Chapter 5

Large Volcanic-SO_2 fluxes: COSPEC measurements at Popocatépetl Volcano (Mexico)

Hugo Delgado Granados

Instituto de Geofísica, Universidad Nacional Autónoma de México, Circuito Exterior, C.U.,
Coyoacán 04510, Mexico, D. F., Mexico, email: hugo@tonatiuh.igeofcu.unam.mx

1. INTRODUCTION

Popocatépetl (*smoking mountain*) is located in central Mexico at the volcanic front of the Trans-Mexican Volcanic Belt (Fig. 1). The volcano is surrounded by several densely populated cities, the most important of which are Atlixco, Cuautla, Cuernavaca, Puebla, Amecameca, Chalco and the largest city of the world, Mexico City. Also, many smaller towns and villages exist close to the volcano: Santiago Xalizintla, San Nicolás de Los Ranchos, San Buenaventura Nealticán, San Pedro Benito Juárez, San Pedro Nexapa, etc. The total population in the region 60 km around Popocatépetl is more than 20 million inhabitants. The size of the population and proximity of the volcano to industrial areas make it important. Thus, the eruptive activity is closely observed and studied.

The volcano started to erupt on December 21, 1994. Before Popocatépetl started to erupt, monitoring had been initiated and then background activity was recognized. One of the most important lines of surveillance is the periodic measurement of SO_2 flux using a Barringer correlation spectrometer (COSPEC) in order to assess the magmatic activity at the volcano. The gas outputs are some of the largest ever measured at any volcano in the world using correlation spectrometry. Thus, the measurement of these very high fluxes have imposed several challenges, notably instrumental, methodological, and of interpretation.

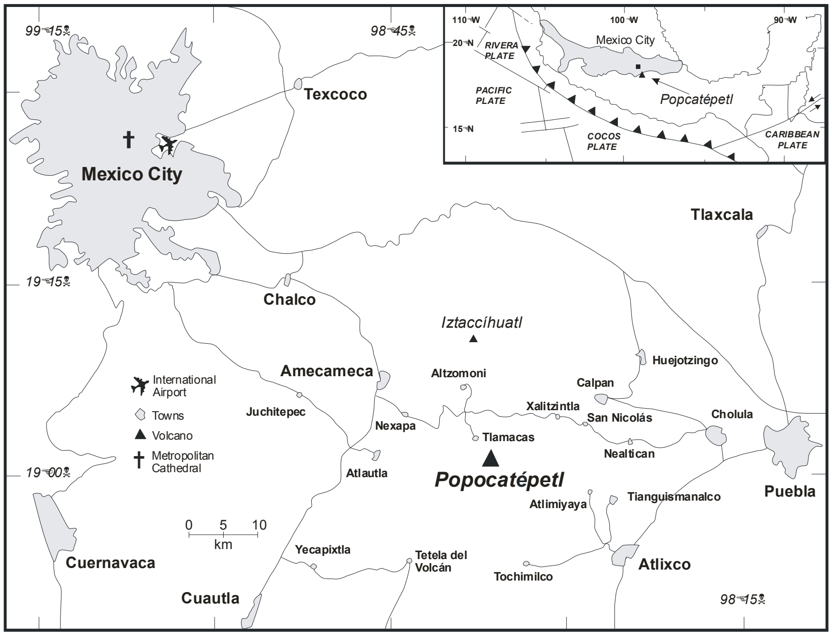


Fig. 1. Main towns surrounding Popocatépetl volcano. Mexico City (boundaries), Puebla and Cuautla are located 40 km from the volcano. Inset depicts the volcano at the front of the Trans-Mexican Volcanic Belt.

Delgado Granados, H. (2008) Large volcanic-SO_2 fluxes: COSPEC measurements at Popocatépetl volcano (Mexico). *In*: Williams-Jones, G., Stix, J. & Hickson, C. (eds.) *The COSPEC Cookbook: Making SO_2 Measurements at Active Volcanoes*. IAVCEI, Methods in Volcanology, 1, 191-217.

Details on the principles of correlation spectrometry, the instrument, and the general methodologies applied to measure SO_2 fluxes at active volcanoes (after Stoiber et al., 1983) are reviewed in different parts of this volume. Therefore, this paper focuses on the methodology adopted to measure large plumes, the magnitude of SO_2 fluxes, and the significance according to our experience at Popocatépetl volcano.

2. METHODOLOGY: MEASURING LARGE SO_2 PLUMES

During the last fourteen years, Popocatépetl has raised several challenges to SO_2 flux monitoring. The experiences measuring large volcanic plumes have led to methodological procedures adapted specifically for Popocatépetl. This methodology is described below.

3. Setup

Light conditions change according to latitude (from Canada to the region of the world where the COSPEC will be operated), and with the hour of the day. Barringer technicians used to set up and calibrate the instruments in Canada, but they had to make some adjustments to the instruments they sold for operation at the latitude of the customer's country. It was thus important to contact the company initially to enquire about the setup of the purchased instrument. Some of these adjustments seemed to be significant modifications when the instrument's manual was consulted.

It was important to recognize the best time for measurements during the day. For this, the instrument was used under blue-sky conditions, removed from the influence of volcanic SO_2, for at least a day. The changes in daylight conditions were identified according to the hour of the day. Repeating this every season (four times a year), it was possible to identify the best measuring times for the entire year. At the latitude of Popocatépetl volcano, the best time for COSPEC measurements most of the year is between 10:00 to 14:00 hrs (local time) based on the curves obtained under blue- sky conditions. During this period of time, the intensity of UV light does not change much, and the calibration plots are very homogeneous. From 8:00 to 10:00 hrs and from 14:00 to 16:00 hrs (even up to 17:00 hrs) the light conditions are still acceptable (particularly during summer time). This time frame allows planning, especially for the ground-based traverses.

4. Planning

It is crucial to plan the measurements due to the size of Popocatépetl and its plumes. For airborne traverses, it is important to know the flight conditions beforehand. For the ground-based traverses, it is important to know where to start, since the distances are very long. There are four sources of information available: weather forecasts; radiosoundings; video images from the volcano; and the air traffic officials (ATO) at Mexico City International Airport (MCIA).

4.1.1. Weather forecasts

It is possible to know in advance the likely conditions at the volcano for the time of the measurements. Special attention is devoted to estimates of the direction of the wind, rainfall, cloudy conditions, visibility, etc. The National Meteorological Service (SMN) of the National Water Commission delivers special reports for the area of Popocatépetl including information on the meteorological conditions at the volcano. For a long time, they provided three forecasts daily

(9:00; 15:00; and 21:00 hrs.) according to radiosoundings and observers posted around the volcano. Observations were made by people posted at Cuernavaca, Puebla and Tlaxcala, providing estimates of the wind direction and speed, and the visual conditions at the volcano from their stations.

SMN included in each report a forecast for the following 12 hours, mentioning the expected conditions at altitudes below the summit of the volcano, at the level of the summit of Popocatépetl, and at different levels above the summit. A 24-hour forecast was also available to us by telephone.

To make plans several days in advance, there are other sources of information in addition to the SMN forecasts. Major news agencies provide reliable weather forecasts through the Internet for the following three or four days (*www.cnn.com* or *www.abcnews.com* with forecasts for most regions in the world). These web sites include a satellite image per region.

4.1.2. Radiosoundings

Two radiosoundings are made in Mexico City every day: one at 6:00 hrs and the other at 18:00 hrs. Since the site where the balloons are released is about 50 km from the vent, the wind reports are very accurate. Simultaneously, radiosoundings are made in Veracruz, 200 km east of the volcano. The SMN provides a daily report including the meteorological data at the different altitudes for the two radiosoundings of the day and constructs a wind profile with the volcano in between Mexico City and Veracruz. A weekly report gives information on the wind distribution patterns for the period.

4.1.3. Video images from the volcano

The Secretaría de Gobernación (Ministry of the Interior) has installed TV cameras: one on the southern flank of Iztaccíhuatl volcano 10 km from the crater of Popocatépetl volcano and transmited by microwaves, the second at Tlamacas 4 km north of the crater, and the last one at Tianguismanalco, 18 km to the east of the crater (Fig. 1). The last two cameras transmit by radio-modem. These cameras send real-time images to Mexico City (CENAPRED) where they are processed and put onto the Internet. Every COSPEC measurement routinely starts with the observation of these images in order to see the sector of the volcano where the volcanic plume is located. Estimates of wind velocities also are made using the images. These estimates are very successful when compared with other data sources, and represent an important tool when other wind data sources fail or are not available.

4.1.4. Air traffic officials at the Mexico City International Airport (MCIA)

MCIA is 50 km northwest of Popocatépetl volcano, therefore, ATO provide very useful data. Due to the heavy air traffic at MCIA and its proximity to the volcano, airline pilots are able to report the status of the activity routinely. The ATO of the Control Center (CC) of the MCIA are in continuous contact with the aircraft pilots taking off or landing at the MCIA. ATO routinely ask the pilots about the visual conditions at the volcano. Some of these observations include information on the presence or absence of ash in the atmosphere from the volcano, qualitative estimates on the density of the ash plumes, altitude of the plumes, direction and position of the plumes. ATO also ask the pilots the wind direction and speed according to their navigation instruments in the plane, when available. Since most of the commercial planes have air-navigational GPS, the CC provides very useful wind data. Whenever possible, a wind profile is constructed with this information. Prior contact with these officials allows measurement planning, while contacting them during ground-based measurements allows us to get real-time wind data at the altitude of the plume.

5. ***During measurements***

In the field, several actions are taken regarding the COSPEC and other resources used to define the plume's propagation. These actions ensure the proper use of the instrument and guarantee the best data acquisition and interpretation.

5.1.1. Calibration

Due to the large magnitude of Popocatépetl emissions, SO_2 concentration plots on the chart record may exceed the height of the high calibration cell during measurements. In order to preserve the linearity conditions for the correlation between the volcanic SO_2 concentration with the calibration cells' SO_2 concentration, it is important to avoid this situation. Andres and Schmid (1997) have made experiments on the effects of exceeding calibration heights. Two things have been done: move away from the volcano (in airborne and ground-based fixed measurements) or change the low-concentration cells for the high-concentration set.

It is very important to calibrate as often as possible (M. Millan, personal communication, 1997). When ground-based mobile measurements are carried out at Popocatépetl, it is important to calibrate frequently due to the length of traverses, since a single traverse might last more than one hour. Also, it is important to calibrate frequently when the measurements are made before or after the optimal times of the day.

Calibration was always done in the same direction of the traverse. The COSPEC is a magnetic field-sensitive instrument and thus, the calibrations used for calculations always should be made with the instrument oriented in the same general direction of the traverse. This is an additional reason to calibrate as frequently as possible.

5.1.2. AGC

An important action is the continuous observation of the automatic gain control (AGC). The presence of ash in the atmosphere has a strong effect on the COSPEC detection of light but cannot be distinguished from natural decreases in SO_2 concentrations without records of AGC (Andres and Schmid, 1997). Hence, the behavior of the AGC traces may be used to assess the possible presence of ash above the instrument, especially if clouds do not allow observation of the volcano. Suspicious chart record shapes or low measurements may be due to the presence of ash in the atmosphere. This effect can be corrected if the AGC is recorded simultaneously. If irregular behavior of the AGC is detected and no visual observations are possible, a phone call to CENAPRED, UNAM, or CC helps to identify ash emissions from the volcano.

5.1.3. Placement of the instrument

Vibration of land vehicles or airplanes may damage the instrument. If the instrument had to be tied in a car or airplane using cords or web, it was important not to lace it from the topmost part. It should be done from its base since the instrument has shock absorbers. If the instrument is tied from the cabinet, the shock absorbers will not work and shaking of the instrument may damage the electronics.

The instrument is placed in the vehicle's shade when possible to avoid differences in light intensity and damage of the instrument due to direct light incidence through the telescope, which is typical of tropical or equatorial latitudes.

5.1.4. Batteries

To operate the COSPEC, the chart recorder, and/or the digital acquisition system and a computer, the best batteries available are required. Long measurement days may affect power supply from batteries. A solution is to use the battery of the vehicle with a voltage regulator in the middle.

5.1.5. Anemometers

Anemometers are useless at high volcanoes. In the case of Popocatépetl volcano, the altitude difference between the plume and the site of measurements is nearly 3,000 m. Estimates of winds using anemometers is meaningless because the ground-level winds and the high-altitude winds are completely different in magnitude and direction (Delgado Granados et al., 1995).

5.1.6. Compass

Compasses are very useful. Since the chart's maximum peak indicates the propagation axis of the gas plume, determination of the azimuth of the line between the COSPEC and the vent gives the wind direction. A compass in airborne and ground-based measurements allows the determination of this azimuth. In the case of airborne measurements, it helps to decide the direction of traverses. During aerial measurements, the direction may vary, with a change of flight direction at every traverse being very difficult for the operator. Thus, once the traverse direction is established, if the wind drifts slightly, the direction obtained with the compass is used to correct fluxes so that every traverse axis is normal to the propagation axis (see Chapter 4).

5.1.7. GPS

Global Positioning Systems (GPS) were possibly the most important additions in the SO_2 flux measurement methodology. During airborne measurements, these instruments can be used to construct wind profiles and to establish traverse posts. During ground-based measurements, a GPS can be used to define the moving path of the instrument and have better control on the distances and angles between inflection points.

Air-navigation GPS is widely used by pilots to navigate between destinations. Most GPS manufacturers guarantee that under normal conditions, a GPS should indicate accurately the horizontal position (latitude and longitude) within ± 10 m (sometimes within ± 5 m). Resolution of GPS in the vertical is not as good in general, but airplanes normally provide more reliable altitude data using other instruments. Normally, a GPS permits a good record of the flight paths, distance and orientation between posts, and distance to the volcanic vent. In addition, if data are properly introduced, most air-navigation GPS systems can provide a very accurate estimation of the wind direction and speed. The instrument needs data such as aircraft altitude, air speed, flight azimuth, ambient pressure and temperature. All these data are obtained from the aircraft's instruments. Some airplanes have a GPS already connected to the instruments, and data are acquired by the GPS automatically in such a way that data may be retrieved real-time by computer.

Use of GPS to record the position of the COSPEC peak values (determining the propagation axis) and use of the data to preserve the perpendicularity of the traverses according to the direction of the propagation axis ensure that the measurements are always calculated properly.

On ground-based measurements, a GPS is used to determine length and orientation of traverse segments. Currently, the GPS data is acquired real-time into a computer and the length and orientation of very small segments can be calculated and the volcanic cloud can be determined very accurately. Also, the GPS may help to measure the distance from the vent to the intersection of the traverse and the propagation axis, and to obtain the plume orientation when the use of a compass is not possible due to reduced visibility. This information better constrains the wind data that will be used for calculations.

6. Data reduction

Since several COSPEC users get charts from the instrument instead of a digital output to a computer, determination of the area defined by the COSPEC records is done in several ways. Those whose chart recorders use millimetric paper, count squares; others (especially when the recorder does not uses millimetric paper), may proceed in several ways like weighing pieces of paper, superposing millimetric paper, scanning or digitizing charts and applying image processing software, etc.

A planimeter is an inexpensive and very convenient tool. Mechanical planimeters can be taken to the field easily, and digital planimeters are also versatile since they are easy to use, quick and reliable. Some digital planimeters calculate statistical parameters after measuring the same areas several times, and accuracy or error involved in the measurements may be estimated. During measurements of SO_2 flux at Popocatépetl volcano, the use of digital planimeters has been an important aid because of the large size of the records.

Currently, at Popocatépetl volcano, software and hardware has been developed for automatic calculation of segments (using the GPS data), areas, and therefore the gas emission in terms of SO_2. The software allows the calculation of SO_2 as the measurement is progressing, and at the end of the traverse the total flux is calculated if the wind data is available.

7. Aerial measurements

7.1.1. Airplanes and safety

Differences in altitude are large at Popocatépetl volcano from one sector to the next. Popocatépetl is a 5,452 m high volcano with a very rugged morphology. Its northern flank rises from a plateau at about 2,300 m towards the northwest and northeast. Its northern neighbour, Iztaccíhuatl volcano (5,230 m), joins Popocatépetl at about 3,700 m approximately 8 km north of the vent. The southern flank reaches the plains at about 1,500 m. The landscape imposes several logistical problems for flight planning.

From 1994 to 1997, nearly 70 airborne measurements were made. All measurements were made using two-engine fixed-wing airplanes, although some measurements were made using rotatory-wing aircraft. Planes used at Popocatépetl include the Cessna 320, Cessna 421, Turbo Commander 980, Turbo Commander 1000, and Bell 412. None of these aircraft, except the helicopter, are equipped with modern turbines (Cessna planes have piston engines). Most of the modern turbines work at temperatures above 1,000°C and thus can easily melt fine volcanic ash, thereby obstructing air and fuel nozzles which may cause engines to stop (Casadevall, 1991). Several ash cloud - airplane encounters that have caused failure of turbines have been successfully resolved (Casadevall, 1991). However, given the morphological features of Popocatépetl, the possibilities of restarting an engine in this region are fairly low. The main reason for choosing two-engine (piston or old turbine) airplanes is to avoid or minimize melting of ash if it is ingested by the engines. In other words, safety during volcano monitoring is a very important issue.

The importance of using two-engine fixed-wing airplanes rather than single-engine airplanes (which are much cheaper) at large volcanoes like Popocatépetl is: a) getting good wind profiles, since the two-engine aircraft are needed to fly at altitudes above the summit, altitudes that single-engine planes can not achieve; and b) safety.

High volcanoes like Popocatépetl may offer additional difficulties. Setting the COSPEC inside the airplane usually implies that the airplane should not be pressurized. Flight safety regulations prohibit the pilots to fly above 3,000 m (10,000 ft) without the use of oxygen masks. Since monitoring flights at Popocatépetl are made usually between 4,000 and 6,000 m and sometimes up to 7,000 m (12,000 to 23,000 ft) it is important to check that the oxygen systems work appropriately.

These flights always have to be done under no pressurization conditions. The consequence of this is a high noise in the cabin. Sometimes, however, good sealing is achieved using duct tape and foam in order to reduce noise inside the aircraft. Pilots may feel confident with this apparently good sealing and turn the pressurization system on. If sealing fails, the auxiliary turbine that pressurizes the cabin of some aircraft automatically may try to compensate for the loss of pressure. This sudden action could cause this turbine to burn out. Thus, the COSPEC operator should instruct the pilots not to attempt to pressurize the aircraft.

It is very important to have good communication among the scientists and the pilots in order to understand the hazards, risks and consequences. Pilots need to know exactly what scientists want, and the scientists need to know the pilots' fears and flight limitations. This is very important to make good measurements and get back home safely.

Measurements using helicopters are normally disliked and avoided by most COSPEC users (Daag et al., 1997; Newhall, personal communication). However, sometimes there is no other aircraft available, and measurements have to be done. Caltabianno (1992) has described successful COSPEC measurements using helicopters. In the case of Popocatépetl, we have found that flux rates are so high that by decreasing the range and increasing the time constant of the instrument, the amount of noise produced by the helicopter's rotors is reduced to allow recognition of the SO_2 signal.

7.1.2. Flight procedures for data acquisition

Wind profiles

Immediately after take off and while approaching the volcano, wind data were acquired using GPS to obtain the distribution and intensity of the winds at different altitudes. Wind data were acquired about every 150 m vertically (every 500 ft) up to altitudes above the summit. In this manner, flight paths for measurements can be determined and the acquired wind data are used for calculations. Orientation and position of the traverses will depend on the wind data. Once the wind profile is obtained, the flight is performed at the safest possible altitude beneath the plume.

Since the wind propagation axis is assumed to be the direction of the volcanic plume, observation of the COSPEC chart record represents an independent way to get the true propagation axis of the plume. When the peak values are detected, compass observations between the place where the peak values are observed and the vent is the true direction of the propagation axis. In addition to the compass, the GPS also may indicate the direction of the propagation axis. If positions of peaks are saved in the GPS memory, the corrections due to obliquity of traverses can be made later in the office.

Traverses

A simple way to perform COSPEC measurements is flying in circles (with same radius) around the volcano. This way, the plane and the traverse will be always normal to the propagation axis of the plume. GPS navigation helps to ensure that the distance to the vent is always the same and gives the radius of the circles to calculate distances between plume edges (plume width). At Popocatépetl, this technique works well whenever the concentrations are not so large. By flying in circles close to the volcano, the operator may find that concentrations are larger than the height of the trace of the high calibration cell or even may produce saturation of the instrument. If the height of the high calibration cell is exceeded, the record can saturate and the measurements are not reliable. Thus, the radius of the circle should be increased up to the point that concentrations fall below the trace of the high calibration cell. However, the appropriate radius of the circle to avoid saturating the records can be so large that circular flying becomes impractical. Then, a linear traverse can be made, perpendicular to the propagation axis.

Since the propagation axis is determined using the COSPEC readings, the GPS and the compass are used to determine a perpendicular path at distances where concentrations do not exceed the calibration heights. The GPS can be used to establish the edges of the traverses by defining way points in its memory, and the navigational functions of the instrument help in passing over the point at every traverse. This is particularly important at a high-altitude volcano where clouds below the traverse altitudes may not allow for recognition of geographical points on the ground in order to orient the traverses and determine posts or check points.

Under high-concentration conditions, several difficulties force the COSPEC operator to increase distance from the vent. These difficulties consist of reduction of flight alternatives when the plume is directed towards the neighboring volcano Iztaccíhuatl or towards another topographical barrier, and hence flying beneath the plume is impossible. Also, it becomes impractical to trace a single line across the plume because it is so widely dispersed (flight distances might be even of hundreds of kilometers). On the other hand, when the propagation axis is directed towards Mexico City, ATO do not approve flying in the heavy traffic area of Mexico City air space for safety reasons. Under these circumstances, the use of GPS is of great importance. The alternative is to trace a traverse across the plume with more than one segment. A polygonal traverse can be achieved determining one or more inflexion points with the GPS, always avoiding exceeding the calibration height. In this way, topographical barriers and prohibited air-space can be surrounded. Integration of the resulting area can be achieved due to the geographical control of the way points in a fashion similar to regular ground-based measurements.

8. Ground based measurements

A good road network surrounds Popocatépetl comprising 260 km including expressways and main federal roads. The distance from the roads to the volcano range from 18 to 49 km (Fig. 2). Due to the mountainous topography, the roads in the region have differences in altitude of nearly 1000 m.

8.1.1. Cellular phones

A cellular telephone is an important tool to confirm that meteorological data and wind direction have not changed. Also, contact with the base in Mexico City is important because they have sometimes a better view of the volcano through the remote video camera. When visibility is good, the measuring crew reports the state of the activity and writes this down in a registration book. If visibility is bad, the base tries to give directions from Mexico City in order to start the measurement. This part of the measurement is crucial, as while the crew are "hunting" for the plume, travel distances may be >200 km, and time is important to take advantage of the best light conditions. Getting information from the CC of the MCIA requires several calls during the day.

In spite of this good road network, at places (especially close to the vent) it is difficult to avoid large SO_2 concentrations that saturate records for a long distance. When possible, smaller roads are taken to get farther away from the volcano. When moving outwards is impossible, the only thing to do is to continue until the signal declines. For determinations of area, only the parts of the graph where linearity is ensured are taken into account during data reduction. This way, the report will be a minimum estimate of the SO_2 flux.

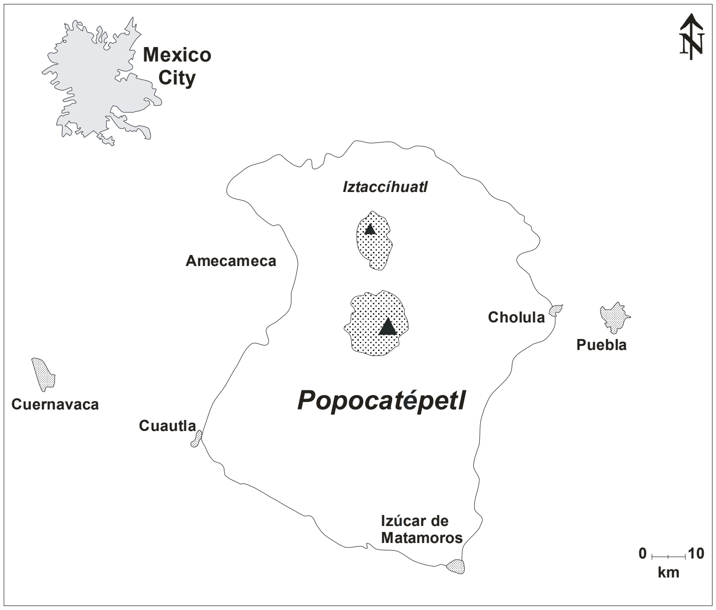


Fig. 2. Schematic roadmap around Popocatépetl volcano showing main cities and towns. This map is used for ground-based SO_2 flux measurements. The total length of the circuit is 260 km.

8.1.2. The art of COSPECing

Getting a good COSPEC record is a craft, especially for ground-based measurements when using a chart recorder. The operator should take care for the presence of trees (which are abundant at forested places), bridges (abundant on expressways), proximity to radio communication towers, power lines, etc. because they produce high frequency noise that affects the record. The solution is quite simple if a chart recorder is used, raise the pen before the obstacles, and put it down after the instrument has recovered its stability. In forested areas, it can be useful to get off the road for a while to an open area where clear sky is available in order to obtain the concentration of the plume at that point on the chart, and then return back to the road. All acquired data (meteorological and volcanological) is written in the registration book and on the chart record. COSPEC turn- on times, starting times, travel times, peak times, checkpoint times, vehicle speed, presence of trees, bridges, power lines, factories (with polluting chimneys), etc., are written on the chart. Additionally, one notes the occurrence of puffs, colour of the emissions, qualitative estimation of the density of the volcanic cloud, altitude of the emissions, altitude of the visible plume, width of the SO_2 plume, propagation axis direction, velocity of the volcanic cloud, if the propagation axis rotates, direction of rotation and speed, etc.

All this information is useful in several ways. One is for calculations, another is for interpreting the volcano's behavior. A software package has been developed to use a computer for digital acquisition of COSPEC data. This software allows the possibility to filter the obstruction of the above-mentioned obstacles such as bridges and trees and recover the trace of the measurement. This tool also acquires the GPS information needed for correction and measurement of distances along the path and accurate determination of the area for flux calculation.

8.1.3. Vehicle speed vs. chart speed

During ground-based measurements, the crew may encounter difficulties normal for road travel, such as busy roads, a slow truck in a single lane road, road maintenance, cars with flat tires that reduce circulation at narrow parts of the road, traffic accidents, traffic lights at some towns, etc. These problems may induce errors in the measurements due to differences in speed between the chart recorder speed (or computer data acquisition system) and the changing speed of the vehicle on the road. In order to adjust chart speed with vehicle's speed, the recorder can be attached through an electronic control connected to the speedometer in order to allow both speeds to be proportional and constant. Barringer provides a system to do this. However, if this attachment is not available, accuracy is not lost if all information is recorded. For instance, the vehicle's speed records on the chart and times help to estimate the appropriate corrections. Nevertheless, at Popocatépetl volcano we have found that changes in the velocity of the vehicle induce very low errors. This problem does not exist when a computer is used for digital acquisition of data.

8.1.4. Wind data

The largest uncertainty source in flux measurements is the wind speed. Stoiber et al. (1983) mention that error due to the estimation of winds might be between 10 and 40%. However, wind velocity obtained during flights using a GPS, does not introduce an error higher than 5%. Wind velocities for ground-based measurements are also obtained by GPS. Thus, the wind velocities are not introducing a large error to the calculations. In addition to the GPS data from commercial planes, we compare the wind data with the radiosoundings, estimations from the video camera and other wind velocity determination sources. Wind data-related errors have been reduced significantly and are not higher than 5% at present.

Field recording of the movement of ash clouds is an additional way to estimate propagation velocities. Routinely, puffing times are recorded, and movement of ash or gas clouds is observed. When the ash or gas parcels reach a place whose position is well known (such as the road or a town), the distance can be determined and thus, propagation speed may be estimated. Current field estimates are very comparable with other estimates (video estimates, commercial plane's GPS wind reports, and radiosounding).

9. POPOCATÉPETL VOLCANO: PAST AND CURRENT ERUPTIVE ACTIVITY

10. Contrasting nature of eruptive history

10.1.1. Eruptive history recognized from geological records

Geological records show that Popocatépetl has produced several plinian eruptions in the last 10,000 years with development of diverse volcanic deposits (i.e., Siebe et al., 1996; González-Huesca et al., 1997; Panfil et al., 1999). The last plinian eruptions occurred at 3,000 BC, 200 BC, and 800 AD. Related deposits show that dispersion axes were towards the east (Siebe et al., 1996; 1999) although an eruption at Popocatépetl occurred 14,000 yr. BP with propagation axis towards the western sector (Siebe et al., 1995; Siebe et al., 1997). The impact of those eruptions was significant, as discussed by Delgado Granados et al. (1994) and Siebe et al. (1996). More recently, Plunket and Uruñuela (2008) stated that two major eruptions devastated prehispanic settlements and rendered the surrounding region uninhabitable for generations. The first eruption occurred about 2000 years BP and the other between AD 700 and 900. Impacts of those eruptions may explain many of the population shifts known in the archaeological record during that time.

10.1.2. Eruptive history during the last centuries

Eruptive history reconstructed from several sources (i.e., ancient codices, reports from missionaries, conquerors, local authorities, travelers, and newspaper reports of 16th - 20th centuries) shows that eruptive activity of Popocatépetl has been mild during the last 700 years (Delgado Granados et al., 1988; De la Cruz-Reyna et al., 1995; Delgado Granados et al., 2008). The last event of the current type of eruptive activity occurred between 1919 and 1927 (Camacho, 1925; Murillo, 1939). None of the historic eruptive activity documented for the last seven centuries has left recognizable deposits except the event of the 17th century.

11. Recent activity

The eruptive activity has been discussed in detail elsewhere (De la Cruz-Reyna et al., 1995; Delgado Granados et al., 2001; Julio-Miranda et al., 2008), and a summary is presented here.

11.1.1. First signs of unrest; 1990

Signs of unrest previous to the onset of the eruption were very clear since 1990. They consisted of an increase in the amount and temperature of fumarolic activity, decrease of pH of crater lake waters, and appearance of earthquakes beneath the volcano (González-Huesca et al., 1997; Werner et al., 1997; Goff et al., 1998; Love et al., 1998; Delgado Granados et al., 2001).

11.1.2. First stage: onset of the eruption; 1994

Popocatépetl volcano started to erupt on December 21, 1994, after 67 years of dormancy. The initial explosive activity occurred at the same vent as the explosions of the previous eruption in 1920-1927. The activity was characterized by a vulcanian phase consisting of strong explosions that opened the conduits and produced ballistic fallout within 1 km from the vent on the eastern flank of the edifice, accompanied by ash falls directed towards the east. Ash emissions were continuous for several days, and the ash fell on towns east of the volcano for several days. All the ash was non-juvenile in composition. More than 24,000 people were evacuated during the first days of activity, and nearly 70,000 people left their homes for 2-3 weeks. This initial explosive event destroyed the small lake that was nested in the interior of the crater and deepened the trough in the center of the crater left by the destruction of the 1921 lava dome after an explosion in January 1922 (Murillo, 1939). The strongest phase of the initial eruptive activity occurred during December 24 and 25. The activity started to decline after the first days of the eruption. In January 1995, the ash emissions were intermittent, becoming more intermittent during February and March.

11.1.3. Second stage: warning of explosive activity; January 1995 – March 1996

The overall eruptive activity declined continuously during 1995. Sporadic explosions with emissions of ash were typical of this phase. Four new bocas were opened at the eastern side of the interior of the crater. By August of the same year, the ash emissions stopped. There were no ash emissions from August-September 1995 to March 1996.

11.1.4. Third stage: explosive activity and start of effusive activity; March – December 1996

The volcano was reactivated by another vulcanian explosion during the morning of March 5, 1996. The ash was distributed to the east (as expected from the wind patterns). This time, the continuous emissions of ash lasted only several hours, becoming intermittent during the following months. Lavas probably appeared for the first time on March 25, 1996 (as suggested by the seismicity) but the growing lava dome was not observed until March 27 during a COSPEC flight (GVN, 1996). On April 30, 1996, another explosion occurred, killing 5 people who had illegally climbed to the top of the volcano. The fallout was distributed again in the eastern sector of the volcano. Pumice was present for the first time in the ash emitted during this event. The lava dome initially grew at effusion rates as large as $3\ m^3\ s^{-1}$, but the growth rate decreased strongly in July-August 1996 (less than $0.1\ m^3\ s^{-1}$), and by late August the dome stopped growing. Since the crater of Popocatépetl was a very large elliptical cylinder ($>1\ km^3$) the lavas did not fill more than 5% of the crater's capacity. Emissions of ash were continuous during most of 1996, and strong explosions occurred on October 28 and December 29 with the same distribution patterns as the previous eruptions. Although ash falls were reported at several towns, no impact on population or infrastructure occurred.

11.1.5. Fourth stage: episodes of destruction and construction of lava domes; December 1996 -

The explosion of December 29, 1996, destroyed the lava dome leaving a pile of rubble inside the crater. A new lava dome started to grow on January 17-19, 1997. This time, the growth of the dome was accompanied by large gas fluxes. During this time, ash emissions decreased, as did the explosivity of the events, until May 11, 1997 when new strong explosions emitted ash again towards the east with ash falling on the city of Puebla. Due to weather conditions, no reconnaissance flights were possible until July 5, five days after the June 30 explosion occurred, which was one of the largest explosions to date. Thus, it is not clear if the second lava dome was destroyed during the May or June explosions. Interestingly, the ash emitted on June 30 was dispersed towards the western sector of the volcano as anticipated by the regional wind patterns (Delgado Granados et al., 1995) falling on Mexico City. A new lava dome was reported on July 5, 1997, growing in the central part of the crater. The eruptive activity to the date of this report consists of sporadic ash emissions of varying sizes.

Intense explosive phases occurred from November 1998 to early January 1999 and again from October 2000 to May 2001. These explosive phases consisted mainly of emission of gases and ash, ejection of ballistics projectiles (Alatorre-Ibargüengoitia and Delgado Granados, 2006), and, less commonly, pyroclastic flows. The number of explosions in 1999-2000 was very few. Short eruptive events of low explosivity characterized by reduced gas emission, and minor ash have been the most frequent during 1996–2001. Nevertheless, the explosive event of January 22, 2001 has been the largest on the volcano in the terms of the volume of magma extruded (Matiella et al., 2008). Most explosive events have been related to destruction of lava domes following a construction process of domes of various sizes.

11.1.6. Musings about Popocatépetl's eruptive history

The process of construction and destruction of domes has led to the filling up of the crater and changed the internal morphology of it. Prior to the eruption, the crater had a cylindrical shape and after the series of lava-dome construction-destruction events, the general shape is much similar to a funnel shape, common at several volcanoes in the world. Due to the filling up of the crater, Macías and Siebe (2005) have hypothesized that accumulation of debris inside the crater may produce a change in eruptive style from this pattern to the formation of external lava-domes that might produce block-and-ash pyroclastic flows. This scenario seems to be of a low-probability due to the fact that domes and debris are removed by the explosive events in a way that during some events the crater has been emptied to a level lower than before the eruption. Nonetheless, the proposed scenario should be considered for future hazard assessment.

The fact that Popocatépetl yields a contrasting eruptive activity (plinian vs. geologically mild, non- detectable eruptive events) does not help much to identify the true magnitude of the current eruption. The lack of data for previous eruptions is due to the absence of instrumental capabilities that are available today. The current eruptive activity may be another mild eruption characteristic of the last centuries, but we may also be witnessing the prelude to a larger eruption (De la Cruz-Reyna and Siebe, 1997), according to the huge gas emissions measured at Popocatépetl as discussed below. This uncertainty enhances the importance of volcano surveillance at Popocatépetl and other similar volcanoes.

12. SO_2 FLUXES AT POPOCATÉPETL VOLCANO

13. COSPEC measurements

13.1.1. Before the eruption

The first SO_2 flux measurements at Popocatépetl volcano were carried out on February 1, 1994 (GVN, 1994; Table 1). The results obtained following these first measurements (1,390 ± 400 t d^{-1}) were very high for a non-erupting volcano. With these initial measurements, Popocatépetl entered into a group of volcanoes of high output rate (>1,000 t d^{-1}) such as Lascar volcano (Chile; Andres et al., 1991), Nevado del Ruiz and Galeras (Colombia; Williams et al., 1990; Fischer et al., 1994), and Masaya (Nicaragua; Stoiber, 1983) as shown in Figure 3.

Several other measurements were carried out during 1994 prior to the eruption. During measurements made in May, July and November, it was observed that high fluxes were sustained at Popocatépetl during l994 with some variations (average of 2,080 ± 1,330 t d^{-1}, maximum of

3,850 t d^{-1} and minimum of 740 t d^{-1}; Table 1). These flux measurements of 1994 indicated that Popocatépetl had undoubtedly reactivated and an eruption was forthcoming.

Table 1. SO_2 fluxes from Popocatépetl volcano, before and during the onset of the eruption. (a) Data obtained by S. N. Williams, T. Fischer, C. Siebe and H. Delgado. (b) Data from Galindo et al. (1995)

Date	SO_2 Conc. ppm-m	No. of Traverses	Wind Speed ($m\ s^{-1}$)	**SO_2 flux ($t\ d^{-1}$)**				**Source**
				Maximum	Minimum	**Average**	std. dev.	
Feb. 1, 1994	30	8	10	2298	870	**1394**	464	a
May 4, 1994	81	9	5	2566	1075	**1573**	500	b
May 5, 1994	59	10	5	1019	579	**738**	159	b
Jul. 1, 1994	103	2	5	4398	2944	**3671**	1028	a
Jul. 2, 1994	180	5	5	5467	2825	**3845**	981	a
Nov. 5, 1994	45	12	11	1877	924	**1261**	538	b
Dec. 23, 1994	81	8	8	2488	1617	**2169**	435	b
Dec. 24, 1994	96	5	10	4555	3402	**3961**	577	b
Dec. 27, 1994	113	13	6	1513	987	**1167**	263	b
Dec. 29, 1994	54	11	8	1616	934	**1237**	340	b
Jan. 6, 1995	39	12	8	1054	716	**836**	123	b
Jan. 14, 1995	52	10	4	652	462	**533**	117	b
Jan. 15, 1995	150	5	20	4020	3125	**3680**	300	a
Jan. 21, 1995	56	11	7	1586	492	**749**	310	b
Jan. 28, 1995	72	10	6	3055	876	**1450**	737	b
Jan. 28, 1995	63	1	10			**2020**		a

13.1.2. During the eruption

First stage

Several measurements were made during the first days of the eruptive activity and in January 1995 (Galindo et al., 1995), Maximum and minimum values were of 3,960 and 530 t d^{-1} with an average of 1,780 ± 1,200 t d^{-1}, respectively (Table 1). The highest values were slightly higher than the highest values obtained before the eruption. However, large amounts of ash were present downwind complicating flights (visibility was 5-10 km and flight distances from the vent were ~10 km when ash fell on Puebla 40 km away) and may have influenced the records. Therefore, the SO_2 flux values of the early parts of the eruption are minimum estimates of the real fluxes. As the initial explosive activity started to decline, SO_2 fluxes also declined (Fig. 4).

Second stage

During this period measurements were made using several COSPECs. This was an important time because it was possible to carry out measurements to test several methodologies. Simultaneous measurements were carried out with the available instruments. Measurements were made: on the ground installing the COSPECs in the same vehicles; in different vehicles running together, separated by a few tens of meters, at different distances, and with opposite traverse directions at the same measurement times; and simultaneous measurements were made on the ground and by air. The results were very important to understand several effects affecting plumes. For instance, the airborne and ground- based fluxes showed no significant differences (Fig. 5) in fluxes nor in standard deviations (Table 2). Details are discussed below.

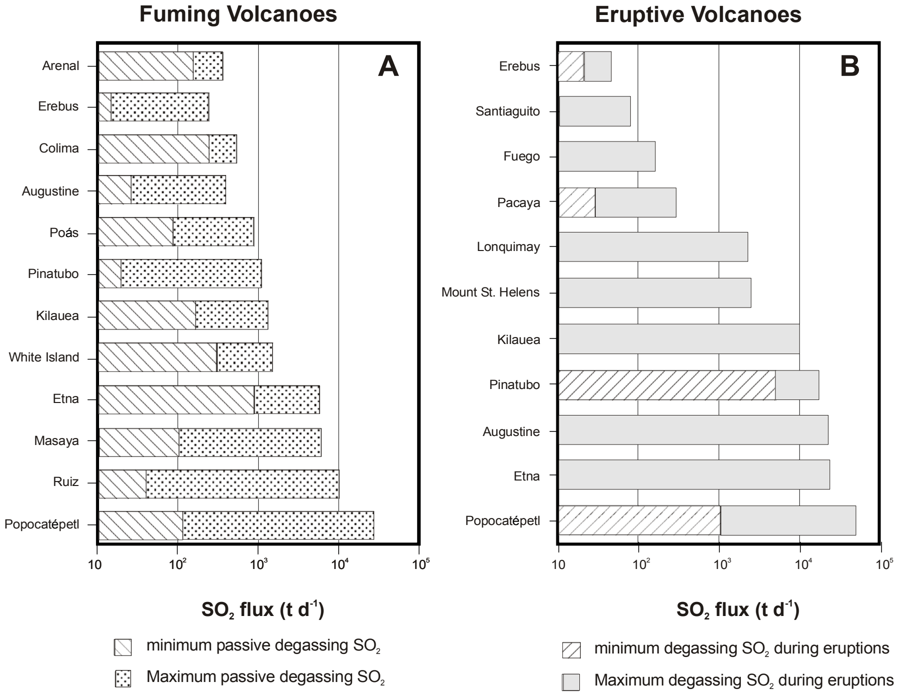


Fig. 3. SO_2 fluxes of fuming and eruptive volcanoes. a) SO_2 fluxes from passively degassing volcanoes compared with Popocatépetl. Ruiz, Masaya, Kilauea, Etna, and Popocatépetl yield passive emissions higher than 1,000 t d^{-1}, but only Ruíz and Popocatépetl have SO_2 fluxes surpassing 10,000 t d^{-1}. b) SO_2 fluxes from eruptive volcanoes. Miyakejima (not shown) and Popocatépetl are the only volcano emitting nearly 100,000 t d^{-1}. Data from Andres et al., 1995 and Daag, et al., 1997.

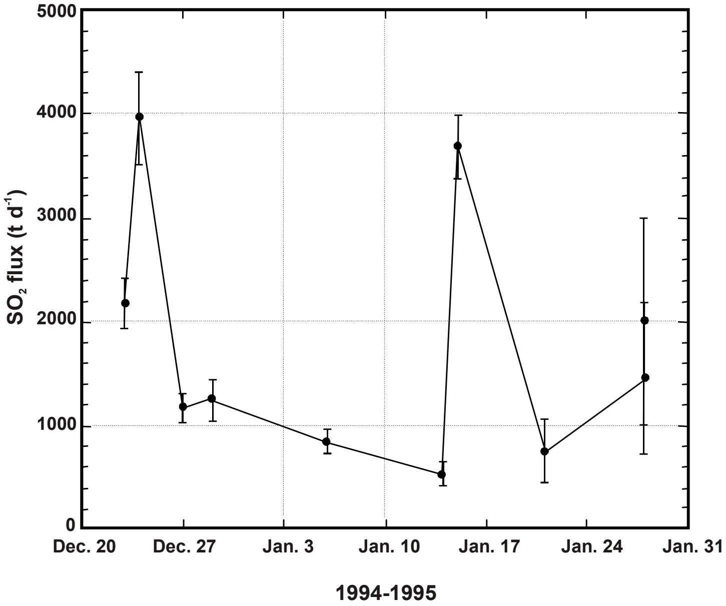


Fig. 4. SO_2 fluxes from Popocatépetl volcano during the first days of the current eruptive period. The general pattern of these measurements was to decline in spite of some high values by mid- January. Data from Table 1.

Table 2. Airborne vs. ground-based measurements. During the second stage of the eruption, measurements did not show significant differences in magnitude or accuracy. The standard deviation, however, reflected the instability of the volcanic system, namely the degree of SO_2 flux variation. Asterisks indicate airborne measurements

Date	**No. of Traverses**	**SO_2 flux ($t\ d^{-1}$)**	
		Average	**std. dev.**
3-Mar-95	4	5050	2820
4-Mar-95	9	7290	780 *
7-Mar-95	8	1930	910
8-Mar-95	7	1520	340 *
8-Mar-95	6	1530	320
10-Mar-95	7	2860	1120
11-Mar-95	4	3080	1000
13-Mar-95	2	5030	3390
14-Mar-95	6	5150	1400 *
18-Mar-95	4	1650	580
21-Mar-95	4	4390	780
23-Mar-95	4	7240	540 *
25-Mar-95	5	1150	590
28-Mar-95	4	3730	1140
29-Mar-95	4	3800	2600
31-Mar-95	3	4510	1060
3-Apr-95	3	1220	910
5-Apr-95	6	2140	400 *
7-Apr-95	4	2720	510
10-Apr-95	4	4140	1090
12-Apr-95	1	3040	
14-Apr-95	2	900	10
18-Apr-95	4	3850	1460
19-Apr-95	9	5060	1150 *
21-Apr-95	4	2320	330
24-Apr-95	2	2040	1590
26-Apr-95	8	1290	430 *
28-Apr-95	3	1240	1180
2-May-95	4	1760	190
3-May-95	9	2190	370 *
6-May-95	4	1560	1020
8-May-95	4	3200	640
10-May-95	9	2310	460 *
12-May-95	1	3670	
15-May-95	4	2000	730
17-May-95	11	1990	520 *
24-May-95	7	5970	2490 *
31-May-95	8	5670	1110 *

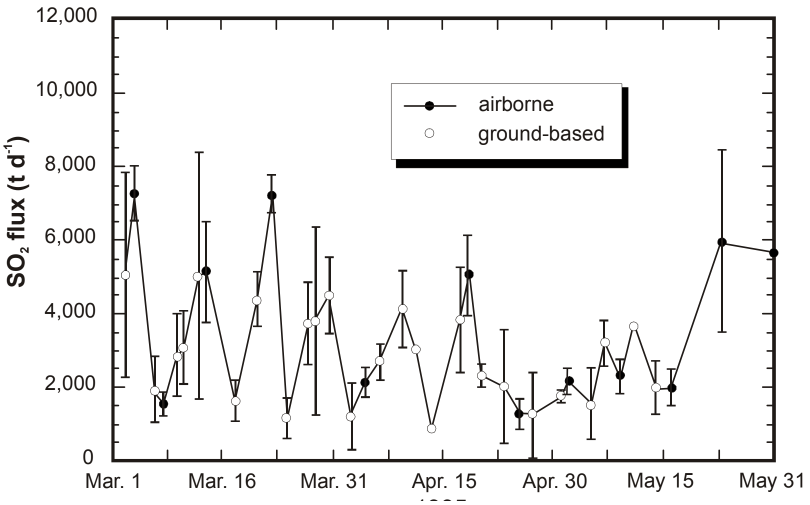


Fig. 5. Airborne vs. ground- based measurements in March-May 1995. No important differences are observed in magnitude, and thus the patterns are complementary. Standard deviation is not a measure of the accuracy of the measurements, but rather a measure of the variability in SO_2 output from the vent. Data from Table 2.

Since ash emissions became more spaced in time, flux measurements were determined with less influence from ash. A possible consequence of this was that SO_2 fluxes were higher than what was determined previously. Besides, gas emissions became more important. The maximum fluxes were 7,360 ± 790 t d^{-1} in March. The contrasts between the high values obtained in March-April 1995, and the values obtained by the end of the year were remarkable. As ash disappeared in August 1995, gas fluxes became lower (Fig. 6). By the end of 1995, the lowest flux measured was 150 ± 70 t d^{-1}. This flux pattern indicated that the volcanic system was experiencing a conduit sealing process. Stage average-emissions were 3,040 ± 2,250 t d^{-1}, the standard deviation reflecting the contrast among high and low values.

Third stage

The sealing process of the conduit system ended with the resumption of eruptive activity on March 5, 1996. The fluxes measured at the beginning of this new phase were high (up to 15,420 ± 3,320 t d^{-1}). The values of SO_2 flux during this time were higher than during the previous period indicating an increase in the volcanic activity. As the eruption progressed the first days, SO_2 flux decreased to values as low as 7,450 ± 1,610 t d^{-1}. This decrease and relatively low values coincided with the early stages of lava extrusion. SO_2 flux increased (21,290 ± 4,620 t d^{-1}) as the dome grew at high effusion rates, but as the lava decreased its effusion rate, the SO_2 flux also decreased (8,680 ± 1,610 t d^{-1} in May 7, 1996).

The maximum flux measured (39,390 t d^{-1} in September 1996) is evidence of the

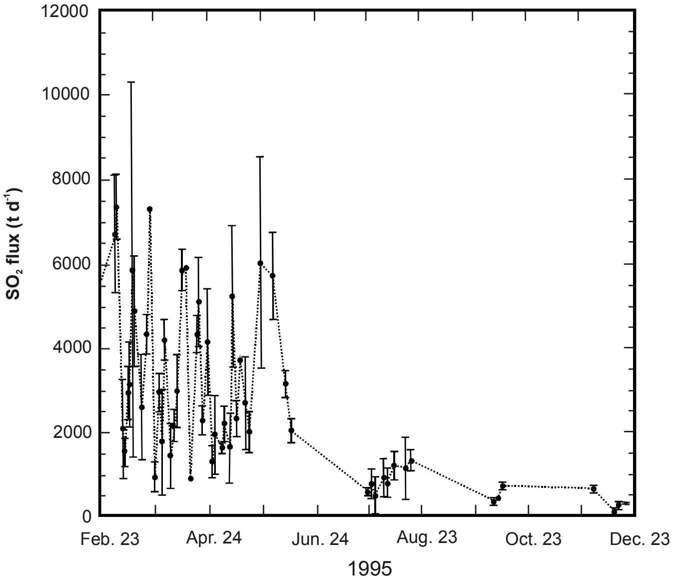


Fig. 6. SO_2 fluxes for the second stage of the eruption. During March and April 1995 the values were high and also the standard deviations. Frequent explosions including ash characterize this time. In July-August 1995, the ash emissions stopped and degassing declined. This trend is interpreted to be a result from a sealing process that did not allow the gases to be emitted freely.

increasing activity. The average flux of 11,280 ± 5,990 t d^{-1} indicates the high level of the emissions. The lowest value was obtained in June 1996 (2,450 t d^{-1}).

This stage ended with the explosion of December 29, 1996. A measurement made two days before the explosion was 7,330 ± 270 t d^{-1}. The SO_2 flux obtained the day following the eruption was 3,520 t d^{-1}. This value indicated that the volcanic system was not venting openly after the explosion since the values obtained were lower than expected after the explosion. Sealing of the conduits was interpreted again.

Fourth stage

The volcano remained sealed after the explosion of December 29, 1996. The fluxes after that event were still relatively lower (4,880 ± 290 t d^{-1} on January 3, 1997). Contrasting dense and mild degassing started some days later with emissions ranging between 22,870 t d^{-1} and 4,680 t d^{-1}. On January 17-19, 1997, a new dome started to grow, and SO_2 fluxes were up to 25,780 t d^{-1} by the end of January 1997. Strong degassing accompanied again the lava dome growth. SO_2 flux declined as the lava effusion rate decreased in April (as low as 3,520 ± 1,290 t d^{-1}). Another lava dome started to grow in July, after a series of explosions in May-June, 1997, then the fluxes increased up to 20,350 t d^{-1}. The average fluxes during this period were 8,650 ± 5,410 t d^{-1}. The standard deviation again reflects the variations in flux from the volcano.

The alternation in construction-destruction of lava domes continued ever since and the fluxes also followed the patterns dictated by the plumbing system or the magmatic events (Delgado Granados et al., 20001). The most impressive emissions ever measured at Popocatépetl volcano were during the eruptive crises in late 2000. On December 17, 2000 an emission rate of 169,490 ± 13,710 t d^{-1} was measured.

14. INTERPRETATION OF SO_2 DATA

15. Dispersion of SO_2 plumes

The numbers mentioned previously are minimum flux estimates. The true numbers can be much larger. For instance, the SO_2 flux calculated for January 20, 1997, was 8,750 t d^{-1}, although the real flux could be as high as 37,420 t d^{-1}. The discrepancy results from the way the fluxes are calculated, which depends on the morphology and structure of the gas plumes.

The SO_2 profiles obtained during the COSPEC measurements at Popocatépetl volcano depict a characteristic morphology (Fig. 7). COSPEC data are seen starting from a baseline which is usually very well defined. Fig. 7 shows two cases, an airborne (Fig. 7a) and a ground-based plot (Fig. 7b). The highest SO_2 concentrations are indicated with arrows, and concentrations are seen decreasing steeply at the flanks. Before the records reach the baseline, a smooth line (with less slope) is recorded. These parts of the record are named the core and shoulders. The core is interpreted as the main part of the plume and shoulders represent the part of the plume that has been dispersed away from the main plume axis. This is better seen by the ground-based measurements because they are carried out at a greater distance and thus, dispersion has a greater impact (Fig. 7b).

This morphology is attributed to convection. The volcanic plume is affected by shearing at the edges, and thus it is dispersed by convection from the core axis outwards (Fig. 8). As the COSPEC moves away from the core, the concentration drops rapidly, and the record becomes a line with a steep slope. If the plume's concentration is not very large, or moderate to high winds

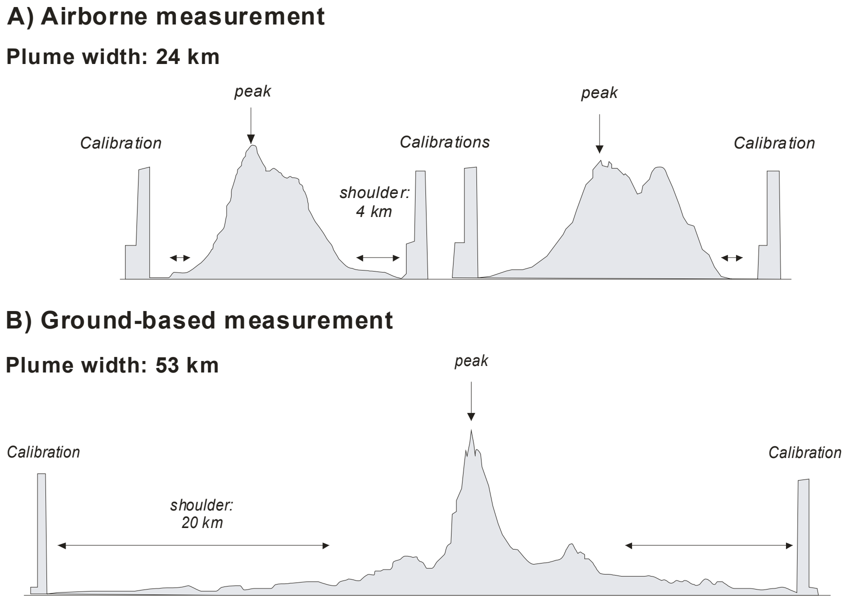


Fig. 7. Morphology of SO$_2$ plumes seen from COSPEC profiles. a) Airborne measurement profile of a 5,000 t d^{-1} flux 10 km from the vent. Horizontal arrows show plume shoulder width and vertical arrows concentration peaks. b) Ground-based measurement profile of a 6,950 t d^{-1} flux, 35 km from the vent. Shoulder width is 5 times larger than the airborne profiles even though the fluxes are comparable. A schematic explanation can be seen in Fig. 8.

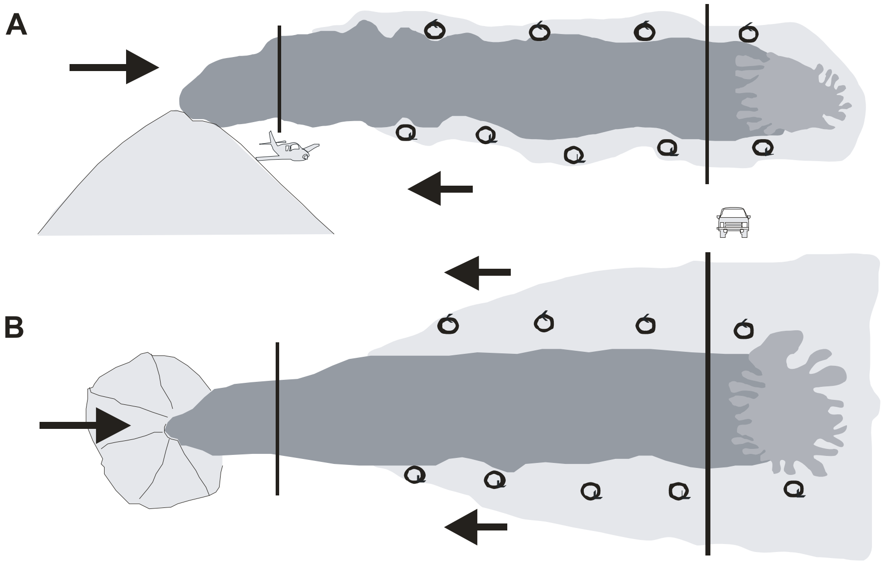


Fig. 8. Propagation and dispersion of the SO$_2$ plume. a) Schematic profile of SO$_2$ flux measurements (airborne and ground-based). Propagation of the plume in any direction will be affected by shearing at the edges (upper and lower). Thus, convection eddies will produce a dispersion of the SO$_2$ and lower concentration. The main body of the plume moves along the propagation axis that coincides with the COSPEC chart peak (Fig. 7). Since wind regimes at plume height are stratified and strong, the plume moves away from the vent for a long distance as a well-defined layer. b) Plan view of propagation and dispersion of the SO$_2$ plume. Convection also produces dispersion away from the propagation axis lowering SO$_2$ concentration. The larger the distance from the vent, the larger the dispersion and the shoulder widths. Ground-based measurements made from the distance will have wider shoulders but less concentrated in SO$_2$ as shown in Fig. 7b. No chemical effects on SO$_2$ are taken into account to transform it to H$_2$SO$_4$ fluxes or SO$_4$.

are prevalent at the height of the SO_2 plume, then the shoulders are narrow and the record finally reaches the baseline. However, if the SO_2 fluxes are high, weak winds are prevalent at the plume height, or the winds yield different patterns at different levels and produce shearing effects, the plume can then show wider shoulders. This is the case of many measured plumes from Popocatépetl volcano. This situation is complicated during calm days when flattening and spreading of the plume occurs. All around the volcano, the COSPEC detects SO_2 and the record is a long flat curve. Fortunately, Popocatépetl is a high altitude volcano and this situation only occurs once or twice a year. During calm days, the best thing to do is to wait some hours for windy conditions that will allow definition of the plume.

SO_2 fluxes which consider only the core of the plume instead of the entire plume may result in a very different calculation. Some COSPEC users neglect the shoulders of the plumes because it is considered that the shoulders represent recycled SO_2. Observations at Popocatépetl suggest that shoulder SO_2 should be considered as part of the propagating plume and thus calculated into the final flux. One of these observations is the airborne and ground-based fluxes measured simultaneously (Table 3). At Popocatépetl volcano the difference between core SO_2 flux and core + shoulder SO_2 flux might be very large. Shoulders' SO_2 flux can be, at times, >50 % of the total flux. In the case of the January 20, 1997 measurements the core fluxes represent 23 % of the total flux.

In summary, the writer believes that the real flux should comprise the entire plume. It most however, be stated clearly when reporting the data as core or total flux.

Table 3. Comparison of SO_2 fluxes obtained by airborne and ground-based methods for two dates. For March 8, 1995, the results are remarkably similar in spite of the different distances to the vent (flight was made 10 km from the vent and ground traverses at 24 km). For February 3, 1997, differences are larger, although these values were obtained during growth of the second lava dome.

Date	**Type**	**SO_2 flux (t d^{-1})**				**No. of Traverses**	**Wind Speed ($m\ s^{-1}$)**	**Plume Width (km)**
		Maximum	**Minimum**	**Average**	**std. dev.**			
Mar/8/1995	a	1,900	890	**1,520**	**340**	7	18	13-15
Mar/8/1995	g	1,910	1,140	**1,530**	**320**	6	18	20-33
Feb/3/1997	a	7,080	4,510	**5,600**	**830**	11	15	16-22
Feb/3/1997	g	10,180	5,980	**6,400**	**2,090**	3	15	33-42

16. Loss of SO_2 in volcanic plumes

SO_2 loss is a major issue at most volcanoes. SO_2 may be transformed in the atmosphere, becoming SO_4^{2-} or H_2SO_4 (Andres and Rose, 1995; Symonds et al., 1995). At several volcanoes, SO_2 loss represents a problem because it does not allow studying the true gas output and evaluating magmatic processes. Reports from volcanoes like Soufrière Hills (Montserrat) or Fuego de Colima (Mexico), show this problem (Delgado Granados, unpublished data). These volcanoes have the same feature: low altitudes and proximity to the sea. They are volcanoes surrounded by liquid water not only in the sea but also in the atmosphere. The physical state of water at low altitudes is in the form of liquid droplets (e.g., Herzog et al., 1998). According to meteorologists, the physical state of water strongly influences the chemistry of volcanic plumes (Herzog et al., 1998) because liquid water will deplete SO_2 more effectively (especially at the edges where shearing lowers SO_2 concentrations). Therefore, at low-altitude volcanoes and particularly those close to the sea, SO_2 loss strongly affects the chemistry of plumes, and

COSPEC measurements do not show the real fluxes. Since the COSPEC only records SO_2, lateral dispersal patterns are not observed at many volcanoes of the world due to loss effects. Thus, their shoulders are narrow or do not exist.

At Popocatépetl volcano, the prevalent temperature at plume altitude is <0°C (Delgado Granados, unpublished data). Atmospheric water is present as tiny ice crystals that do not react with the plume SO_2. Therefore, volcanic SO_2 is not depleted at all until the plume reaches an altitude where liquid water is present. For this reason, airborne and ground-based measurements at Popocatépetl are quite comparable, in spite of the differences in distance to the vent (Table 3). According to this, at large volcanoes such as Popocatépetl, loss of SO_2 plumes is minimal due to low volcanic gas - water interactions in the atmosphere, therefore, the dispersal of the plume can be observed and measured. Nonetheless, loss can be more important depending on changes in humidity and temperature.

The magnitude of plume loss depends on the season of the year. This is because humidity and temperature at high altitude vary with the time of the year. Therefore, during the dry season (i.e., December - May) the measurements are not affected by loss (Table 3). In contrast, during or at the end of the rainy season (i.e., June – September) loss is more effective and can be quantified. Measurements made across the plume at different distances indicate a linear relationship between distance to the vent and the plume width (Table 4, Fig. 9a). Individual measurements also show linear trends when compared to their distances to the vent or to plume widths (Fig. 9b and 9c). These measurements indicate a loss of 54 % comparing distal measurements to the near- vent measurements. Looking at these numbers, it is easy to understand why COSPEC measurements are difficult far from the vent at other volcanoes. At Colima volcano, for instance, sometimes passive degassing does not exceed 50-100 t d^{-1}, and monitoring of such small fluxes from the distance is impossible. These loss figures for Popocatépetl volcano do not account for possible effects produced by differences in flux through the time such as puffing.

17. Volcanic activity and SO_2 fluxes

The variations in SO_2 flux during the current eruptive episode at Popocatépetl volcano correlates very well with the different eruptive events. Furthermore, the flux data has allowed identification processes that are useful for eruption forecasts. For instance, the sealing process documented with COSPEC measurements at the end of 1995 (Fig. 6) suggests that the volcano was pressurizing, and an eventual explosive event was likely. No precise predictions were possible, but the diagnosis was that the volcano had the potential to resume explosive activity.

The flux data also led us to think that the eruptivity was increasing from the first stage towards the fourth stage (Fig. 10). Average and maximum values per stage show an increasing pattern. During the fourth stage, the maximum fluxes reached the highest levels, and the average flux is slightly higher than the average of the previous stage. According to the average flux, the activity of the volcano has also been increasing during the last stage. Nevertheless, the construction and destruction of domes during the last stage together with the highest maximum values led us to think that activity was increasing.

Another interesting thing is that a different league of volcanoes has developed since 2000, when the eruption of Miyakejima (Kazahaya et al., 2004) and Popocatépetl volcanoes injected >100,000 t d^{-1} of SO_2 into the atmosphere at peak days of gas emission during their eruptions.

Table 4. Loss effects on a volcanic SO_2 plume. Data was obtained during an airborne measurement at the end of the rainy season where each traverse was carried out at the same altitude but at a different distances from the vent. The effects of loss are shown in terms of decreasing SO_2 concentration with the distance. However, plume width preserves a linear relationship with the distance from the source. See Fig. 9.

Distance to vent m	**Plume width** m	**Average Concentration** ppm-m
3600	17350	94
3950	17400	88
7950	19190	63
11100	19830	62
33800	26340	27

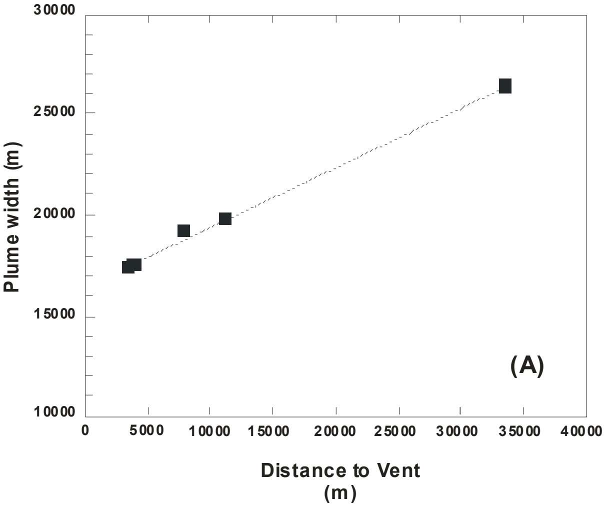
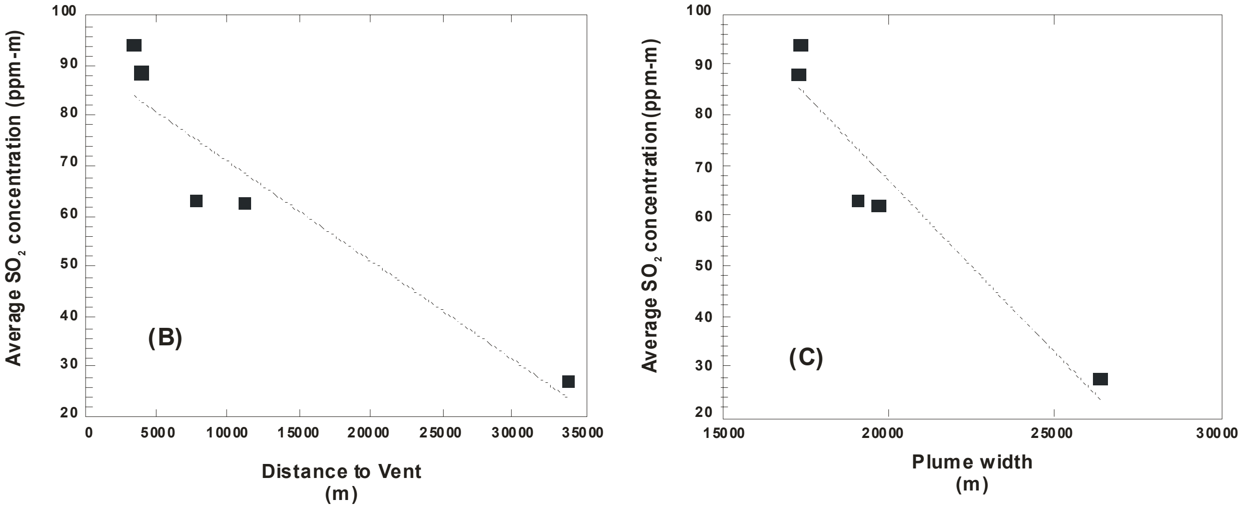


Fig. 9. A study of SO_2 concentrations measured at the same altitude and different distances from the vent of Popocatépetl, showing the effects of loss at the end of the rainy season. a) The volcanic plume widens proportionally with distance to the vent. b) SO_2 average concentrations decrease due to loss as distance to the vent increases. c) SO_2 average concentrations also decrease as the volcanic plume widens due to loss. Data from Table 4.



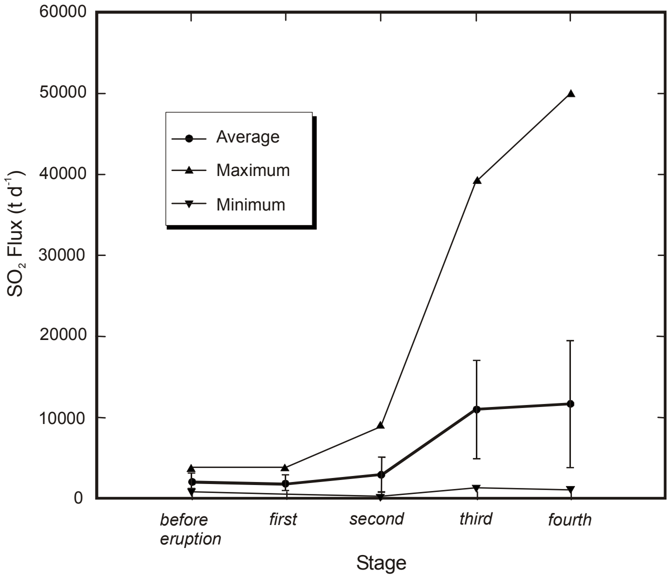


Fig. 10. Flux data suggest an increase in the volcanic activity with time. From the first to second stage, the emissions increased slightly, but from the second to third stage, the fluxes increased more than three times. Even though the average output of SO_2 shows a slight increase from the third to fourth stage, the maximum fluxes show a strong increase. This is reflected in the explosivity of the eruptions. At the end of the third stage and during most of the fourth stage, the explosive events have been more energetic. This plot was built using total plume data (i.e., core + shoulder SO_2). Fourth stage depicts activity up to 1998.

18. CONCLUSIONS

Measurement of large volcanic plumes represents a methodological challenge. This challenge consists in measuring volcanic plumes that have very high SO_2 concentrations and large widths at distances of tens of kilometers. Large plumes require modification of a specific methodology to carry out the measurements properly, but at the same time safely. These adaptations of the established methodology are designed to minimize costs without loss of accuracy. Once the measurements are properly obtained, then the magnitudes can be interpreted.

Popocatépetl volcano shows a contrasting eruptive history. Studies indicate that Popocatépetl has undergone large plinian eruptions in the geological past. The plinian events may occur every 1,000 years on average according to the records of the last 5,000 years (Siebe et al., 1996). However, the recorded history does not mention any large eruption during the last 800 years. Thus, the current eruptive activity might be another small-scale eruption like those of the last centuries. Nevertheless, the SO_2 fluxes measured at Popocatépetl are the largest ever recorded for a passively degassing volcano (the largest obtained with a COSPEC). Hence, it is possible that this eruption may develop into a larger eruption.

The current eruption has comprised four phases. The first phase was the onset of the eruption consisting of vulcanian events emitting ash. During this phase, the SO_2 fluxes were not very high (<4,000 t d^{-1}) compared to measurements made before the eruption. It is believed that the low values were due to the influence of ash. The second phase consisted of decreasing explosive activity that finally stopped. The flux values were high during most of the phase (>7,500 t d^{-1}), but interestingly the trends of the flux decreased consistently to 120 t d^{-1}. This behaviour is interpreted as the expression of a conduit sealing process. The third stage of the eruption was initiated with an explosive event that opened the conduits. During this phase, pumice was ejected and a lava dome started to grow. As the lava dome grew, the SO_2 flux decreased, but after the lava dome stopped to grow, the fluxes increased again. This behaviour may reflect the conditions at depth, such as the presence of a new batch of magma (higher flux rates) that made the lava rise; after the lava plugged in the conduits, the flux decreased. At the fourth stage, lava dome growth and destruction by explosive events has been the dominant behavior. The SO_2 fluxes reached maximum values during this phase (~170,000 t d^{-1}).

Dispersion and loss of the volcanic plumes at Popocatépetl volcano show important features. The dispersion of volcanic plumes due to shearing at the edges of the plume defines morphology typical of the COSPEC profiles. The shape of the profiles depicts a core and two shoulders. The core represents the main body of the plume whilst the shoulders represent the dispersed part of the plume. At Popocatépetl, the flux calculated at the shoulders may represent more than 50% of the total flux. The chemistry of volcanic plumes is controlled by the physical state of water at the altitude of the plume. Thus, loss depends on the humidity and temperature in the atmosphere. Water in droplets is an effective loss mechanism while ice crystals do not dilute SO_2. At Popocatépetl, the temperatures at the altitude of the plume are <0°C most of the year. However, during the rainy season temperatures and humidity increase. Hence, at Popocatépetl loss depends on the seasons. During the dry season, loss is nearly zero but during the rainy season the SO_2 concentrations may decline >50%, 30 km from the vent. A linear relationship exists among distance to the vent, plume width, and SO_2 concentration.

The flux measurements using the COSPEC at Popocatépetl volcano have helped to track the eruption and give a diagnosis on the activity. Sealing episodes, new intrusions of magma at depth, convection in the conduits or in the magma chamber are possible alternatives for the degassing trends.

Acknowledgements

This manuscript was first ready for publication in 1998 but delaying made it a kind of story on “old fashion” instrumentation and methodologies. Ten years later however, the writer believes that several of the experiences mentioned on this text might still be useful. The writing and some of the data has been amended but the version approved by the referees was kept intact. The efforts to study the gas fluxes from Popocatépetl volcano would be impossible without the strong support of the National Center for Disaster Prevention (CENAPRED) of the Secretaría de Gobernación and the Instituto de Geofísica of the Universidad Nacional Autónoma de México (UNAM). The author is deeply indebted to G. Suárez Reinoso, R. Meli Piralla, D. Novelo Casanova, J. Urrutia Fucugauchi, and R. Quaas for encouragement and support. Also, the author expresses his deep gratitude and respect to the technicians and students who have helped acquire the COSPEC data at Popocatépetl volcano. The friendship and dedication of L. Cárdenas, J. J. Venegas, N. Piedad, L. E. Rayón, R. Villalpando, L. Galván, R. Molinero, P. Cervantes, A. González, and P. Julio has been important all this time. Claus Siebe interested the author in COSPEC studies at Popocatépetl, and together initiated them with the help of S. Williams and T. Fischer. The author thanks C. Siebe for his support and encouragement. SO_2 flux monitoring at Popocatépetl volcano has been a tough job. Understanding the processes that make these fluxes the highest ever reported have taken time, and still many problems remain to be solved. However, the advice at the first stages of COSPEC monitoring at Popocatépetl and fruitful discussions all along from Stan Williams are greatly acknowledged. Advice, discussion and friendship from M. P. Doukas, T. M. Gerlach, and K. A. McGee (Cascades Volcano Observatory) also have been of enormous benefit.

REFERENCES

Alatorre-Ibargüengoitia, M. A., Delgado Granados, H. (2006) Experimental determination of drag coefficient for volcanic materials: Calibration and application of a model to Popocate´petl volcano (Mexico) ballistic projectiles, Geophysical Research Letters, v. 33, L11302, doi:10.1029/2006GL026195.

Andres, R.J., Rose, WI., Kyle, P.R., deSilva, S., Francis, P., Gardeweg, M., Moreno Roa H. (1991) Excessive sulfur dioxide emissions from Chilean volcanoes, Journal of Volcanoloy and Geothermal Research, v. 46, p. 323-329.

Andres, R.J., Rose, WI. (1995) Remote sensing spectroscopy of volcanic plumes and clouds. In: Monitoring Active Volcanos, McGuire W.K., Kilburn C.R.J, Murray J. (eds), London: UCL Press, p. 301-314

Andres, R.J., Schmid, J.W. (1997) The effect of volcanic ash on COSPEC measurements, IAVCEI General Assembly, p. 27.

Caltabiano, T., Guiduzzi, G,,Leuzzi, S., Romano, R. (1992) Helicopter borne COSPEC flux measurement, Acta Vulcanologica, Marinelli, v. 2, p. 95-98.

Camacho, A. (1925) Apuntes acerca de la actividad actual del Popocatépetl en relación con la sismologia, Anales del Instituto de Geologia de Mexico, v.II-1-3, p. 38-67.

Casadevall, T. (1991) Volcanic hazards and aviation safety: Lessons, of the past decade, Aviation Safety Journal, 11 p.

Daag, A., Tubianosa, B. S., Newhall, C. G., Tuñgol, N. M., Javier, D., Dolan, M. T., Delos Reyes, P., Arboleda, R. A., Martinez, M. L., and Regalado, M. T. M. (1997) Monitoring sulfur dioxide emission at Mount Pinatubo. In: Pinatubo: Fire and Mud, University of Washington Press.

De la Cruz-Reyna, S., Quezada, J.L., Peña, C., Zepeda, O., and Sánchez T. (1995) Historia de la actividad reciente del Popocatépetl, (1354-1995). In Estudios realizados durante la crisis de 1994-1995, CENAPRED-UNAM, p. 3-22.

De la Cruz-Reyna, S., Siebe, C. (1997) The giant Popocatépetl stirs, Nature, v. 388, p.227.

Delgado Granados, H., Carrasco, G., Urrutia, J., Casanova, M. (1988) Analysis of the eruptive record of the Popocatépetl volcano, Mexico, Kagoshima International Conference on volcanoes, proceedings, p. 510-513.

Delgado Granados, H., Panfil, M., Gonzalez, E.a., Uruñuela,, G., Plunket, P., Gerdner, T., Abrams, M. (1994) Lessons from Popocatépetl volcano (Mexico): ancient settlement buried by lavas, mudflows, and air-fall deposits, EOS Trans. American Gephysical Union, p. 737.

Delgado Granados, H., Gonzalez, A.E. (1994) Analysis of the historical activity of volcan Popocatépetl and the increase of its activity: implications for a future eruption, Cuarta Reunion Internacional Volcán de Colima, Abstracts, p. 156.

Delgado Granados, H., Carrasco, G., Cervantes, P., Córtes, R., Molinero, R. (1995) Patrones de viento en la región del volcán Popocatépetl y Cd. de Mexico. In: Volcãn Popocatépetl Estudios realizados durante la crisis de 1994-1995, CENAPRED-UNAM, p. 295-326.

Delgado Granados, H., Cárdenas González, L., Piedad Sánchez, N. (2001) Sulfur dioxide emissions from Popocatépetl volcano (Mexico): case study of a high-emission rate passively degassing erupting volcano, Journal of Volcanology and Geothermal Research, v. 108, p. 107–120.

Delgado Granados, H., De la Cruz-Reyna, S. Tilling R. I. (2008) The 1994–present eruption of Popocatépetl volcano: Background, current activity, and impacts, Journal of Volcanology and Geothermal Research, v. 170, p. 1–4.

Fischer, T., Morrissey, M., Calvache, M.L., Gómez, D., Torres, R., Stix, J, Williams, S. (1994) Correlation between SO_2 flux and long-period seismicity at Galeras volcano. Nature, v. 308, p. 135-137.

Galindo, I., Gonzalez, A., Ayala, R. (1995) Emisiones de bióxido de azufre del volcán Popocatépetl, Mexico, durante la erupción de diciembre de 1994. In: Volcán Popocatépetl Estudios realizados durante Ia crisis de 1994-1995, CENAPRED-UNAM, p. 245-256.

Goff, F., Janik, C., Delgado Granados, H., Werner, C., Counce, D., Stimac, J., Siebe, C., Love, S., Williams, S., Fisher, T., and Johnson, L. (1998) Geochemical surveillance of magmatic volatiles at Popocatepetl volcano, Mexico, Bulletin of the Geological Society of America, v. 110, p. 695-710.

Gonzalez, A.E, Delgado, H., Urrutia, J. (1997) The San Nicolas lahar at Popocatépetl volcano (Mexico): a case study of glacier-ice-melt-related debris flow, triggered by a blast at the onset of plinian eruption.IAVCEI General Assembly, Abstracts, p. 22.

GVN (1994) Gas and visual observations following the small 21 December eruption, Bulletin of the Global Volcanic Network, 19, 12.

GVN (1996) Continued ash emissions; new lava dome and lava flows in summit crater, Bulletin of the Global Volcanic Network, 21, 03.

Herzog, M., Graf, H.F., Textor, C., Oberhuber, J. (1998) The effect of phase changes of water on the development of volcanic plumes. Journal of Volcanology and Geothermal Research, v 87, p. 55-74.

Kazahaya, K., Shinohara, H., Uto, K., Odai, M., Nakahori, Y., Mori, H., Iino, H., Miyashita, M., Horabayashi, J. (2004) Gigantic SO_2 emission from Miyakejima volcano, Japan, caused by caldera collapse, Geology, v. 32, p. 425-428.

Love, S.P., Goff, F., Counce, D., Siebe, C., Delgado, H, (1998) Passive infrared spectroscopy of the eruption plume at Popocatepetl volcano, Mexico. Nature, v. 396, p. 563-567.

Macías, J. L., Siebe, C. (2005) Popocatépetl's crater filled to the brim: significance for hazard evaluation, Journal of Volcanology and Geothermal Research, v. 141, p. 327-330.

Matiella Novak, M.A., Watson, I.M., Delgado-Granados, H., Rose, W.I., Cárdenas-González, L., Realmuto, V.J. (2008) Volcanic emissions from Popocatépetl volcano, Mexico, quantified using Moderate Resolution Imaging Spectroradiometer (MODIS) infrared data: A case study of the December 2000–January 2001 emissions, Journal of Volcanology and Geothermal Research, v. 170, p. 76–85.

Murillo, G. (Dr. Ati) (1939) Las erupciones de Popocatépetl, Serie volcanes de México, Ed. Polis, p. 13-16.

Panfil, M. S., Gardner, T. W., Hirth, K. G. (1999) Late Holocene stratigraphy of the Tetimpa archaeological sites, northeast flank of Popocatépetl volcano, central Mexico. Geological Society of America Bulletin, v. 111, p. 204–218.

Plunket, P., Uruñuela, G. (2008) Mountain of sustenance, mountain of destruction: The prehispanic experience with Popocatépetl Volcano. Journal of Volcanology and Geothermal Research, v. 170, p. 111–120.

Siebe, C., Abrams, M., Maclas, J.L. (1995) Derrumbes gigantes, depósitos de avalancha de escombros y edad del actual cono del volcán Popocatépetl. In: Estudios realizados durante la crisis de 1994-1995, CENAPREDUNAM, p. 195-200.

Siebe, C., Maclas, J.L., Obenholzner, J. (1996) Repeated volcanic disasters in Prehispanic time at Popocatépetl, central Mexico: past key to the future, Geology, 24, v. 24, p. 399-402.

Siebe, C., Maclas, J.L., Abrams, M., Rodriguez, S., Castro, R. (1997) Catastrophic Prehistoric eruptions at Popocatépetl and Quaternary explosive volcanism in the Serdán-Oriental Basin, East-Central, Mexico, Fieldtrip Guidebook, IAVCEI General Assembly, p. 88

Siebe, C., Schaaf, P., Urrutia-Fucugauchi, J. (1999) Mammoth bones embedded in a late Pleistocene lahar from Popocatépetl volcano, near Tocuila, Central Mexico. Geological Society of America Bulletin, v. 111, p. 1550–1562.

Stoiber, R.E., Maliconico, L.L., Williams, S.N. (1983) Use of the Correlation Spectrometer at Volcanoes. In: Forecasting volcanic events, H. Tazieff & J.C. Sabroux (eds.), Amsterdam: Elsevier, p. 425-444.

Symonds, R., Rose, W., Gregg, J., Bluth, S., Gerlach, M.(1994) Volcanic-gas studies: methods, results and applications. In: Volatiles in magmas, Carroll, M.R & Holloway (eds), Mineralogical Society of America, Reviews in Mineralogy, v. 30, p. 1-41.

Werner, C., Janik, C., Gofi F., Counce, D., Johnson, L., Siebe, C., Delgado, H., Williams, S., Fisher, T. (1997) Geochemistry of summit fumarole vapors and flanking thermal/mineral waters at Popocatépetl volcano, Mexico, Los Alamos National Laboratory LAMS-Series report.

Williams, S.N., Sturchio. N.C., Calvache, M.L., Mendez, V.R., Londono, F.A, Garcia, N.P. (1990) Sulfur dioxide from Nevado del Ruiz volcano, Colombia: Total flux and isotopic constraings on its origin. Journal of Volcanology and Geothermal Research, v. 42, p. 53- 68.