower degassing observed on the most recent visit. The range in SO<sub>2</sub> emission rates went from as low as 10 to as high as 220 tonnes/day.

### 3.6. San Miguel

San Miguel volcano usually has a faint plume from its summit crater. SO<sub>2</sub> emission rates (Table 6) were measured for the first time on January 28 and 29, 2002. The average emission rates ranged between 200 and 300 tonnes/day, and “puffing” was observed from its deep crater. The emission rates were measured with stationary techniques, and because of the plume geometry, horizontal scans above the vent were done on both days. The range of SO<sub>2</sub> emission rates measured was highly variable, ranging from 40 to 690 tonnes/day.

## 4. Discussion

### 4.1. SO<sub>2</sub> emissions and volcanic activity

#### 4.1.1. Pacaya

We have presented here the results obtained from COSPEC measurements during the 4-year period of 1999–2002. The activity at Pacaya during that period was characterized by continuous degassing, with occasional Strombolian explosions and lava flows. At basaltic systems, such as Pacaya, sulfur exsolves as the magma decompresses and eruptive events are preceded and accompanied by increased SO<sub>2</sub> emission rates, which rapidly decay once activity at the surface has ceased (Edmonds et al., 2003a). The lack of measurements during the last two major eruptions at Pacaya, January 16 and February 29, 2000, prevents us from making better correlations between the SO<sub>2</sub> emission rates and periods of higher activity. We can, however, make some generalizations, based on the 1999–2002 SO<sub>2</sub> emission rate time series.

Dense plumes were observed at the end of 2000. Vegetation (pine trees and cornfields) was damaged downwind of the crater (prevailing winds to the south and west) in November 2000, which suggests that SO<sub>2</sub> emission rates were high at that time (GVN Bulletin, 2002c). On 22 January 2001, an increase in the level of seismicity occurred, with tremor and a rumbling sound reported from the crater. At the

beginning of February 2001, the SO<sub>2</sub> emission rates were greater than 1100 tonnes/day (see Fig. 3) and the level of seismicity increased further. A lava lake formed inside the crater at the end of August 2000, which remained until June 2001 (GVN Bulletin, 2002c). Incandescence was observed during the months of February to June 2001, caused by the lava lake activity. Measurements during this period averaged 1570 tonnes/day. At the end of October 2001, there were minor Strombolian explosions with ash falling south of the volcano (GVN Bulletin, 2002c). Measurements in November 2001 averaged 1950 tonnes/day. Activity since then consisted of persistent gas emissions and no visible lava lake activity. However, during January 2002 a glow was observed from the crater, suggesting that magma was at a high level in the conduit.

There have been no lava flows reported from Pacaya since February 2000, yet SO<sub>2</sub> emission rates consistently increased during 2001–2002 and reached a level significantly higher than the 20-year average reported by Andres et al. (1993). This suggests that the source for the SO<sub>2</sub> emissions could be a shallow convecting magma body beneath the volcano that has not yet reached the surface. Sulfur exsolves or partitions from magma at variable depths, according to magma geochemistry, pressure and temperature (Scaillet et al., 1998). It forms a fluid phase, together with water, carbon dioxide, hydrogen chloride, and other minor species. This migrates upwards through the magma storage region and conduit, either carried in the magma as gas bubbles or moving through a magma body through fracture and bubble networks (Scaillet et al., 1998). The arrival of the fluid phase at the surface depends on the chemistry of the magma and the permeability of the edifice, which is largely controlled by the rates of magma ascent and by sealing processes (Stix et al., 1993; Edmonds et al., 2003b).

The biggest concern at Pacaya is related to collapse of the active cone, due to the magma body being probably in a high level on the cone. Hydrothermal alteration can be observed clearly on the south flank of the edifice. Precursory activity is difficult to detect, with only one seismic station operating at Pacaya and infrequent monitoring of gas emissions. The determination of a baseline emission rate at Pacaya could help identify periods of enhanced risk for a sector collapse.

This is because a significant decrease in SO<sub>2</sub> emission rates can indicate that the gas is trapped in fracture and bubble networks, therefore the permeability decreases and there is a pressure buildup in the upper part of the conduit, which could lead to an explosive event.

#### 4.1.2. Santiagouito

Santiagouito dome is considered a low SO<sub>2</sub> emitter (120 tonnes/day), but it is one of Guatemala's most dangerous volcanoes. Ash explosions, generally occurring at least twice every hour (based on our observations on January 2002), typify the activity at Santiagouito. Paired explosions or two emissions separated by a few minutes were also observed during the time of measurement. Observations from the top of Santa María volcano on January 11, 2002 indicated the occurrence of a ring feature on the crater (about 70 m in diameter). This was apparent at the beginning of some of the ash explosions (which originated on it), which is the reason why it was interpreted as a surface representation of the conduit. The periods of continuous degassing or fuming occur on different time scales from the sporadic ash explosions and consequently a wide range of SO<sub>2</sub> emission rates were measured. This makes it difficult to determine the volcano's background gas fluxes. Preliminary results of higher temporal resolution SO<sub>2</sub> measurements at the beginning of 2003 (using a mini-UV spectrometer) in Santiagouito indicate an increase in the SO<sub>2</sub> emission rates prior to or together with the explosive events, followed by lower level degassing.

Since 1970 extrusive activity shifted back to the main Caliente vent. The lava extrusion rate is characteristically episodic at this volcano and evidence suggests that the magma composition is changing through time (Barmin et al., 2002; Harris et al., 2003). Geochemical analysis (whole rock analysis by X-ray fluorescence) of 39 lava samples erupted between 1922 and 2001 was undertaken by Harris et al. (2003). The results of the analyses indicate a gradual change towards more mafic magma compositions in the last 33 years, with silica weight fractions ( $X_{\text{SiO}_2}$ ) changing from 65 to 63 wt.% since 1970. This decrease in  $X_{\text{SiO}_2}$  would result in a ~30% decrease in viscosity (Harris et al., 2003). We suggest that this may be the cause of the increase in SO<sub>2</sub> emission rate during 1999–2002, when compared with

the 20-year average calculated by Andres et al. (1993). Basaltic–basaltic andesite melts are capable of dissolving a greater mass of sulfur than more silicic melts (Carroll and Rutherford, 1985).

Extrusion rates have shown a marked cyclicity, where 3–6-year-long periods of higher extrusion (0.6–2.1 m<sup>3</sup> s<sup>-1</sup>) are separated by 4- to 11-year-long periods of lower (~0.2 m<sup>3</sup> s<sup>-1</sup>) extrusion rate (Rose, 1972b, 1987; Harris et al., 2003, 2004). The extrusion rate appears to have increased from ~0.6 m<sup>3</sup> s<sup>-1</sup> (2000–2001) to ~1.4 m<sup>3</sup> s<sup>-1</sup> (2002), which is extremely high for Santiagouito (Harris et al., 2004) (Fig. 4). This cyclicity in the extrusion rates at Santiagouito probably affects the SO<sub>2</sub> emission rates. It could explain the difference between the results obtained in the 1999–2002 period versus the 20-year average calculated by Andres et al. (1993). Similar results have been observed at Soufriere Hills volcano, Montserrat, during its current eruption (Young et al., 1998a,b; Edmonds et al., 2003b). Edmonds et al. (2003b) observed that SO<sub>2</sub> emissions during dome building at the Soufriere Hills fluctuate, with high emission rates corresponding to periods when lava extrusion rates are high and when the conduit is open after large collapse events. At the other hand, low emission rates correlate with periods when dome growth stops or when the conduit and dome system become sealed due to precipitation of hydrothermal minerals. Santiagouito appears to undergo rapid changes in eruptive conditions over short time scales, which makes sporadic SO<sub>2</sub> emission measurements difficult to interpret. The study of SO<sub>2</sub> emission at Santiagouito would benefit from more frequent measurements and an in-depth study of geochemical volatile signatures in the erupted lavas.

#### 4.1.3. Fuego

Volcanic activity began to increase in December 2001, when a period of tremor started. This was closely followed by a sequence of phreatic explosions, which began on 4 January 2002. The arrival of fresh magma at the surface occurred soon afterwards and progressively filled the crater formed by eruptive activity in May 1999. Lava began to overflow the crater walls on 23 January 2002 (GVN Bulletin, 2002d). SO<sub>2</sub> emission began to increase at the end of 2001, from 140 tonnes/day measured on 15 November 2001 to 220 tonnes/day on 7 January 2002 (Table 5).

On 1 February 2002, a particularly energetic Strombolian eruption of ash, steam and juvenile lava occurred and by 10 February 2002, 400 explosions were taking place each day (compared with a daily average of 75 during “normal” activity). During Strombolian activity, large gas emissions occur after small gas bubbles accumulate, coalesce and escape in a slug (Andres et al., 1993; Jaupart and Vergnolle, 1988). On 12 February 2002, a lava flow breached the crater wall and flowed 2 km down the eastern flank (GVN Bulletin, 2002d). The rate of increase of SO<sub>2</sub> emissions accelerated in February and March 2002, with an increase from 250 tonnes/day on 2 February 2002 up to a maximum of 820 tonnes/day on 22 March 2002. This continuous increase in the emission rates could indicate a constant or increasing supply of mafic magma that supplies the sulfur from depth, as well as an opening of the system by propagation of fractures and the formation of bubble networks (Edmonds et al., 2003b). SO<sub>2</sub> emissions decreased in April 2002, when an average emission rate of 530 tonnes/day was measured. These lower emission rates are indicative of decreases in the permeability of the system.

The next measurements were taken in June 2002 and the SO<sub>2</sub> emission rate had decreased to 320 tonnes/day, although the lava flow was still active at this time. On 16 July 2002, high-frequency tremor began and the number of Strombolian explosions occurring each day increased. The level of seismicity further increased on 29 July 2002 and the lava flow reached 3 km in length (Chigna and Vulcanología INSIVUMEH, 2002; GVN Bulletin, 2002d).

The SO<sub>2</sub> emission rate was 390 tonnes/day on 2 August 2002 (see Fig. 5), when the energy of explosions changed and the activity switched from Strombolian to Vulcanian, with explosions sending ash 800–1400 m vertically, which then drifted westwards (Chigna and Vulcanología INSIVUMEH, 2002; GVN Bulletin, 2002d). These explosions produced moderate to strong rumbling sounds, which were accompanied by acoustic waves, which caused vibration of glass and roofs in the nearby towns (west and southwest) (Chigna and Vulcanología INSIVUMEH, 2002). A hypothesis to explain this change in eruptive style to Vulcanian activity could be closed system degassing at depth. As magma ascends, volatiles are exsolved and accumulate at the top of the shallow magma body. The gas is released into a

conduit connected to the summit crater when the strength of the surrounding rock is exceeded by pressure (Morrissey and Mastin, 2000). Since this style of activity was only observed for a short time during the current eruptive phase, comparisons with gas measurements are not possible, as there was only one day of measurements during the period.

After this peak in activity, the level of seismicity decreased once again and measurements made on 20 August 2002 showed that the SO<sub>2</sub> emission rate had declined to 220 tonnes/day (see Fig. 5).

#### 4.1.4. Santa Ana

There has been no publication of measurements of SO<sub>2</sub> emission rates at Santa Ana volcano prior to the 2001 data presented here. However, an increase in gas emissions from the fumarolic field was observed in May 2000, which was accompanied by an increase in lake temperature from 19 to 30 °C and a net increase in dissolved chlorides and sulfates (Bernard et al., 2004). Increasing lake temperature can be a precursory signal for the renewal of magmatic activity and the only likely source for chloride is by condensation of magmatic vapors. The fact that the recent activity is characterized by phreatic and phreatomagmatic eruptions suggests the presence of a large and permanent hydrothermal system at shallow levels within the volcano. The crater lake acts as a calorimeter and chemical condenser and integrates most of the flux of heat and volatiles released by shallow magma (Bernard et al., 2004).

The SO<sub>2</sub> emission rates measured in 2001 were between 110 and 280 tonnes/day and are higher than we would expect from a volcano that is displaying no signs of magmatic activity close to the surface. This is substantiated by the high-temperature fumaroles around the crater lake (up to 532 °C in 2000 and 632 °C in 2002) (GVN Bulletin, 2001; Bernard et al., 2004). Degassing volcanoes that host hot lakes typically produce SO<sub>2</sub> emission rates between ~50 and 400 tonnes/day, which is comparable to estimates from volcanoes without a lake (Delmelle and Bernard, 2000). The lack of significant seismicity precludes the presence of a moving magma body close to the surface, however (GVN Bulletin, 2001). Various hypotheses have been proposed to account for the high SO<sub>2</sub> emission rate at this volcano. One hypothesis is that the SO<sub>2</sub> is sourced from a deep convecting

magma body, overlain by a highly developed hydrothermal system, composed of amorphous silica and clay minerals, which formed over time as the magma body has cooled, degassed and crystallized. Such a mechanism was discussed in more detail by Giggenbach et al. (1990) for Nevado del Ruiz. Leaking of the hydrothermal cap could explain the SO<sub>2</sub> emission rates measured. Bernard et al. (2004) suggested that the high-temperature fumaroles and significant SO<sub>2</sub> emission rates at Santa Ana could indicate the presence of a high-temperature vapor-dominated zone at some depth below the subsurface hydrothermal system. The gases released then reach the surface largely unaffected by condensation or interaction with the subsurface hydrothermal system. Oppenheimer (1996) suggested that high SO<sub>2</sub> emission rates at “wet” volcanoes may result from remobilization of previously deposited sulfur. From a more tectonic perspective, El Salvador experienced two high magnitude earthquakes at the beginning of 2001, on January 13 (M 7.6) and February 13 (M 6.6) (Andrade-Cruz et al., 2001), both with epicenters about 150 km southeast of Santa Ana volcano. These events could have influenced the increase in fumarolic activity by opening cracks or fractures on the hydrothermal cap. In January 2002, puffing was observed from the vent, but low SO<sub>2</sub> emission rates were measured (<100 tonnes/day).

#### 4.2. Contributions to the global sulfur budget

The annual contributions of SO<sub>2</sub> from each of the six volcanoes studied were obtained by calculating an annual mean (tonnes/day) of the daily averages throughout the period 1999–2002 (Table 7), which

Table 7  
Annual SO<sub>2</sub> contributions from volcanoes in Guatemala and El Salvador (1999–2002)

Volcano	Emission rate (tonnes/day)	Mean (tonnes/day)	Annual rate (Tg/year)	Annual Mean (Tg/year)
Pacaya	350–2380	1350	0.13–0.87	0.49
Fuego	140–820	340	0.05–0.30	0.12
San Miguel	220–280	260	0.08–0.10	0.09
Santa Ana	30–280	140	0.01–0.10	0.05
Santiaguito	20–190	130	0.006–0.07	0.05
Tacaná	30	30	0.01	0.01
Total	740–3990	2240	0.28–1.45	0.82

were then converted to teragrams per year (Tg/year). These annual emission rates were added to obtain their contribution to the atmosphere, which was calculated to be of 0.82 Tg/year (2240 tonnes/day). Andres et al. (1993) calculated an approximate 1% contribution from Pacaya, Santiaguito, and Fuego volcanoes to the atmosphere, based on data from 1972 to 1992. Chin and Jacob (1996) developed a global three-dimensional model and determined the contribution of volcanic sulfur emission to be of 6.7 Tg S/year. Graf et al. (1997) calculated the global mean volcanic sulfur emission to be 14±6 Tg S/year. Based on the annual contributions, these six Guatemalan and Salvadorian volcanoes contribute about 5.86% (using Graf et al., 1997) to 12.2% (using Chin and Jacob, 1996) of the global mean volcanic sulfur emission.

Although the contribution of these Central American volcanoes to global, annual SO<sub>2</sub> emissions is small, the effects can be regionally significant. Volcanic air pollution could affect life and air quality in the region, becoming a chronic volcanic hazard (Sutton et al., 2001). One example can be found at Santa Ana volcano, where there were reports of damage to the woods and of people with respiratory problems during the period of May 2000 to January 2001, during an increase in the fumarolic activity consistent with strong gas emissions (Escobar, 2003).

Graf et al. (1997) recognized the importance of natural as well as anthropogenic sulfur sources and suggested that knowledge about volcanic sources and their time–space variability should be improved. The growing number of volcanoes being regularly monitored has improved our understanding of eruptive processes and our knowledge regarding the role of natural SO<sub>2</sub> sources as climate-forcing agents (Sutton et al., 2001). This is important in order to create better models of the global sulfur budget. SO<sub>2</sub> and its oxidation products contribute to atmospheric pollution as primary and secondary volcanic hazards (Sutton et al., 1997). Recent studies have suggested that 18–40% of the global tropospheric sulfate burden is volcanogenic, compared with 7–14% of the SO<sub>2</sub> burden (Chin and Jacob, 1996; Chin et al., 1996; Graf et al., 1997, 1998). This suggests that individual non-erupting volcanoes, like those that have intermittent explosive events, can be major polluters. The disproportionality could be due to higher altitudes of the vents and

therefore lower reactivity of the SO<sub>2</sub> emitted into the free troposphere.

## 5. Improvements to SO<sub>2</sub> emission measurements and interpretations

Errors related to plume speed and calculating the plume geometry are the most significant problems associated with COSPEC measurements of SO<sub>2</sub> emission rates. The extent to which we can reduce the errors on these parameters is dependent on the logistical ease of access at each volcano and the atmospheric conditions on the day of the measurement.

The temporal resolution of the measurements is another parameter that can become important, depending on the objective of the investigation. The COSPEC has proven to be an important tool in the study of volcanic SO<sub>2</sub> gas emissions throughout the years, but in most circumstances measurements are made, at the most, daily or weekly. New instruments, like the Mini-UV Spectrometer (MUSE), based on the technique of Differential Optical Absorption Spectroscopy (DOAS) (Galle et al., 2003; Edmonds et al., 2003a) and the FLYSPEC (Horton et al., in press; Williams-Jones et al., in press b), are revolutionizing volcanic gas monitoring. They still have most of the errors of the COSPEC instrument, but, depending on the configuration, a measured spectrum can be obtained every few seconds. With the capability of taking continuous measurements and being deployed permanently in the field, they will bring gas monitoring to a level in which it could be correlated with other continuous monitoring techniques like seismic and deformation monitoring. With a more complete record of emission rates, a baseline level could be determined, and any departures from that could be detected.

The time resolution of the data presented here are typical of COSPEC measurements. This low time resolution is the aspect of gas monitoring that requires most attention, in order to understand eruptive processes with respect to gas emissions at volcanoes. The SO<sub>2</sub> emission rates of each of the volcanoes studied here were calculated simply by averaging the individual measurements taken each day, for a number of days per year (Tables 3–6). In

order to better understand the relationship between emission rates and activity several strategies could be undertaken. Firstly, the data can be interpolated in order to fill in the holes or time gaps when measurements were not made. Secondly, the data can be weighted, based on the number of measurements made and confidence in the results, in order to determine a more accurate average of the data. However, both of these methods are somewhat subjective, and in truth the only way to improve emission rate measurements is to increase their temporal resolution and coverage. In order to recognize eruptive processes, monitoring the behavior of SO<sub>2</sub> emission rates should be combined with other measurements, such as temperature, seismicity, and deformation. The key to any improvement of measurements and interpretations of gas data is the combined use of different techniques and parameters.

One of the objectives of measuring the SO<sub>2</sub> emissions from volcanoes in arc systems is to understand eruptive processes and to estimate their contributions of SO<sub>2</sub> to the atmosphere. In this paper, we have presented the results from 4 years of measurements at the six most active volcanoes in Guatemala and El Salvador, which are part of the northern Central America volcanic arc. The annual emission rates calculated do not represent the total output of this section of the arc, because of various reasons: (1) we are not including every degassing volcano in the arc (ignoring other low emitters in Guatemala and El Salvador); (2) the measurements are only of the coherent inputs to the atmosphere (only the SO<sub>2</sub> in the plume, ignoring diffuse loss by leaking out of e.g. fractures); and (3) the gas data is intermittent (problems with averaging). As mentioned previously, this aspect is the one that needs to be improved the most, especially through the use of models and more thorough statistical analysis and weighing of the data, in order to improve the averages being calculated.

With the recent advances in satellite remote sensing, and the possibility of measuring passive degassing using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), it might be possible to quantify the output of the arc. If images can be obtained for the different volcanoes on a particular day, their SO<sub>2</sub> plumes could be mapped.

The data could therefore be used to establish baseline emission rates for these volcanoes, detect deviations from the baseline rates, which could indicate unrest, and map the atmospheric products of their eruptions (Realmuto, 2000).

## 6. Conclusions

COSPEC measurements were made at the principal active volcanoes in Guatemala and El Salvador during the period of 1999 to 2002. The average SO<sub>2</sub> emission rates measured at the Guatemalan volcanoes were: 1350 tonnes/day for Pacaya, 340 tonnes/day for Fuego, 120 tonnes/day for Santiaguito, and 30 tonnes/day for Tacaná. In El Salvador, Santa Ana and San Miguel volcanoes were measured, obtaining average emission rates of 140 and 260 tonnes/day, respectively. On a global scale, the six volcanoes studied account for about 6% (using Graf et al., 1997) to 12% (using Chin and Jacob, 1996) of the mean annual global volcanic output of SO<sub>2</sub>.

Although a baseline SO<sub>2</sub> emission rate is very difficult to measure, because of intermittent data sampling, the daily and annual averages calculated help acquire a better understanding of the eruption processes at these Central American volcanoes, in particular during the current eruption of Fuego volcano. In order to compare relative changes in SO<sub>2</sub> degassing and eruptive activity, as well as to be able to correlate these with results from other monitoring techniques (e.g. seismicity), more continuous measurements are necessary. If this goal is achieved, a baseline emission level could be determined that could potentially be used in the future to detect signs of volcanic unrest. Modeling and weighing of the data can help produce more accurate averages of the emission rates, but both of these methods are somewhat subjective. The only way to improve emission rate measurements, therefore, is to increase their temporal resolution and coverage.

## Acknowledgements

We would like to thank the Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología (INSIVUMEH) of Guatemala for providing the

equipment (COSPEC) used to conduct our research, as well as transportation and field assistance. We would also like to thank the Coordinadora Nacional para la Reducción de Desastres (CONRED) in Guatemala and the Centro de Investigaciones Geotécnicas in El Salvador, for all their support during the different field seasons in Central America. This research was supported by an NSF grant (INT 0118587) and the Graduate Assistance to Areas of National Need (GAANN) from the Department of Education.

## References

- Anderson, S.W., Fink, J.H., Rose, W.I., 1995. Mount St. Helens and Santiaguito lava domes: the effect of short-term eruption rate on surface texture and degassing processes. *Journal of Volcanology and Geothermal Research* 69, 105–116.
- Andrade-Cruz, R.A., Escobar-Flores, C.A., Flores-Alvarado, A.V., Nieto Lovo, M.R., 2001. Reporte de los Eventos Sísmicos Ocurridos el Primer Trimestre de 2001 en El Salvador, 2001. [http://www.eeri.org/earthquakes/Reconn/ElSalvador/español/el\\_salvador.html](http://www.eeri.org/earthquakes/Reconn/ElSalvador/español/el_salvador.html)
- Andres, R.J., Kyle, P.R., Rose, W.I., Stokes, J.B., 1987. SO<sub>2</sub> emissions during eruptive episode 48A, Kilauea Volcano, Hawaii. *International Union of Geodesy and Geophysics, 19th General Assembly*, vol. 2, p. 407, Abstract.
- Andres, R.J., Rose, W.I., Stoiber, R.E., Williams, S.N., Matías, O., Morales, R., 1993. A summary of sulfur dioxide emission rate measurements from Guatemalan volcanoes. *Bulletin of Volcanology* 55, 379–388.
- Barmin, A., Melnik, O., Sparks, R.S.J., 2002. Periodic behavior in lava dome eruptions. *Earth and Planetary Science Letters* 199, 173–184.
- Bernard, A., Escobar, C.D., Mazot, A., Gutiérrez, R.E., 2004. The acid volcanic lake of Santa Ana volcano, El Salvador. In: Rose, W.I., Bommer, J.J., Lopez, D.L., Carr, M.J., Major, J. (Eds.), *Natural Hazards in El Salvador*. The Geological Society of America Special Paper, vol. 375, pp. 121–133.
- Carroll, M.R., Rutherford, M.J., 1985. Sulfide and sulfate saturation in hydrous silicate melts. *Journal of Geophysical Research* 90, C601–C612.
- Chesner, C.A., Rose, W.I., 1984. Geochemistry and evolution of the Fuego Volcanic Complex, Guatemala. *Journal of Volcanology and Geothermal Research* 21, 25–44.
- Chigna, G.M., Vulcanología INSIVUMEH, 2002. Boletín Volcán de Fuego (1402-09), Nuevo Ciclo Eruptivo. 10 August.
- Chin, M., Jacob, D.J., 1996. Anthropogenic and natural contribution to tropospheric sulfate—a global model analysis. *Journal of Geophysical Research* 101, 18691–18699.
- Chin, M., Jacob, D.J., Gardner, G.M., Foreman-Fowler, M., Spiro, P.S., 1996. A global three-dimensional model of tropospheric sulfate. *Journal of Geophysical Research* 101, 18667–18690.

- De La Cruz Martínez, V., Hernández Zuniga, R., 1986. Geología del Volcán Tacaná. *Geotermia: Revista Mexicana de Geoenergía* 2 (1).
- Delmelle, P., Bernard, A., 2000. Volcanic lakes. In: Sigurdsson, H., Houghton, B., McNutt, S.R., Rymer, H., Stix, J. (Eds.), *Encyclopedia of Volcanoes*. Academic Press, pp. 877–895.
- DeMets, C., 2001. A new estimate for present-day Cocos-Caribbean plate motion: implications for slip along the Central American volcanic arc. *Geophysical Research Letters* 28, 4043–4046.
- Edmonds, M., Herd, R.A., Galle, B., Oppenheimer, C.M., 2003a. Automated, high time-resolution measurements of SO<sub>2</sub> flux at Soufriere Hills volcano, Montserrat. *Bulletin of Volcanology* 65, 578–586.
- Edmonds, M., Oppenheimer, C.M., Pyle, D.M., Herd, R.A., Thompson, G., 2003b. SO<sub>2</sub> emissions from Soufriere Hills Volcano and their relationship to conduit permeability, hydrothermal interaction and degassing regime. *Journal of Volcanology and Geothermal Research* 124, 23–43.
- Escobar, D., 2003. Cronología de erupciones, Volcán Santa Ana. Report of Servicio Nacional de Estudios Territoriales (SNET), El Salvador.
- Galle, B., Oppenheimer, C., Geyer, A., McGonigle, A., Edmonds, M., Horrocks, L.A., 2003. A miniaturized ultraviolet spectrometer for remote sensing of SO<sub>2</sub> fluxes: a new tool for volcano surveillance. *Journal of Volcanology and Geothermal Research* 119, 241–254.
- Giggenbach, W.F., García, P.N., Londono, C.A., Rodríguez, V.L., Rojas, G.N., Calvache, V.M.L., 1990. The chemistry of fumarolic vapor and thermal-spring discharges from the Nevado del Ruiz volcanic-magnetic-hydrothermal system, Colombia. *Journal of Volcanology and Geothermal Research* 42, 13–40.
- Graf, H.-F., Feichter, J., Langmann, B., 1997. Volcanic sulfur emissions: estimates of source strength and its contribution to the global sulfate distribution. *Journal of Geophysical Research* 103 (D9), 10727–10738.
- Graf, H.-F., Langmann, B., Feichter, J., 1998. The contribution of Earth degassing to the atmospheric sulfur budget. *Chemical Geology* 147, 131–145.
- GVN Bulletin, 1996. Pacaya. Smithsonian Institution, Washington, D.C., 21 (12).
- GVN Bulletin, 1998. Pacaya. Smithsonian Institution, Washington, D.C., 23 (5).
- GVN Bulletin, 1999a. Pacaya. Smithsonian Institution, Washington, D.C., 24 (2).
- GVN Bulletin, 1999b. Santiaguito. Smithsonian Institution, Washington, D.C., 24 (3).
- GVN Bulletin, 1999c. Fuego. Smithsonian Institution, Washington, D.C., 24 (4).
- GVN Bulletin, 1999d. Pacaya. Smithsonian Institution, Washington, D.C., 24 (12).
- GVN Bulletin, 2000. Pacaya and Fuego. Smithsonian Institution, Washington, D.C., 25 (1).
- GVN Bulletin, 2001. Santa Ana and Pacaya. Smithsonian Institution, Washington, D.C., 26 (4).
- GVN Bulletin, 2002a. San Miguel. Smithsonian Institution, Washington, D.C., 27 (2).
- GVN Bulletin, 2002b. Santiaguito. Smithsonian Institution, Washington, D.C., 27 (5).
- GVN Bulletin, 2002c. Pacaya. Smithsonian Institution, Washington, D.C., 27 (7).
- GVN Bulletin, 2002d. Fuego. Smithsonian Institution, Washington, D.C., 27 (8).
- Harris, A.J.L., Rose, W.I., Flynn, L.P., 2003. Temporal trends in lava dome extrusion at Santiaguito 1922–2000. *Bulletin of Volcanology* 65, 77–89.
- Harris, A.J.L., Flynn, L.P., Matías, O., Rose, W.I., Cornejo, J., 2004. The evolution of an active silicic lava flow field: an ETM+ perspective. *Journal of Volcanology and Geothermal Research* 135, 147–168.
- Horton, K., Williams-Jones, G., Garbeil, H., Sutton, A.J., Elias, T., Clegg, S., in press. FLYSPEC: Validation of a robust and versatile ultraviolet correlation spectrometer for the real-time measurements of volcanic SO<sub>2</sub> emissions. *Bulletin of Volcanology*.
- Jaupart, C., Vergnolle, S., 1988. Laboratory models of Hawaiian and Strombolian eruptions. *Nature* 331, 58–60.
- Lacis, A., Hansen, J., Sato, M., 1992. Climate forcing by stratospheric aerosols. *Geophysical Research Letters* 19, 1607–1610.
- Mann, P., Schubert, C., Burke, K., 1990. Review of Caribbean neotectonics. In: Dengo, G., Case, J.E. (Eds.), *The Caribbean Region*. Geological Society of America. *Geology of North America Series*, H., pp. 307–338.
- Millan, M.M., 1980. Remote sensing of air pollutants: a study of some atmospheric scattering effects. *Atmospheric Environment* 14, 1241–1253.
- Millan, M.M., Hoff, R.M., 1978. Remote sensing of air pollutants by correlation spectroscopy-instrumental response characteristics. *Atmospheric Environment* 12, 853–864.
- Morrissey, M.M., Mastin, L.G., 2000. Vulcanian eruptions. In: Sigurdsson, H., Houghton, B., McNutt, S.R., Rymer, H., Stix, J. (Eds.), *Encyclopedia of Volcanoes*. Academic Press, pp. 463–475.
- Oppenheimer, C., 1996. On the role of hydrothermal systems in the transfer of volcanic sulfur to the atmosphere. *Geophysical Research Letters* 23 (16), 2057–2060.
- Pullinger, C., 1998. Evolution of the Santa Ana Volcanic Complex, El Salvador. MS Thesis, Michigan Technological University. 152 pp.
- Realmuto, V., 2000. The potential use of earth observing system data to monitor the passive emission of sulfur dioxide from volcanoes. In: Mouginiis-Mark, P.J., Crisp, J.A., Fink, J.H. (Eds.), *Remote Sensing of Active Volcanism*. Geophysical Monograph, vol. 116. American Geophysical Union, Washington, DC, pp. 101–115.
- Rose, W.I., 1972a. Santiaguito Volcanic Dome, Guatemala. *Geological Society of America Bulletin* 83, 1413.
- Rose, W.I., 1972b. Pattern and mechanism of volcanic activity at the Santiaguito volcanic dome, Guatemala. *Bulletin of Volcanology* 36, 73–94.
- Rose, W.I., 1987. Volcanic activity at Santiaguito Volcano, 1976–1984. Special Paper - Geological Society of America, vol. 212, pp. 17–28.

- Rose, W.I., Mercado, R., 1986. Report on UNDRO/OFDA mission to Tacaná Volcano, Guatemala/Mexico: INSIVUMEH, Guatemala. 30 pp. +3 maps (in English or Spanish).
- Rose, W.I., Anderson, A.T., Woodruff, L.G., Bonis, S.B., 1978. The October 1974 Basaltic Tephra from Fuego Volcano: description and history of the magma body. *Journal of Volcanology and Geothermal Research* 4, 3–53.
- Sanchez Bennett, E.H., Rose, W.I., Conway, F.M., 1992. Santa María, Guatemala: a decade volcano. *Eos Transactions - American Geophysical Union* 73, 521–522.
- Scaillet, B., Clemente, B., Evans, B.W., Pichavant, M., 1998. Redox control of sulphur degassing in silicic magmas. *Journal of Geophysical Research* 103, 23937–23949.
- Shannon, J.M., Watson, I.M., Bluth, G.J., Carn, S., 2001. Investigating errors in static COSPEC measurements of volcanic SO<sub>2</sub> Plumes. *Eos Transactions American Geophysical Union*, 82(47), Fall Meeting Supplement, Abstract V42B-1008.
- SEAN Bulletin, 1987. Tacaná. Smithsonian Institution, Washington, D.C., 12 (6).
- Simkin, T., Siebert, L., 1994. *Volcanoes of the World: A Regional Directory, Gazetteer, and Chronology of Volcanism During the Last 10,000 Years*, Second edition. Geoscience Press, Arizona, 134 pp.
- Stix, J., Zapata, G.J.A., Calvache, V.M., Cortes, J.G.P., Fischer, T.P., Gomez, M.D., Narvaez, M.L., Ordóñez, V.M., Ortega, E.A., Torres, C.R., Williams, S.N., 1993. A model of degassing at Galeras Volcano, Colombia, 1988–1993. *Geology* 21, 963–967.
- Stoiber, R.E., Rose, W.I., 1970. The geochemistry of Central American volcanic gas condensates. *Geological Society of America Bulletin* 81, 2851.
- Stoiber, R.E., Rose, W.I., 1974. Fumarole incrustations at active Central American volcanoes. *Geochimica et Cosmochimica Acta* 38, 495.
- Stoiber, R.E., Rose, W.I., Leggett, D.C., Jenkins, T.F., Murrmann, R.P., 1971. Organic compounds in volcanic gas from Santiaguito Volcano, Guatemala. *Geological Society of America Bulletin* 82, 2299.
- Stoiber, R.E., Malinconico, L.L., Williams, S.N., 1983. Use of the correlation spectrometer at volcanoes. In: Tazieff, H., Sabroux, J.-C. (Eds.), *Forecasting Volcanic Events*. Elsevier, Amsterdam, pp. 425–444.
- Sutton, A.J., Elias, T., Hendley, J.W.I., Stauffer, P.H., 1997. Volcanic air pollution—a hazard in Hawaii. *US Geological Survey Fact Sheet* 169–97 (2 pp.).
- Sutton, A.J., Elias, T., Gerlach, T.M., Stokes, J.B., 2001. Implications for eruptive processes as indicated by sulfur dioxide emissions from Kilauea Volcano, Hawaii, 1979–1997. *Journal of Volcanology and Geothermal Research* 108, 283–302.
- Williams-Jones, G., Stix, J., Hickson, C.J., in press a. Using the COSPEC in the field. In J. Stix, C.J. Hickson (Editors), *Theory, use, and application of the COSPEC correlation spectrometer at active volcanoes*. Geological Survey of Canada Bulletin.
- Williams-Jones, G., Horton, K., Garbeil, H., Mouginiis-Mark, P.J., Harris, A.J.L., Sutton, A.J., Elias, T., in press b. Accurately measuring volcanic plume velocities with multiple UV spectrometers. *Bulletin of Volcanology*.
- Young, S.R., Francis, P.W., Barclay, J., Casadevall, T., Gardner, C.A., Darroux, B., Davies, M.A., Delmelle, P., Norton, G.E., Maciejewski, A.A.M., Oppenheimer, C.M., Stix, J., Watson, I.M., 1998a. Monitoring SO<sub>2</sub> emission at the Soufrière Hills Volcano: implications for changes in eruptive conditions. *Geophysical Research Letters* 25 (19), 3681–3684.
- Young, S.R., Sparks, R.S.J., Aspinall, W.P., Lynch, L.L., Miller, A.D., 1998b. Overview of the eruption of Soufrière Hills Volcano, Montserrat, July 18, 1995 to December 1997. *Geophysical Research Letters* 25 (19), 3389–3392.