Sulfur Dioxide Emissions from Pu'u O'o Vent, Kilauea, Hawaii and Mount Erebus, Antarctica

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Table of Contents

List of Figures

List of Tables

Abstract

Volcanic sulfur dioxide emissions were measured using a Correlation Spectrometer (COSPEC) at Pu'u O'o Vent (1989) and Mount Erebus, Antarctica (1987,1988,1989). COSPEC measurements made since 1988 utilize an automatic scanning head, automatic computer interface and computer aided data reduction.

The long term and constant scanning frequency afforded by the automation of the COSPEC allowed the data to be analyzed for periodic behavior. The strongest periodic behavior occurred with 1-3 minute period and is associated with volcanic gas pistoning known as puffing. Other periodic behavior of 20-175 minute period was identified and may provide insights to the dynamics of magma within the volcanic plumbing system.

The prolificacy of data combined with synchronous video tape footage of the plume provided enough data to establish the validity of each scan used. Daily SO_2 emission rates have been established for both vents to a high level of confidence (±7 - 18%) for the study period, despite a high standard deviation due to periodic behavior.

At Pu'u O'o the average daily emission rate was calculated to be 194 ± 84 Mg/day. At Mount Erebus, the average daily emission was 44.2 ± 27 Mg SO_2/day during 1987; 27.3 ± 9 Mg SO_2/day during 1988 and 59.3 ± 22 Mg SO_2/day during 1989.

Acknowledgements

Much gratitude is owed to many people for sharing the knowledge that was necessary to complete this project. Among these are Philip Kyle, Nelia Dunbar, Bill McIntosh and Dave Caldwell for their insights into volcanology and their experience in Antarctic travel. Additional thanks go to J. Barry Stokes of HVO for providing COSPEC data from the Chain of Craters Road. Special thanks go to Nelia Dunbar and Paul Domski for their reviews of early versions of this manuscript.

As with any major project, this thesis required a great deal of effort from the people closest to me. I would like to take this opportunity to thank my friends and family, who, for no compensation and very little recognition, supported this project from the outset.

I dedicate this thesis to the memory of my grandfather, Ed Sybeldon, for the high value he placed on education and for his ability to fly a station wagon.

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CHAPTER 1: INTRODUCTION

Volcanic gas emissions provide important insights into the mechanisms at work inside volcanoes, as well as the long and short range environmental impact of eruptions. Some workers believe that by monitoring the amount and composition of gas emissions at volcanic vents, eruptions can be predicted (Malinconico, et al, 1979; Casadevall, et al, 1981).

Generally, H_2O (35 to 90 mole %), CO_2 (5 to 50 mole %) and SO_2 (2 to 30 mole %) are the most abundant volatiles in basaltic and andesitic magmas (Anderson, 1975). Sulfur can be analyzed more precisely than water or CO_2, and is less likely to be subjected to contamination by groundwater, meteoric water and air surrounding the vent (Gerlach, 1980). The oxidizing conditions found at most volcanic vents result in nearly all volatile sulfur being present as SO_2 (Gerlach and Nordlie, 1975; Jaeschke, et al, 1987; Symonds, et al, 1990). For these reasons, the sulfur content is considered the most sensitive of the abundant volatiles as a guide to monitor the loss of volatiles from magma (Fisher and Schmincke, 1984).

Measured SO_2 emission rates from individual volcanoes are used to calculate the total output of other volatiles and particulate matter from the vent. They are also useful for the estimation of the total SO_2 output due to volcanoes on the global scale.

Every year, over 250 Tg of sulfur enters the atmosphere from all sources (Cullis and Hirschler, 1980)(Appendix A). Man made emissions comprise 65 Tg of the total (Manahan, 1984). Less than 19 Tg of sulfur enter the atmosphere through volcanic emissions of sulfur gases (Stoiber, et al, 1987). Nonetheless, volcanoes are important to earth's sulfur cycle since they expel large amounts of gaseous sulfur over small areas and short periods of time. The fate of these gases therefore holds great importance to the communities surrounding the vent or fumarole in terms of acid rain and damages caused by acid gases and particulate matter to the landscape.

On a larger scale, volcanic sulfur gases may be injected by volcanic eruption or transported by microphysical processes into the stratosphere (Toon and Farlow, 1981). Once there, sulfur gases oxidizes further to sulfate particles that become incorporated into the stratospheric aerosol layer. Isotopic studies of sulfates collected in the stratosphere indicate that large quantities of volcanic sulfur are absorbed into the aerosol layer (Lazrus, et al, 1979).

The concentration of non-volcanic sulfate in the aerosol layer is approximately 0.30 to 0.40 parts per billion (mass) (ppbm) (Sedlacek, et al, 1984). Samples of the aerosol layer taken by filter packs mounted on the wings of high altitude aircraft within a few months of an eruption show large enrichments in sulfate. Concentrations as high as 2.83 ppbm sulfate have been measured following volcanic eruptions (Sedlacek, et al, 1984).

Between the years 1970 and 1982, the total sulfate concentration in the stratospheric aerosol layer averaged 0.95 ppbm over the northern hemisphere (Sedlacek, et al, 1984). Volcanic emissions of sulfur gases into the stratosphere are therefore estimated to be responsible for about 58% of the sulfate found in the lower stratosphere (Sedlacek, et al. 1984).

As sulfate, the particles undergo coagulation or condensational growth and become too large to remain in the stratosphere (Toon and Farlow, 1981). They are removed from the stratosphere by gravitational sedimentation. Once injected into the stratosphere, SO_2 gases require about one year for removal by these processes (Kellogg, et al. 1972).

It is obvious that volcanic emissions of sulfur gases are very important on a global scale. It is difficult to estimate the actual amount of sulfur gas emitted by any single eruption, let alone any single volcano. This study represents the continuation of an ongoing effort to monitor the sulfur gas emissions from two volcanoes, Mount Erebus, Antarctica and Pu'u O'o Vent, Kilauea Volcano, Hawaii.

SO_2 emission has been routinely measured at both Mount

Erebus and Kilauea for several years. Of particular interest at both volcanoes are measurements taken since the mid-1980's.

Background

Kilauea Volcano, Hawaii

SO_2 emission has been monitored regularly at Kilauea and along its East Rift Zone (ERZ) since the onset of the Pu'u O'o sequence of eruptions in January 1983. To this date, 47 eruptive episodes separated by short periods of repose have characterized the sequence.

Measurements of SO_2 output have been made routinely at Kilauea's summit (Casadevall, et al, 1987), and sporadically at Pu'u O'o Vent (the most active vent during this series) (Chartier, et al, 1988) and along the entire ERZ (Andres, et al, 1990). Measurements have been made during high eruptive fountaining activity, repose periods and during effusive eruptive events. The data collected for this study measures SO_2 emission from the Pu'u O'o Vent between 18 and 22 March 1989 and along the entire ERZ between 20 and 22 March 1989 (Stokes, unpublished data). A comparison of the SO_2 emission from the Pu'u O'o Vent is made to the emission of the ERZ, of which Pu'u O'o is a part.

The current eruptive phase (episode 48B) has been effusive in nature and continuous since May 1988 (SEAN Bulletin, V. 13, No. 4, 1988; Andres, et al, 1990). The total annual SO_2 output for this activity is calculated and compared to annual emission rates for earlier episodes characterized by high fountaining eruptive activity. The average emission rates found for each day in this study are compared and evaluated for accuracy. Differences in day to day emission measurements are explained. The data are analyzed for periodicities and their origins are considered.

Mount Erebus, Antarctica

At Mount Erebus, SO_2 emission rates used in this report were measured during the 1987, 1988 and 1989 field seasons. Annual emission averages are calculated for each year and compared to the annual averages calculated in other studies for previous years back to 1983.

Daily SO_2 output is calculated for each day data were collected. The daily averages collected each year are compared for statistical consistency. Large differences are analyzed and discussed.

The data sets for each day are individually analyzed for periodic trends. This inspection is carried out both qualitatively, by visual inspection of the data set, and quantitatively, by Fast Fourier Transform analysis. The physical significance of any periodicities is discussed.

Objective

The objectives of this study were: 1) To quantify the amount of sulfur dioxide emitted from Pu'u O'o vent and Mount Erebus during the study period. 2) To determine average SO_2 outputs for annual budget estimates. 3) To determine whether or not trends exist in the data. Trends in the data may be long (annual), medium (daily) or short (minutes to hours) term. If trends are discovered their physical significance is assessed.

CHAPTER 2: EXPERIMENTAL TECHNIQUE

In this study, SO_2 emission rates from Pu'u O'o vent and Mount Erebus were made utilizing a Barringer COSPEC V correlation spectrometer (Table 1). Measurements were made in the stationary mode where the instrument remained in a fixed position and then scanned across the volcanic plume (Stoiber et al. 1983). Since the 1987 field season, an automatic scanning head that provides constant scan angles and scan rates with minimal aberrations due to operator interaction was used to collect all of the data. When the automated technique was used, the data was collected by the COSPEC while mounted on a scanning head and recorded into the memory of a Toshiba T1200 HB lap-top computer utilizing the software program COSPEC. Depending on the ambient wind condition, the COSPEC was used either in pan mode (horizontal scans) or in tilt mode (vertical scans). The data was reduced using the program ASPEC (both COSPEC and ASPEC are listed in Appendix C).

The Correlation Spectrometer

The correlation spectrometer (COSPEC) has been used since 1972 to remotely monitor SO_2 emissions from volcanoes (Stoiber, et al, 1983). The COSPEC is particularly useful for volcanological studies since it is portable and useful in a variety of modes (e.g., stationary scans, vehicle mounted scans). It detects SO_2, which is the dominant species of sulfur gas emitted from most volcanoes (Gerlach and Nordlie, 1975; Jaeschke, et al, 1987).

The COSPEC operates by dividing light into several different spectral bands and evaluating the energy of those bands. A telescope on the COSPEC (field of view 23 milliradians by 7 milliradians) scans incident solar radiation. Four masks containing seven grating slits each filter and separate the light according to wavelength. Two bands of radiation are of particular interest; the first is the band of radiation of the wavelength where energy is absorbed by atmospheric sulfur dioxide. The second is the band of radiation where the presence of atmospheric sulfur dioxide produces energetic radiation (Millan, et al, 1985). The ratio of the energies of these two sets of radiation in the absence of extraneous sulfur dioxide provides a base line for the analysis. The energy ratio is proportional to the amount of excess sulfur dioxide present. The COSPEC electronically produces an output voltage signal proportional to the ratio. Assessment of measurable quantities including plume velocity, distance to the plume and scan rate allow the conversion of the voltage to the quantity of sulfur dioxide emitted.

The COSPEC contains an automatic gain control (AGC) to correct for changes in the intensity of ultra violet radiation during the day. The AGC adjusts the sensitivity of the instrument based on the intensity of the incoming radiation. This along with frequent (about every half-hour) calibrations of the instrument by inserting a fused quartz chamber containing a known quantity of SO_2 into the field of view of the instrument against a plume free background allow the calculation of SO_2 emission rate.

COSPEC data collected in 1987 used the manual scan technique described by Stoiber et al. (1983), Chartier (1987) and others. The manual scan technique requires the constant presence and attention of the operator to provide a steady scan rate and scan angle for accurate SO_2 measurements. The data collected in this manner was recorded on an Hewlett-Packard strip chart recorder and analyzed by calculating the area beneath the resulting curve. (Analytical techniques are outlined in Appendix B).

Table 1: COSPEC Data Measurements Used in This Study

Date	Location	Number of Scans	Measurement Period
1987:			
Dec. 7	Erebus	25*	2.8 hours
Dec. 8	Erebus	227*	12.0 hours
Dec. 12	Erebus	55*	5.6 hours
Dec. 16	Erebus	20*	0.7 hours
*Measurements were made using hand scan techniques.			
1988:			
Dec. 14	Erebus	310	10.8 hours
Dec. 16	Erebus	383	7.4 hours
Dec. 17	Erebus	164	3.0 hours
Dec. 21	Erebus	84	1.7 hours
1989:			
Dec. 3	Erebus	130	3.4 hours
Dec. 11	Erebus	235	4.5 hours
Dec. 18	Erebus	269	7.7 hours
Dec. 20	Erebus	511	10.5 hours
Dec. 21	Erebus	260	5.6 hours

Table 1: COSPEC Data Measurements Used in This Study

Date	Location	Number	Measurement
Hawaii 1989:			
Mar. 18	Pu'u O'o	130	2.5 hours
Mar. 19	Pu'u O'o	475	8.6 hours
Mar. 21	Pu'u O'o	196	6.5 hours
Mar. 22	Pu'u O'o	207	5.1 hours

The distance between the COSPEC site and the plume was determined using topographic maps of the field areas. The scan angle for each data set was measured by means of a Brunton compass mounted on the COSPEC as it operated. The distance to the plume and scan angle are used to calculate the width of the plume.

Wind Velocity and Plume Rise Rate Calculations

The vast majority of the data used in this study is accompanied by video tape footage of the plume taken from the COSPEC site as the measurements were taken. This video record allows for the accurate determination of the plume velocity - an essential factor for the reduction of the raw COSPEC data to the final SO_2 emission measurement. The video data was utilized in different ways for the separate cases of Kilauea and Mount Erebus.

At Kilauea, windspeed measurements were taken on site during the COSPEC sessions as a supplement to video recordings of the plume. Since taking actual wind speed measurements at the altitude of the plume was unfeasible for this study, plume velocities were calculated based on the assumption that the plume was carried almost entirely by the wind. Any component of the plume velocity due to its thermal energy as it was released from the vent was considered negligible relative to wind velocity. Ground based anemometer measurements were used to calibrate video measurements for plume velocity determination. Direct calculation of plume velocity from the video tapes was not possible since topographic features were not visible on the video taken at Pu'u O'o. Also, the landscape in the area surrounding Pu'u O'o vent is in a dynamic state and maps showing accurate placement of topographic features were not available. Examples of the graphical data illustrating the technique used are given in Fig. 1.

Mount Erebus presents different problems to COSPEC measurements. Due to the small volume of the volcanic plume at Erebus, and the distance from the COSPEC site to the plume (approximately 2 km), COSPEC data was only collected on windless days when the plume rose vertically. In this case, plume velocities depend only on thermal inertia.

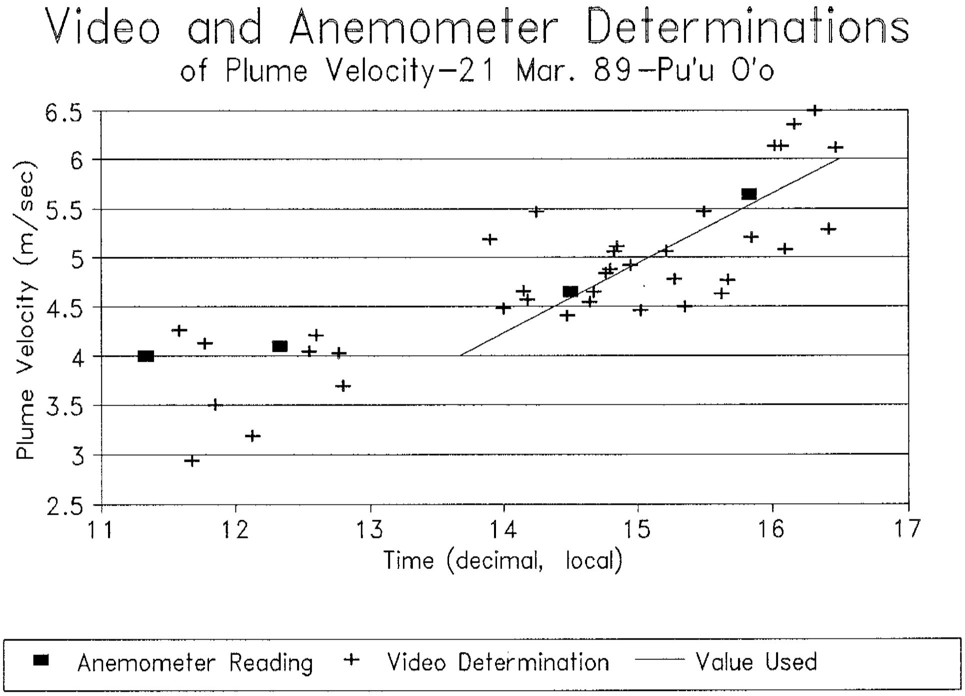

Figure 1: Anemometer readings and plume travel times used to calculate plume travel rates for the Pu'u O'o vent.

Because the rise rate of the plume is not constant, rise velocities were determined from the video record for each COSPEC measurement.

The distance from the COSPEC/camera site at Erebus as well as the distance between topographical landmarks on the rim of Erebus are well known. Plume velocities can therefore be calculated directly from video tapes. The technique involved in plume velocity calculations required timing with a stopwatch some distinguishable feature of the plume (e.g., a discoloration or the leading edge of a puff) as it traveled known distances on the video screen. Once time and distance traveled are established, the calculation of plume velocities is trivial. In circumstances where the video was unsuitable (due to no visible plume, for instance) or where no video was made, average plume velocities from COSPEC sessions immediately preceding and/or following the times of "video gaps" were used. Nearly all measurements of plume travel times made using this method were better than ± 5% statistical error, thereby greatly improving accuracy in one of the greatest sources of error (Table 2) involved with correlation spectrometry observations.

The Automation of the COSPEC

Prior to 1988, all measurements made by COSPEC were recorded in analog form on a chart recorder. This data was then analyzed by computing the area under the resultant curves on the chart using a digitizer, a planimeter or manually, by counting squares on the graph paper. This area, the COSPEC output, was compared to the calibration data taken near the same time, then multiplied by the width of the volcanic plume to find the SO_2 cross section of the plume. The SO_2 cross section multiplied by the wind speed or plume velocity gives the SO_2 emission rate for that data set (See Appendix B for details of the algorithms used to calculate emission rates).

Table 2: Uncertainties in COSPEC data

Error Source	Pu'u O'o	Erebus	
		w/ video	w/o video
Windspeed / Rise Rate	± 15%	± 5%	± 10%
Distance to plume	± 10%	± 3%	± 3%
Scan Rate	± 2%	± 2%	± 2%
Data Reduction w/ ASPEC	± 2%	± 2%	± 2%
Cumulative Error (square route of the sum of the squares)	± 18%	± 7%	± 11%

Error is based on reproducibility, except distance and scan rate errors, which are best estimates.

Since 1988, the COSPEC has been automated by mounting the unit on a scanning head capable of operating in either sideways scan (pan) or vertical scan (tilt) mode. The scanner and the COSPEC have also been modified so their outputs interface with a portable lap top computer. The accuracy of COSPEC measurements prior to automation was commonly estimated to be ±15 - 40% (Stoiber, et al. 1983). The cumulative error has been greatly reduced by automation.

Modifications on the COSPEC

In order to facilitate the addition of a scanner and the interface with the computer, the COSPEC unit underwent a few minor modifications. Microswitches were installed on the High and Low Calibration cells of the instrument. The switches are read by the computer as digital inputs that sense whether or not the calibration cells have been inserted into the visual path of the COSPEC. An additional plug mounted on the COSPEC was used as the output to the computer for the voltage signal, the automatic gain control (AGC), two supplemental output signals of the COSPEC and the calibration microswitches.

In several cases, the output voltages from the COSPEC were too high to be input into the data acquisition card in the computer. Voltage dividers installed on these outputs reduced the output voltages to within acceptable levels.

The Scanning Head

A Pelco heavy duty scanning head used as a base for the COSPEC. It is a standard heavy duty scanner normally used in remote video surveillance systems. In this case, the scanner came equipped to operate in the pan mode but not in the tilt mode. The tilt mode is essential in cases such as that normally seen at Pu'u O'o, where the plume is blown by the wind and travels parallel to the ground. Vertical scans with the COSPEC are required to measure the plume perpendicular to its travel direction. Appropriate modifications were made to allow the automatic tilt mode of operation.

The angles over which the scanner can operate are variable and are manually set to accommodate the plume being measured. The scan rate is variable and can be continuously adjusted to operate at any speed between 0.2° and 2.0° per

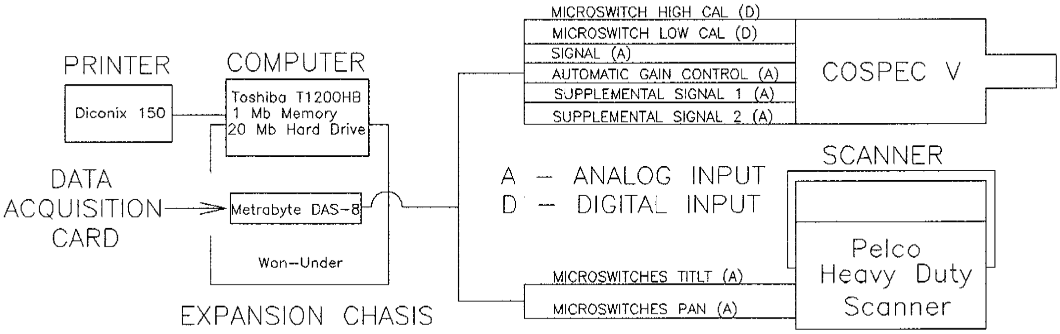

Figure 2: Schematic diagram of the automated COSPEC system.

second.

Microswitches on the scanner control the pan and tilt drives. Voltage dividers were connected to these switches which were then connected to the computer. The switches provide an analog voltage output that indicates the scanning direction. Changes in direction are sensed by the computer and used to calculate the scanning rate.

The disadvantage of the scanning apparatus is that it is heavy (nearly 30 kg) and requires a 120 Volt power supply (provided in our case by gasoline powered Honda generator).

The Computer

The outputs from the COSPEC (voltage output, AGC, outputs 1 & 2 and the microswitches on the calibration cells) and the scanner are fed as input into a computer through a Metrabyte DAS-8 data acquisition card. The card accepts three digital inputs and eight analog signals with voltages less than 10 V. The computer selected for the automation was a Toshiba T1200 HB with 20 megabyte hard disk. This computer was chosen on the merits of its portability and ability to operate on a 12 V power supply. This particular computer had no slots for standard IBM-compatible cards (e.g., the Metrabyte DAS-8 data acquisition card) required for the automation. To facilitate this card, a Won-Under expansion chassis was attached to the bottom of the computer.

Software programs were written by Dr. W.C. McIntosh to first acquire and then reduce the data collected using the COSPEC. The first of the programs (named COSPEC) is used to acquire the data and archive it in data files. The second program (named ASPEC) uses a two step process for the reduction of the archived data.

In the first step in data reduction, the ASPEC program searches the data file for calibration data sets. Calibrations sets may be either high (590 parts SO_2 per million-mass) or low (180 parts SO_2 per million-mass), and they occur sporadically throughout the data file, typically once every half-hour or once every 50 data scans. Calibration data is evaluated on the computer screen by moving the cursor (with a mouse) to the four corners of the calibration curve. The calibration values are then calculated based on the known concentrations of SO_2 in the calibration cells and output to a calibration data file.

The SO_2 output data then may be determined using the raw data from the data file and the input values of plume velocity and distance to the plume. SO_2 emission rate is calculated separately for each data set. The calibration value used in the calculation for SO_2 output is a time interpolation of the two nearest calibration measurements, since calibration data varies systematically with time.

The Fast Fourier Transform

The SO_2 emission data was then analyzed for periodic behavior using the Fast Fourier Transform Algorithm found in MathCad software. The transform takes oscillatory data sets measured at regular intervals over time and transforms them from time series to frequency series. The output of the data plots frequency against magnitude. The magnitude can be considered a rank of the power of the frequency with which it is associated, i.e., the higher the magnitude, the stronger the frequency in question. The designation high magnitude frequency will, for the purpose of this study, refer to a frequency whose magnitude is greater than the lowest 3% of the total range of magnitudes expressed by the Fourier Transform. Relatively few frequencies have amplitudes in this range.

CHAPTER 3: DEGASSING OF SULFUR DIOXIDE AT THE PU'U O'O VENT

Background Geology

The island of Hawaii is the southernmost and largest of the Hawaiian Island volcanic chain. The island consists of five volcanoes, of which Kilauea (lat. 19° 25' N; long. 155° 17' W) is the youngest and most active: The two oldest, Kohala and Mauna Kea, are both dormant; the younger volcanoes; Mauna Loa, Hualalai and Kilauea; have all been active during historical time (Wolfe, et al, 1987).

Kilauea volcano is situated on the east central part of the island (Fig. 3). It is a small basaltic shield volcano that consists of a summit caldera, the Halemaumau intra-caldera crater and two radially extending fissure zones known as the East Rift Zone (ERZ) and the South West Rift Zone (SWRZ). All historic activity has occurred on or along the rift zones (Greeley, 1974) (Fig. 4).

Inside Kilauea's summit caldera, Halemaumau crater has been the occasional site of an active lava lake. The existence of this lake has been documented between 1823 and 1924 (Brown, 1925); during 1952 (Eggers and Decker, 1969) and most recently accompanying an eruption in 1967-1968 (Connor, 1988). The sporadic presence of the lava lake may correspond to the development of the extensive underground magma conduit system that is currently active (Gerlach and

Graeber, 1985).

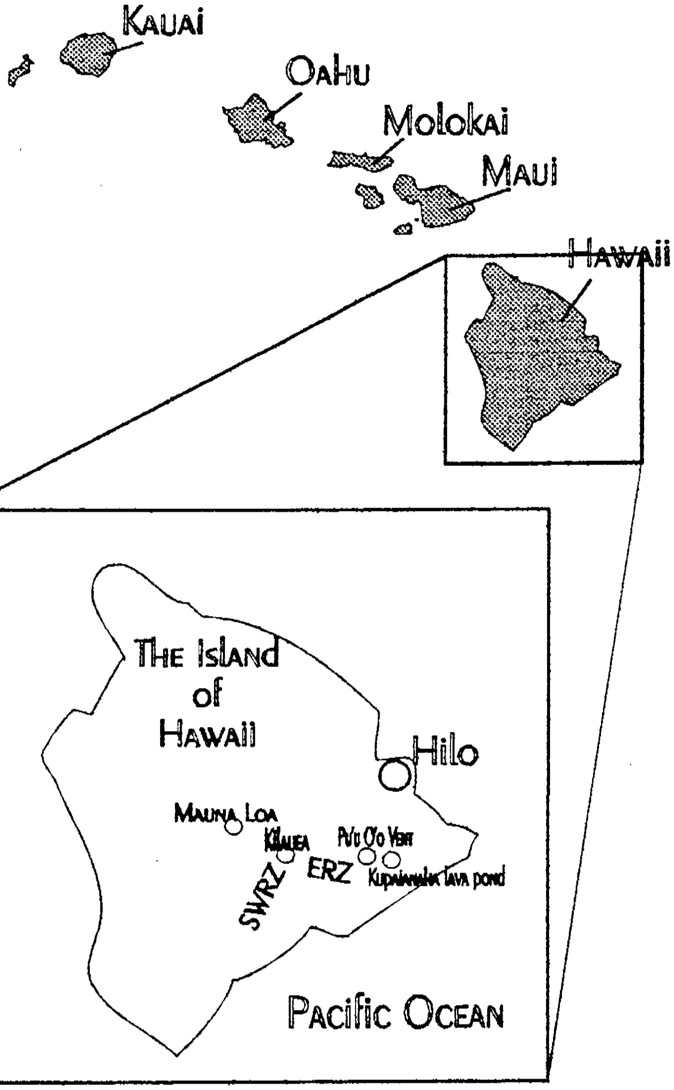

Figure 3: Location map showing the island of Hawaii, Kilauea and the ERZ.

The ERZ - Pu'u O'o Eruption: January 1983 - Present

The present phase of eruptive activity, known as the Pu'u O'o sequence, has been the longest and most voluminous in Kilauea's history. The current and ongoing activity on

Kilauea's east rift zone commenced 3 January 1983 with an eruption at Napau Crater (Fig. 4). This eruption re-opened the existing east rift conduit system and injected magma along the ERZ, resulting in fissure-style eruptive activity. By the fourth episode, eruptive activity became centralized, first at the 1123 Vent and then at Pu'u O'o Vent (Neal, et al, 1988).

Prior to the commencement of the eruptive sequence, a period of sustained summit inflation occurred during the autumn of 1982. Episode 1 began on 3 January 1983 and lasted approximately 9.5 hours. The end of episode 1 was marked by the start of re-inflation at the summit (Wolfe, et al., 1987). Subsequent eruptive episodes were characterized by high levels of harmonic tremor and subsidence (i.e., deflation at the summit). Low levels of harmonic tremor and summit inflation defined the repose periods between episodes.

During the first 41 eruptive episodes (January 1983 to January 1986) a cumulative volume of 470 x 10^6 m^3 of lava was extruded (Chartier, et al, 1988). The episodes characteristically consisted of about one day of high lava output from Pu'u O'o vent followed by an average of 25.5 days of repose (Chartier, et al, 1988). The eruptive activity at Pu'u O'o and along the ERZ through 1986 is well documented, and is the subject of USGS Professional Papers 1350 and 1463. Eruptive episode 48A commenced on 20 July

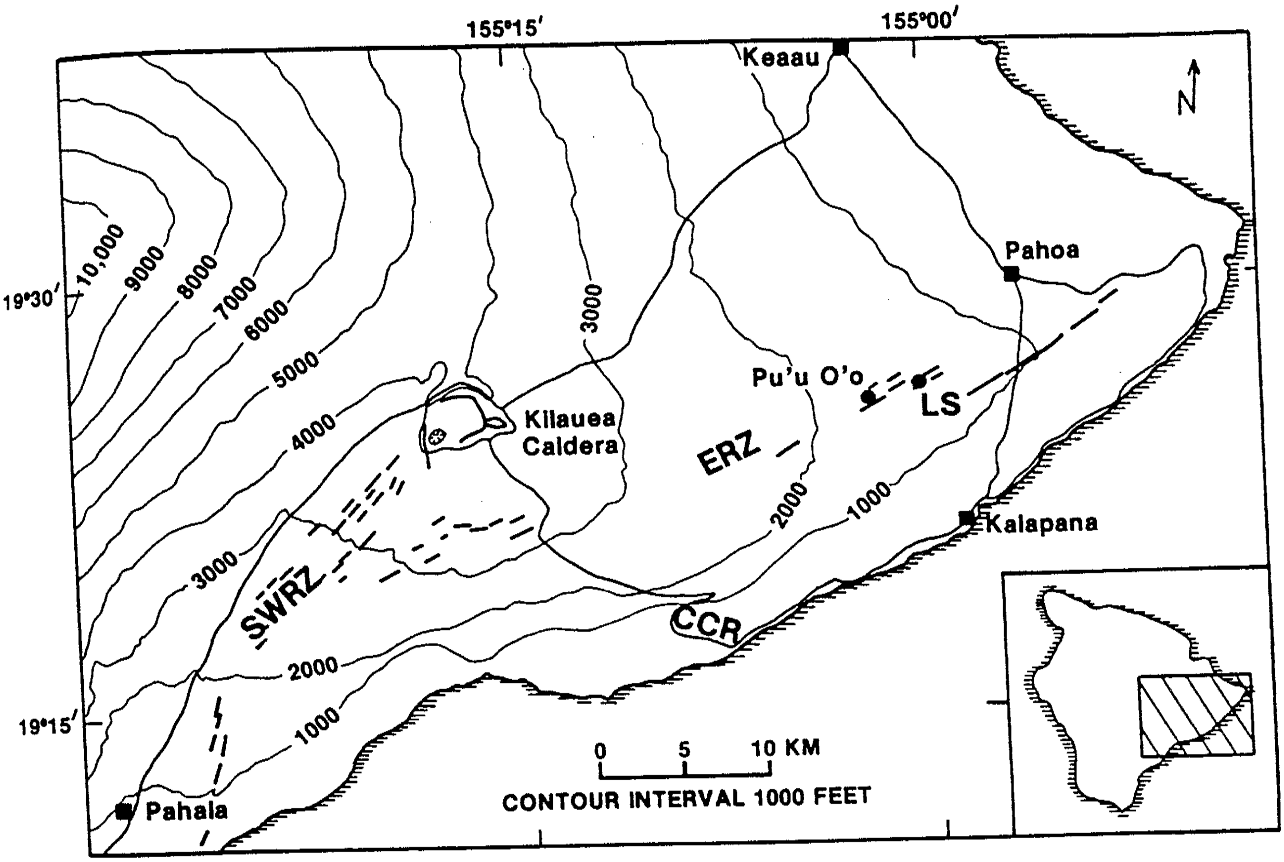

Figure 4: Kilauea's East Rift Zone(ERZ), Southwest Rift Zone (SWRZ) and Pu'u O'o Vent (modified from Casadevall, et al, 1987).

1986 and continued through 24 April 1988. After one week of quiescence, episode 48B began and continues as of this writing. Episodes 48 A & B marked a change in the eruptive behavior at along the ERZ, and are described below.

Marked changes in eruptive behavior occurred during 1986. Fissure eruptions up and down rift from Pu'u O'o Vent on 18 July 1986 resulted in the disruption of the Pu'u O'o conduit system. By 20 July, the eruption site migrated 3 Km down rift to Kupaianaha where continuous daily output of 0.5 x 10^6 m of lava formed a lava shield containing an active lava pond (Bulletin of Volcanic Eruptions, No. 26, 1986).

By January 1987, lava reoccupied a tube system that extends SE from the shield (SEAN Bulletin, V. 12, No.1, 1987). Outbreaks from this system were accompanied by 365 m lava fountains produced by tube fed flows. Continuing activity developed a new tube system along the west side of the shield. The majority of volume added to the lava shield was added through the tube fed flows, as opposed to lava pond overflows (SEAN Bulletin, V. 12, No.1, 1987). By May 1987, above-ground and subterranean tube systems finally allowed lava to reach the ocean, producing steam clouds, black sands and pillow lavas (SEAN Bulletin, V. 12, No. 5, 1987). Lava flow reached a steady output of approximately $0.5 * 10^6$ m^3 per day (SEAN Bulletin, V. 12, No. 9, 1987). The shield produced by these flows as they entered the ocean became known as Kupaianaha shield (SEAN Bulletin, V. 13, No. 4, 1988).

The level of lava that occupied Pu'u O'o crater and Kupaianaha lava pond dropped dramatically on 24 April 1988. Activity along the entire system quieted until 1 May, when lava re-entered Pu'u O'o crater, marking the beginning of eruptive episode 48B (SEAN Bulletin, V. 13, No. 4, 1988). Through continuous lava flow the tube systems became quite well developed and provided the route for 70 - 80% of the lava from Kilauea that reached the sea (SEAN Bulletin, V. 14, No. 1, 1989). The development of these tube systems resulted in diminished but sustained activity at Pu'u O'o vent. The activity that characterized the steady state of this eruptive episode included occasional lava breakouts that resulted in some surface activity and collapses in the tube system (SEAN Bulletin, V. 14, No. 4, 1989). Seismic activity was characterized by short periods of gas pistoning and relatively steady harmonic tremor (SEAN Bulletin, V. 14, No. 4, 1989). Eruptive episode 48B continued in a similar manner through the remainder of 1989 (SEAN Bulletin, V. 14, No. 12, 1989), and continues to date.

RESULTS

SO_2 Emission Data

The automation of the COSPEC and the improved techniques developed to calculate SO_2 emission rates allow more SO_2 flux measurements to be made per hour with greater precision than ever before. In four separate days of data collection at the Pu'u O'o Vent, 1008 usable scans were made with the COSPEC over a period of 22.75 total hours (Table 3). This corresponds to a rate of over 40 scans per hour compared to an optimum rate of 15-20 scans per hour using the manual technique. This proliferation of SO_2 emission data provides a statistically more accurate description of the actual amount of SO_2 emitted from Pu'u O'o.

Bright sun and clear atmospheric conditions are required for COSPEC operation and video determination of the plume velocity. COSPEC measurements, therefore, could not be taken all day, every day during the study period.

Wind conditions (Table 4) varied from zero velocity (a vertically rising plume) on the morning of 18 March 1989 to light winds from the south and southwest (Kona winds) on the afternoon of 18 March and all day on 19 March. The slightly stronger trade winds from the north and northwest prevailed on 21 and 22 March (Table 4). COSPEC measurements were made simultaneously at Pu'u O'o vent (Table 3) and along Chain of

Craters Road (COSCHAIN data) (Table 5) using the vehicle mounted scan technique described by Stoiber, et al, (1982) during trade wind conditions on 20, 21, and 22 March 1989 (Stokes, unpublished data). The COSCHAIN measurements record SO_2 emissions along the entire ERZ, including the Pu'u O'o vent, Kupaianaha Lava Lake and all fissure vents.

Table 3: Daily Average SO_2 emissions (Mg/day) from Pu'u O'o: March, 1989

	18 Mar.	19 Mar.	21 Mar.	22 Mar.
time	14.28-16.80	8.55-17.12	10.57-17.09	9.61-14.75
ave.=	109.52	192.59	552.66	402.63
std=	25.19	90.40	190.58	119.36
scans=	130	475	196	207
min.=	56	24.2	141.2	142.2
max.=	183	462.3	1167.9	828.4
wind	Kona	Kona	trade	trade

Average SO_2 emission rate during 1) Kona winds: 194 ± 84; 2) trade winds: 475.6 ± 175.

Table 4: Wind Conditions at Pu'u O'o

18 March - 22 March 1989

Date	Average Velocity (m/sec)	Minimum Velocity (m/sec)	Maximum Velocity (m/sec)	Direction of Origin
18 March	3.9	3	4.6	Kona (150-190)
19 March	3.5	2.9	3.7	Kona (140-190)
21 March	5	4	6.2	Trade (350-010)
22 March	4.6	4	5.4	Trade (000-020)

Plume and light conditions during the early morning hours were generally not good enough to make reasonable COSPEC measurements. Measurements made before 9:30 A.M. were discarded prior to calculating average emission rates. All the data sets also included some periods where either the plume was obscured by clouds or the COSPEC mechanisms were behaving erratically. The output from the COSPEC during these periods of erratic behavior was indecipherable and the readings taken during these times was discarded. These periods appear as obvious gaps in the graphs depicting the SO_2 emission data (Figs. 8-14). In all cases, these

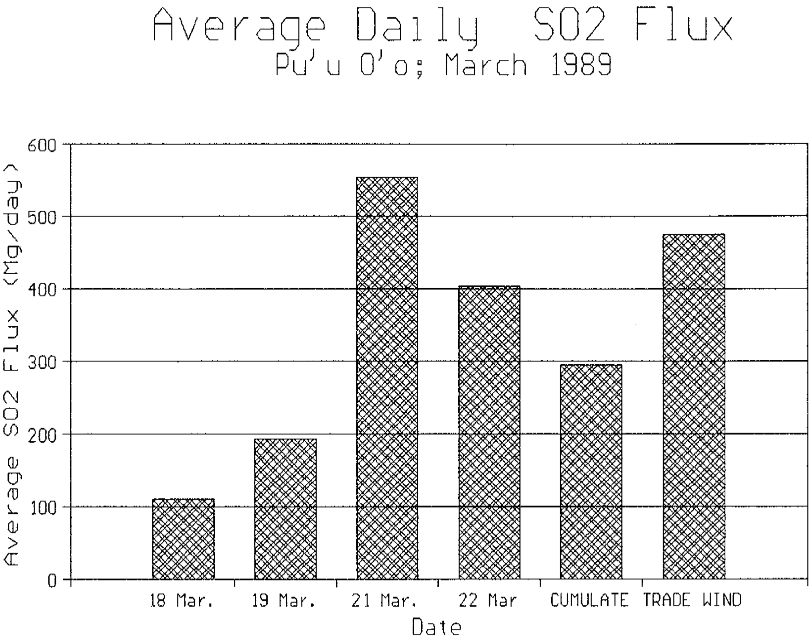

Figure 5: Daily SO_2 emission averages for Pu'u O'o vent, Mar., 1989. The cumulate average takes all measurements into account. The trade wind average uses only data collected on 21 and 22 March.

gaps and omissions occur over short periods relative to the time interval over which the entire data set was collected. They should not affect the accuracy of the average emission rates for the purposes of this study. Where large gaps occurred, data sets were broken apart for FFT analysis.

Despite the great amount of data gathered to estimate the SO_2 emission at Pu'u O'o, standard deviations range from 23 to 47 % of the daily averages. These high standard deviations result form emissions being released in discrete bursts, a phenomenon known to volcanologists as "puffing". Puffing is observed not only at Kilauea, but also at other volcanoes including Mount Erebus. The phenomenon is not well understood, although it is most likely due to vesiculation and bubble growth in magma (Wilson and Head, 1981; Sparks, 1980). These fluctuations, or puffs, can alter the measured flux rate of SO_2 from a vent by up to hundreds of Mg/day within minutes.

The average emission rate for the period 18 to 22 March, 295 ± 197 Mg SO_2 per day, has a extremely high standard deviation of 67%. The data gathered on days when the prevailing winds were from the south (Kona winds) display emissions of less than one half of those measured when the prevailing winds were from the north.

The direction that the COSPEC is aimed during trade winds, may cause the instrument to pick up an additional SO_2 signal from the Kupaianaha Lava Lake, located several kilometers to the northeast of Pu'u O'o vent. The measurements made during trade winds should therefore be considered as somewhat inflated due to this factor. The geographical difference between measurements made during trade winds and measurements made during Kona winds may reasonably lead to the assumption that measurements made during Kona winds represent a more realistic estimate of the SO_2 output from the Pu'u O'o vent alone. The average for all measurements taken during Kona

Table 5: SO2 Emission Rate Measured Along Chain of Craters Road
Spring, 1989

Date	Time	Rate (Mg SO2/day)
20 Mar. 89	16:21	2172.77
	16:55	1076.73
	17:09	486.68
	17:26	1050.31
	17:45	1736.13
	Average	1304.52 ± 587
21 Mar. 89	12:40	1458.42
	13:01	2246.09
	13:33	1691.23
	13:47	1040.48
	14:03	1738.59
	16:25	573.14
	16:41	1388.37
	Average	1448.05 ± 495
22 Mar. 89	11:00	2024.25
	11:24	1265.27
	12:26	2700.71
	12:54	2295.74
	13:13	1949.51
	13:33	954.25
	14:10	1176.60

Table 5: SO2 Emission Rate Measured Along Chain of Craters Road
Spring, 1989

Date	Time	Rate (Mg SO2/day)
	14:30	1789.14
	14:51	1557.36
	15:35	1037.19
	16:00	1778.58
	16:29	401.33
	Average 1577.49 ± 614	
12 April 89	10:58	319.60
	13:04	1692.21
	13:41	3705.28
	14:12	745.14
	14:49	1756.70
	15:14	3384.94
	Average 1933.98 ± 1248	
		Cumulate Average 1573.09 ± 787

wind conditions during the study period is 193 ± 84 Mg SO_2 per day. This average will be considered the best estimate for emissions from the Pu'u O'o vent during the study period. The average SO_2 emission during trade winds, 475 ± 175 Mg/day is probably inflated due to the presence of Kupaianaha lava pond. It could, however, be considered a maximum for SO_2 output from Pu'u O'o vent.

On 20, 21, and 22 March, and 12 April, 1989, compatible SO_2 emission measurements were made using a vehicle mounted COSPEC and the techniques described by Casadevall (1987). Utilizing these methods, the COSPEC is aimed out the vehicle window and scans as the vehicle is driven at constant speed under the plume along Chain of Craters Road. This technique allows the emission rate of the entire ERZ, of which Pu'u O'o vent is a part, to be calculated. Since each measurement taken in this manner required nearly a half an hour to complete, relatively few measurements were made each day. The emission rates for the ERZ based on these measurements are summarized in Table 5.

It is important to note that the standard deviation associated with the measurements made along Chain of Craters Road is very high (50%). These measurements cannot be strongly affected by "puffing", since the time taken for each measurement is long (20 - 30 minutes) relative to the period associated with the puffs (1 - 3 minutes). The large error can only reflect large scale changes in either the emission rate or the physical conditions under which the measurements are made. Since wind velocity measurements are made only once per measurement, and the measurements are taken over a considerable area, it is very possible that wind conditions may have changed drastically throughout the course of one measurement. There may be eddies in the wind velocity, or drafts and breezes generated by geographical constraints that affect the measurement. It is also reasonable to suspect that in some cases the plume has stagnated or even doubled back on itself during the course of measurement. It is therefore logical to suggest that at least some of the measurements presented in Table 5 are overestimates due to meteorological conditions. The average emission rate of 1573 ± 787 Mg/day may be inflated and should only be used bearing these circumstances in mind.

Periodicity in Hawaii Data

The puffing of the gaseous plume at many volcanoes, including the Pu'u O'o vent of Kilauea presents large amplitude, short period cyclicities in the SO_2 emission data. This periodicity results in a dramatic change from maximum SO_2 output to practically zero within only a few minutes time. This puffing is difficult to explain since there is little known about the actual physical conditions present and the processes active inside a magma chamber.

The puffing characteristic is most likely due to the volatilization of gaseous components in the magma once pressure and temperature conditions are such that they exsolve. The gas exsolving from the magma forms bubbles that somehow coalesce and grow (Wilson and Head, 1981). The larger bubbles migrate to the surface and eventually escape from the magma. This process continues until the magma in the zone of exsolution becomes depleted in volatile components, thereby becoming denser than its volatile rich counterpart below it. The denser magma sinks, and is replaced by "fresh" magma (Fig. 6). This convective process may be the explanation for longer term periodicities in the SO_2 emission data.

Periodicities that are longer than the high amplitude, high frequencies caused by sort term puffing are also noted in most data sets (Figs. 7-15). These periodicities are of great importance in studying the longer period convective processes active in volcanoes. Periodicities of both short (minutes) and medium (hours) lengths are discussed in this section.

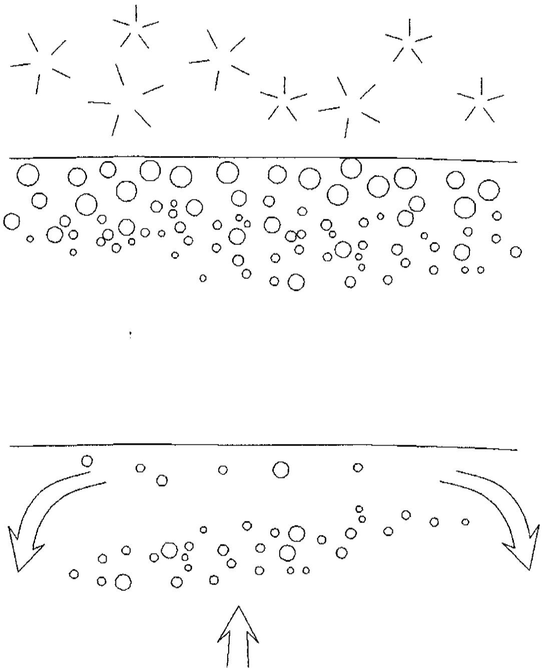

Figure 6: Volatilization of gases in magma as a possible explanation for cyclic behavior in SO_2 emissions. Exsolution results in the depletion of magma in volatiles. Denser, depleted magma sinks.

Collecting SO_2 measurements at both a high rate and for prolonged periods of time (several hours at a time) allows for an examination of any periodic trends that may occur in the data set. Periodicity is visually apparent based on the regular, discrete bursts seen in the emissions at Pu'u O'o Vent. Mathematical methods (the Fast Fourier Transform Algorithm) were used to identify any true periodicities in the data sets.

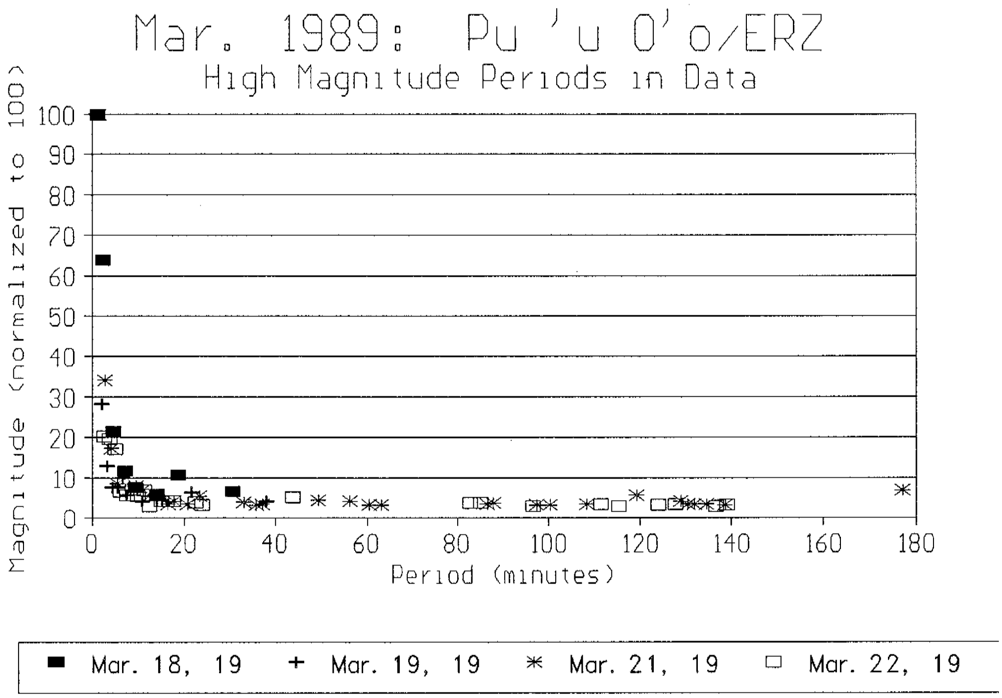

Figure 7: Graphical depiction of the high magnitude cyclicities seen during the period 19-22 Mar. 1989, at Pu'u O'o Vent, ERZ, Hawaii. Amplitude for all data has been normalized to 100 as a maximum.

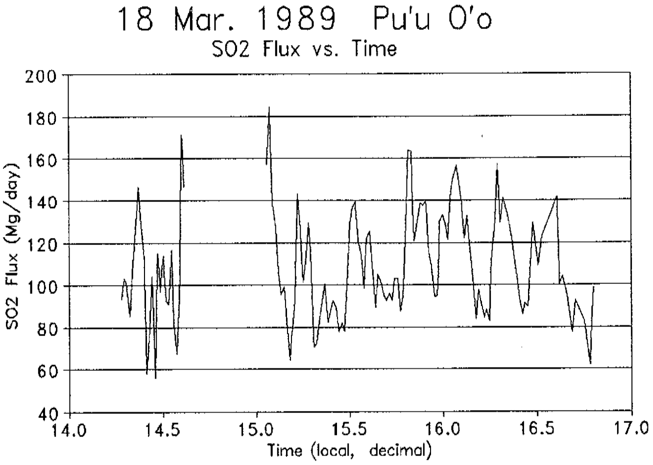

Figure 8: SO_2 emission from Pu'u O'o vent measured 18 Mar. 1989.

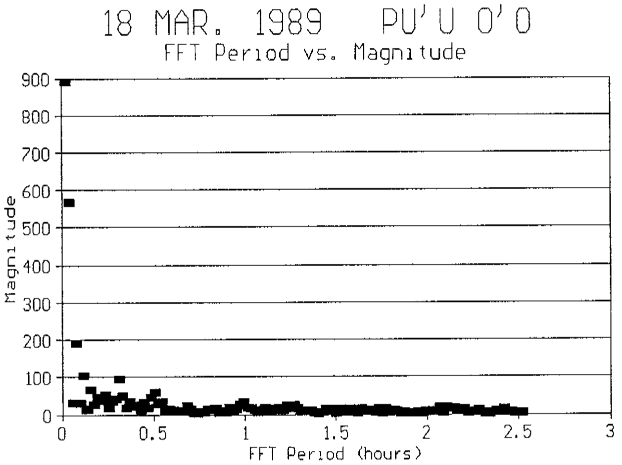

Figure 9: Fourier Transform of SO_2 emission vs. time for data collected at Pu'u O'o vent, 18 Mar. 1989.

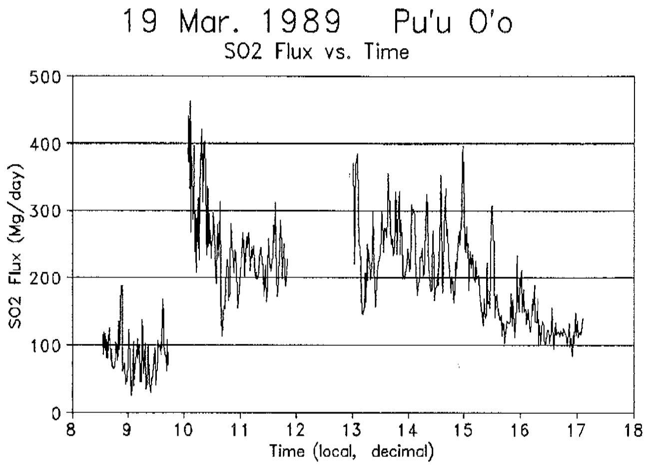

Figure 10: SO_2 emission from Pu'u O'o vent measured on 19 Mar. 1989.

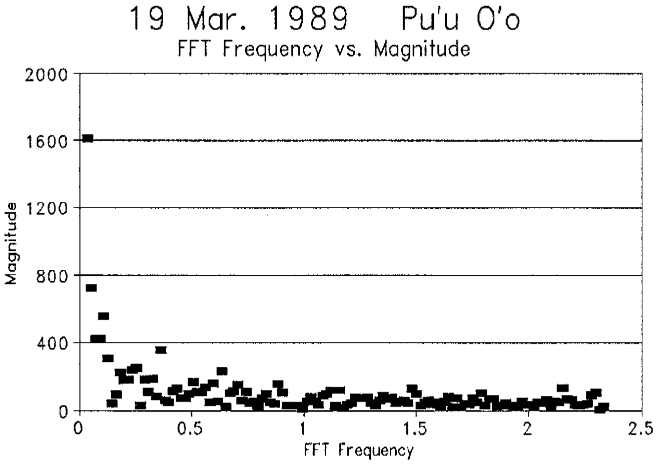

Figure 11: Fourier Transform of SO_2 emission vs. time for data collected at Pu'u O'o Vent, 19 Mar. 1989.

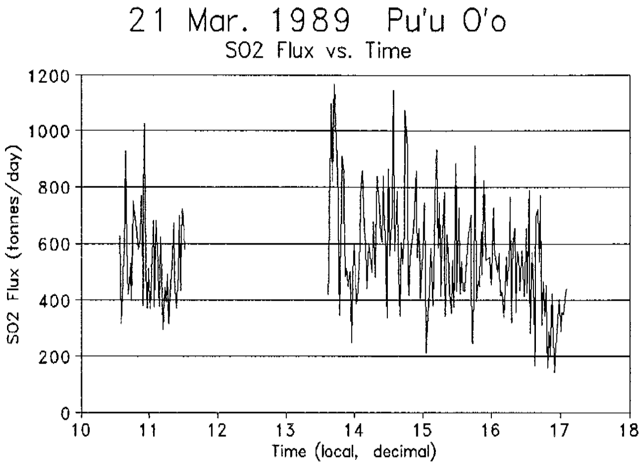

Figure 12: SO_2 emissions from Pu'u O'o vent, measured 21 Mar. 1989.

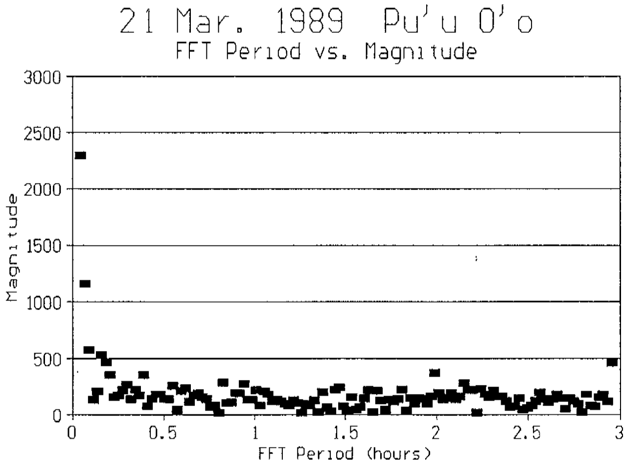

Figure 13: Fourier Transform of SO_2 emission vs. time for data collected at Pu'u O'o vent, 21 Mar. 1989.

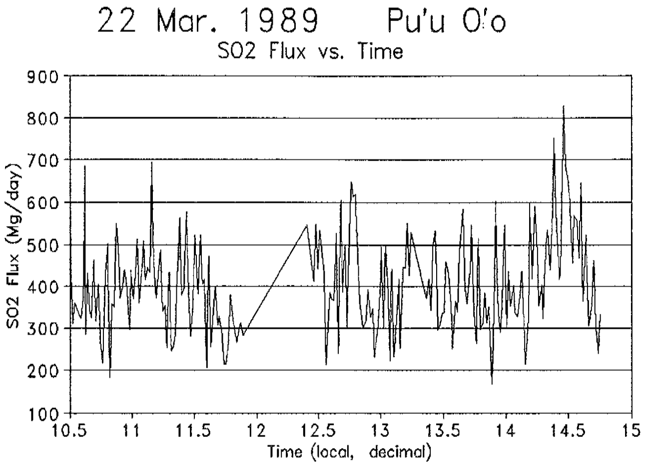

Figure 14: SO_2 emissions from Pu'u O'o Vent, measured 21 Mar. 1989.

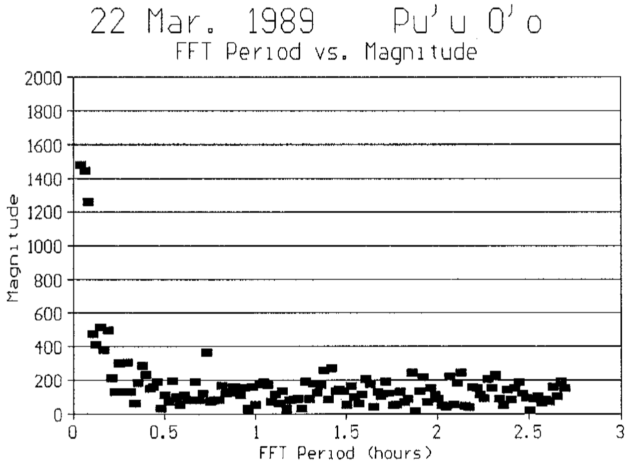

Figure 15: Fourier Transform of SO_2 emission vs. time for data collected at Pu'u O'o vent, 22 Mar. 1989.

The periodicities with the highest magnitudes in all the data sets occur at the shortest period (the sampling interval) and are probably due to the large minute to minute fluctuations in SO_2 output brought about by volcanic puffing. There are other fluctuations that appear in the data as well. Strong periodicities of between 6 and 10 minutes occur in all the data sets. Additionally, relatively strong periods of 1) 13 and 29 minutes occur on 18 March (Figs. 10, 11); 2) 22 minutes occurs on 19 March (Figs. 12, 13); 3) 23 minutes and also 177 minutes occur on 21 March (Figs. 14, 15) and 4) 17.5 and 44 minutes occur on 22 March (Figs. 16, 17).

The high magnitude periods in the data may give valuable insights to the subsurface geometry and the dynamics of magma movement through the Pu'u O'o conduit system. The length of the period may reflect the time required for the convective overturn of magma in the conduit system. During times of effusive eruption (e.g., episode 48B) the periods of gas emission probably depend mainly on the magma supply rate and the paths along which magma travels through the conduit system. Not enough information regarding the specific geometry of the conduit systems that make up the rift is available to make any conclusive statements at this time.

The Evolution of Pu'u O'o and the ERZ

Since the commencement of the Pu'u O'o eruptive sequence in 1983, SO_2 output has been measured regularly at Kilauea's summit, along the ERZ, and at the Pu'u O'o vent (Table 6). SO_2 emissions at Kilauea's summit showed an increase prior to the start of the sequence. This increase probably indicates an increased magma supply rate to the summit chamber where equilibrium pressure conditions are low enough (<100-150 m lithostatic) that significant sulfur exsolution takes place (Gerlach, 1986; Greenland, et al, 1989).

Since the onset of the Pu'u O'o Eruptive sequence, most of the SO_2 emissions are measured along the ERZ and a relative decrease in summit emissions has been noted. ERZ SO_2 emissions increased significantly and are now responsible for 3-4 times the SO_2 emitted from the summit (Andres, et al, 1990).

The COSPEC measurements made simultaneously at Pu'u O'o and along the Chain of Craters Road (COSCHAIN) indicate that Pu'u O'o emits about 30% of all the SO_2 from the ERZ. The measurements taken along Chain of Craters Road represent the sum of all vents along the ERZ, including Pu'u O'o vent, Kupaianaha lava pond and all other lava flows, vents and fumaroles along the rift.

No other studies include simultaneous measurements from the Pu'u O'o site and Chain of Craters Road, although both stationary measurements at Pu'u O'o and vehicle mounted Chain of Craters Road measurements were made during episode 48A, in the autumn and winter of 1986. The 1986 average

Table 6a: SO_2 at Kilauea's Summit:

SO2 Output	Date	Comment	Ref.
170 ± 50	1979-1982	One Erz and Two Summit Eruptions	1
260 ± 90	1983-1984	Beginning of ERZ Eruptions	1
290 ± 80	1984-1986	ERZ Eruptions - pre 48A	2
340 ± 90	1986-1988	Concurrent with episode 48A	2
380 ± 90	1988-	Concurrent with episode 48B	2

Table 6b: Pu'u O'o Vent Only:

SO2 Output	Date	Comment	Ref.
5100-32000	1983-1984	High-fountaining Episodes	1
20-260	1983-1985	Interphase Emissions	1,2,3
650	9/86	Episode 48A	4
500	1/87	Episode 48A	4
730 ± 150	1986-1988	Episode 48A (Kupaianaha)	2
880 ± 200	1988-1989	Episode 48B (Kupaianaha)	2
295 ± 197	3/89	Episode 48B	5

Table 6a: SO_2 at Kilauea's Summit:

SO2 Output	Date	Comment	Ref.
Table 6c: Chain of Craters Road (Entire ERZ)			
1170 ± 400	10/86-11/86	COSCHAIN Data Episode 48A	4
1573 ± 787	3/89-4/89	COSCHAIN Data Episode 48B	2

References:

(1) Casadevall, et al, 1987.

(2) Stokes, unpublished data.

(3) Chartier, et al, 1988.

(4) Andres, et al, 1990.

(5) This Study.

emission along Chain of Craters Road was 1170 ± 400 Mg SO_2 per day during October and November. Measurements made at the Pu'u O'o site taken in September 1986 and January 1987 gave averages of 650 Mg per day and 500 Mg per day, respectively [Note: These measurements were taken during trade winds and therefore likely overestimate the output] (Andres, et al, 1990). These measurements indicate that the Pu'u O'o vent emitted approximately half of all the SO_2 attributed to the ERZ, and compare favorably to the ratio of 30% found in this study.

Relationships between pressure, density and depth in the Pu'u O'o conduit have been analyzed during high fountaining eruptive activity using the solubilities of H_2O,

CO_2 and SO_2 in magma (Greenland, et al 1989). The lower limit imposed by pressure constraints for the exsolution of these volatiles is 520 m lithostatic (15 bars). Due to gases exsolving at depths less than 520 m below the Pu'u O'o crater the rapid increase in volume disaggregates the magma. After eruption, the upper 520 m of Pu'u O'o's conduit becomes filled with degassed magma that has fallen back into the conduit.

As an upper limit, pressures greater than 400 bars (2170 m) allow very little gaseous exsolution. In other words, the SO_2 measured at Pu'u O'o comes only from magma that exists between 520 and 2170 m below the crater.

Based on the consistency in SO_2 emission rates cited by three independent sources, Greenland, et al (1985), determined that the degassing rate of Hawaiian basalts is 3 kg SO_2 per m^3 magma and remains constant over time. Using the technique described by Greenland,et al (1989), and an average rate of 475 Mg/day at Pu'u O'o and 1573 Mg/day for the ERZ, magma supply rates have been calculated as $0.177 * 10^6$ and $0.594 * 10^6$ m^3/day, respectively (Greenland, et al, 1985; Chartier, et al, 1988).

Based on inter-episode SO_2 emission measurements, Greenland, et al (1989) estimated the volume of the conduit below Pu'u O'o as $2.6 * 10^6$ m^3. If, at Pu'u O'o, magma is indeed degassing at $0.177 * 10^6$ m^3/day, then the conduit must be flushed and replenished once every 15 days. During the current phase of activity, magma travels along under the ERZ at three times the inter-episode rate proposed by Greenland (1989). The volume of magma that apparently does not pass under Pu'u O'o may indicate that different conduit system, bypassing Pu'u O'o entirely, has developed, or that magma passes under the vent at a rate to high enough that most of its volatiles are retained. This estimation assumes, however, that there is no difference in magmatic character between periods of eruptive and effusive volcanic activity, and by that token may be an over-simplification.

Annual Atmospheric SO_2 Budget for the ERZ

Since the current eruptive style along the ERZ is a departure from the normal activity from 1983-1986 a re-evaluation of the sulfur budget is in order. Based on SO_2 output of 193 Mg/day at Pu'u O'o and 1573 Mg/day along the ERZ, and assuming these rates have remained more or less constant during episode 48B, annual SO_2 emissions are 0.107 Tg/year at Pu'u O'o and 0.575 Tg/year along the ERZ. The ERZ output corresponds to 3.8% of the global volcanic SO_2 output of 15.2 Tg/year as suggested by Berresheim an Jaeschke, (1983) or 3.1% of Stoiber et al's (1987) estimation of 18.7 Tg/year. This represents a slight increase from the annual budget of 0.5 Tg/year estimated by

Chartier (1986) and extends a continuous increase in Kilauean SO_2 output since January 1983 (Fig.7).

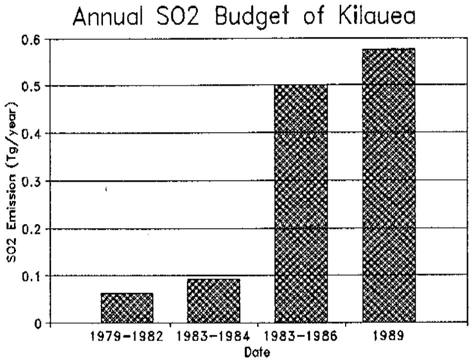

Figure 16: Annual SO_2 gas output from the ERZ, based on daily output rates presented in Table 6.

Despite the increase in SO_2 flux, the long term climatic effects are negligible because these outputs still only represent about 0.2% of the annual flux of SO_2 into the atmosphere from all sources (Cullis and Hirschler, 1980). Furthermore, unless large amounts of SO_2 are injected into the stratosphere, climactic impact is negligible. Few basaltic volcanic eruptions inject significant amounts of SO_2 past the tropopause (Self and Rampino, 1988). Locally, however, wet and dry deposition (Appendix A) of sulfate and sulfur rich volcanic ash has resulted in acid rain: Rainwater with pH as low as 3.0 and 3.6 was observed near Halemaumau near the summit (Harding and Miller, 1982). Acid rain has resulted in the leaching of lead from painted rain-catchment-systems, thus contaminating some private water supplies.

CHAPTER 4: SULFUR DIOXIDE EMISSIONS AT MOUNT EREBUS, ANTARCTICA

BACKGROUND GEOLOGY

Mount Erebus, Ross Island, Antarctica, 3794 m, 77.58° S, 167.17° E is the southernmost active volcano in the world. The summit crater of this composite intraplate strato-volcano is 550-m in diameter, 120-m deep. It contains an inner crater of 220-m diameter and 95-m depth. Small strombolian eruptions occur daily from the anorthoclase phonolite lava lake. The active, convecting lava lake was first discovered in 1972 (Giggenbach, et al, 1973) making Erebus host to one of a very limited number of such features in the world. The lava lake at Erebus is the only known phonolitic lava lake.

Since the discovery of the lake, its size has been monitored annually. Areal increases in lake size were seen annually between 1972 and 1978 (Kyle, et al, 1982), at which time the lake size stabilized and remained constant until 1984. The motion of the lava in the pool(s) in the summit crater are characterized by either slow convective movement or explosive eruptive activity. Eruptions range from strong explosions that emit ash and bombs through weak explosions brought on by bubble ruptures within the lake. Non-explosive eruptions that emit dark ash from vents on the

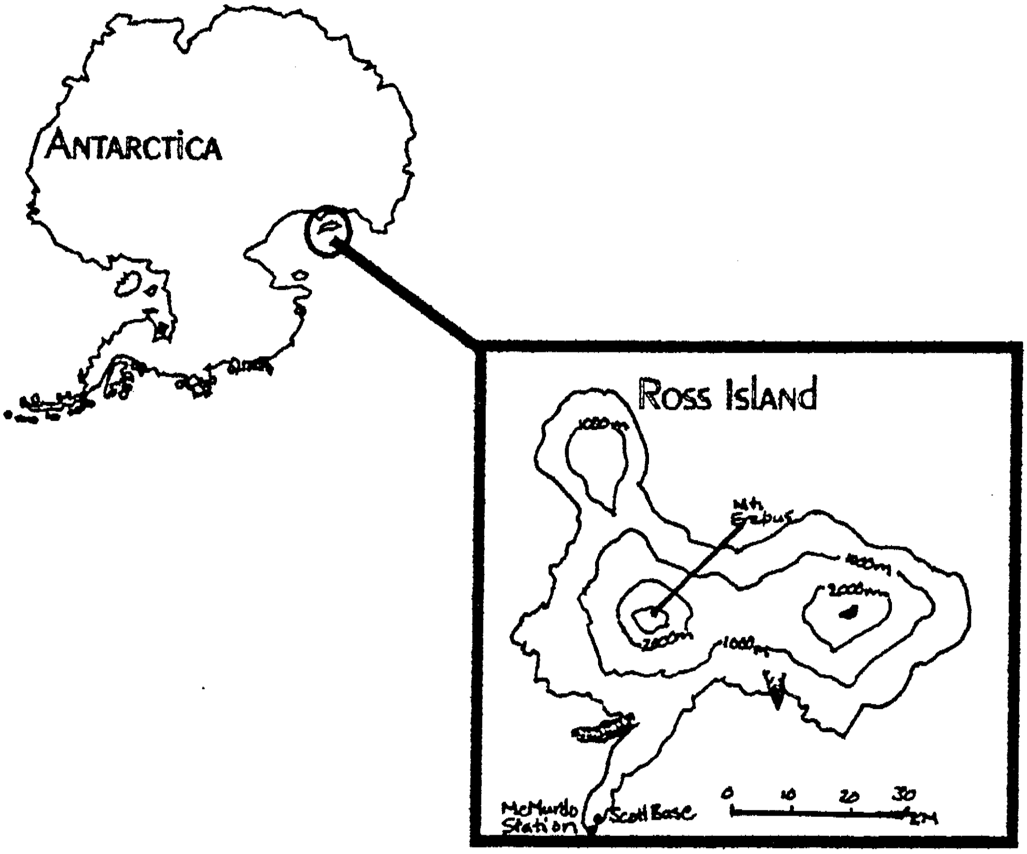

Figure 17: Location map of Mount Erebus. Erebus is situated on Ross Island, Antarctica, about 30 km away from McMurdo Station.

side of the lake are also common (Dibble, et al, 1988).

Sixty to 150 seismic daily events, as well as several annual earth quake swarms (250 or more seismic events per day) occurred between December 1980 and August, 1984 (Kaminuma and Shibuya, 1987). Small strombolian eruptions occurred at a rate of 2-6 per day from 1972 until 1984

(Kyle, et al, 1982; Dibble, et al, 1984) and often spewed bombs and ejecta onto the crater rim. On 13 September 1984, stronger strombolian eruptions were heard, seen, and recorded at Scott Base and McMurdo Station, 37 km away. Such violent activity had not been observed since the first observed volcanic activity at Erebus in 1841 (Giggenbach, et al., 1973). During the ensuing four months, bombs up to 10 m diameter were ejected up to 2 km from the vent. Bombs and other ejecta engulfed Erebus' inner crater and buried the lava lake. Beginning in early 1985, seismic activity has decreased to less than its pre-1984 level (Kaminuma and Shibuya, 1987). The lava lake has gradually exhumed itself and has shown annual areal increases with an except during 1988, when the area of the lake as well as the SO_2 emission rate decreased by 36%.

The position of the lava lakes and the "active vent" are in similar configurations as prior to September 1984. Chemical and mineral analysis indicated that no change in the composition of the anorthoclase phonolite magma has occurred since 1972 (Caldwell, et al, 1989). There have been no indications that the conduit system beneath Erebus has been altered in any way. Therefore,it may be considered stable and well developed during the study period.

SO_2 Emission Measurements

SO_2 emissions were measured and analyzed on four separate days during 1987, four days during 1988 and five days during the 1989 field season. During 1987, 327 hand scan measurements were made over a total of 19 hours; a rate of 17 measurements per hour. In 1988, with the advent of the automated COSPEC a total of 941 measurements were made in 22 hours, resulting in a scan rate of 43 measurements per hour. The 1989 data set is made up of 1405 scans made over 31.5 hours of collection time, thus averaging 45 scans per hour. All data was measured with the COSPEC operating in either manual (1987) or automatic scan made. Measurement of SO_2 emission required a vertically rising plume and clear sky as a background for the plume.

Occasional lapses in the background clarity or temporary mechanical malfunctions in the equipment appear as gaps in the graphical display of the data (Figs. 18, 20, 22). These gaps are small relative to the length of the data sets (except in 1987), and therefore should not have had significant affect on the daily or annual SO_2 emission rates. For the purpose of using the fast Fourier Transform algorithm, short gaps in the data set that resulted form instrument calibration are changed to the standard interval of sampling for the data set.

During 1987, SO_2 emissions were measured on 7, 8, 12, and 16 December. The data collected on the eighth was collected over a period of 14 hours, and therefore should reflect emissions for the entire day (Table 7). The data collected on 7, 12, and 16 December was done over time intervals of 2 to 4 hours, and therefore may not actually represent the emission for its representative day. All the data collected are within statistical agreement.

The cumulative average SO_2 emission rate for all the data measured in 1987 was 44.2±26.6 Mg/day. The standard deviations for average daily output ranged from 30.9% to 51.8%, the average standard deviation for these data (weighted based on the number of measurements made each day) is 49.6% (Table 7; Fig. 18).

During 1988, measurements were made on four days; 14, 16, 17, and 21 December. The averages of 3 of the 4; Dec. 14, 16, and 21; agreed very well at 25-29 Mg SO_2/day. Measurements made on 17 Dec. reflected relatively low emissions, with an average of 3.4 Mg/day. The data collected on the seventeenth was collected when the plume was barely visible, although clear sky and windless conditions prevailed. The low readings were made over a period of 2 hours and are not in statistical agreement with the other measurements made in 1987. This may have been due to atmospheric mixing below the scan height, resulting in the plume "boiling over" the rim. These measurements were not included in the calculation of the cumulative average emission rate estimate for the study period.

The cumulative average for all the 1988 data is 27.3±9.2 Mg SO_2/day (standard deviation of 34%). The 1988 daily averages had standard deviations ranging from a low of 27.1% to a high of 52.3%. The weighted standard deviation is 36.8% (Table 8; Fig. 20).

Measurements were made on five days in 1989; December 3, 11, 18, 20 and 21. The average daily emissions calculated from measurements made on the 3, 18, 20, and 21 agree remarkably well, between 48 and 55 Mg SO_2/day. The average for 11 December is higher than the rest at 93.2±27.0 Mg/day. All the data was measured over time intervals greater than five hours, thus using them to estimate daily average emission rates is reasonable.

The standard deviations in the 1989 data ranged from 29.0% to 42.5%, the weighted standard deviation is 38.4%; the cumulative average is 59.3 ± 27 Mg SO_2/day (standard deviation of 45.7%) (Table 9; Fig. 22).

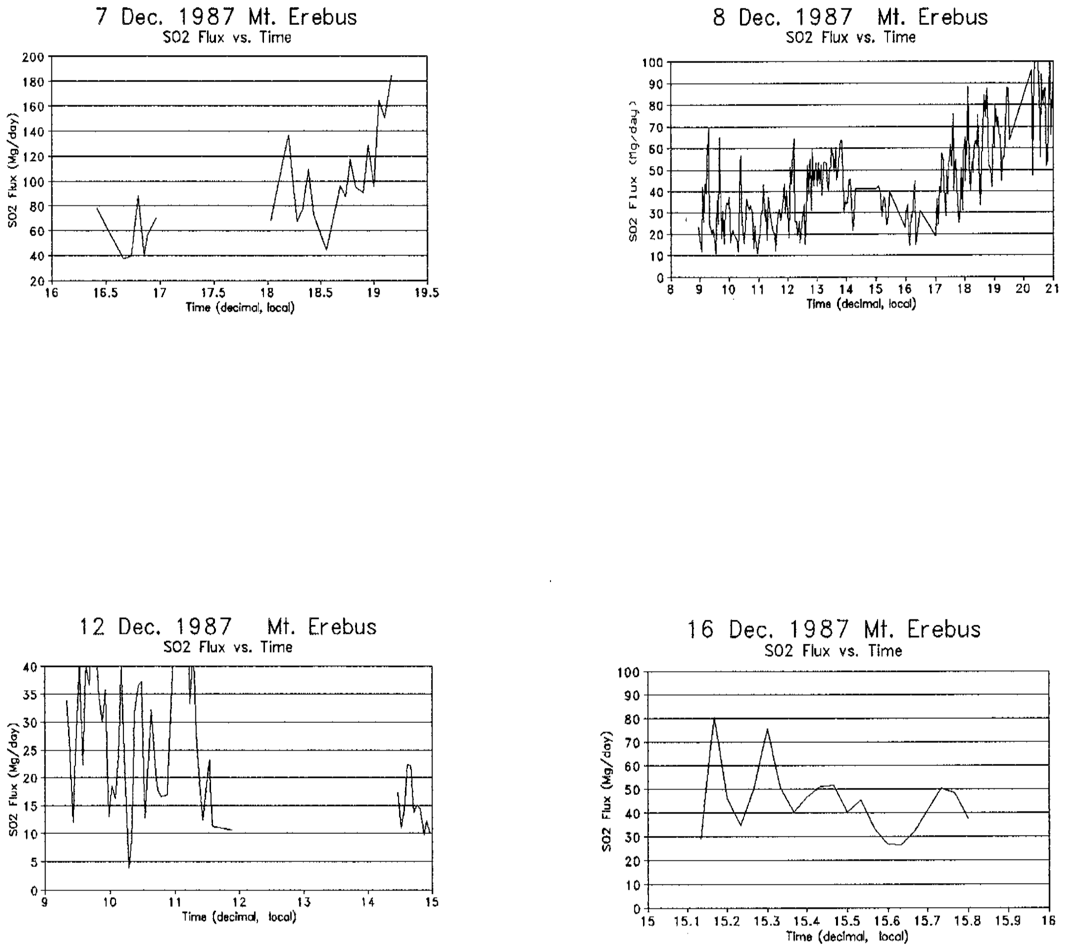

Figure 18: Graphical depiction of SO_2 emissions measured at Mt Erebus during 1987. Note that both vertical and horizontal scales vary among diagrams.

Table 7: Average SO2 Output for Mount Erebus: 1987

	7 Dec. 87	8 Dec. 87	12 Dec. 87	16 Dec. 87	Cum. Ave.
Time	16.41-19.17	8.95-20.98	9.33-14.97	15.13-15.80	
Ave.:	90.55	43.49	25.95	44.91	44.22
STD	38.41	21.88	13.63	13.89	26.62
Min:	37.37	10.61	3.79	26.33	3.79
Max:	184.96	117.31	61.42	80.62	184.96
n:	25	227	55	20	327

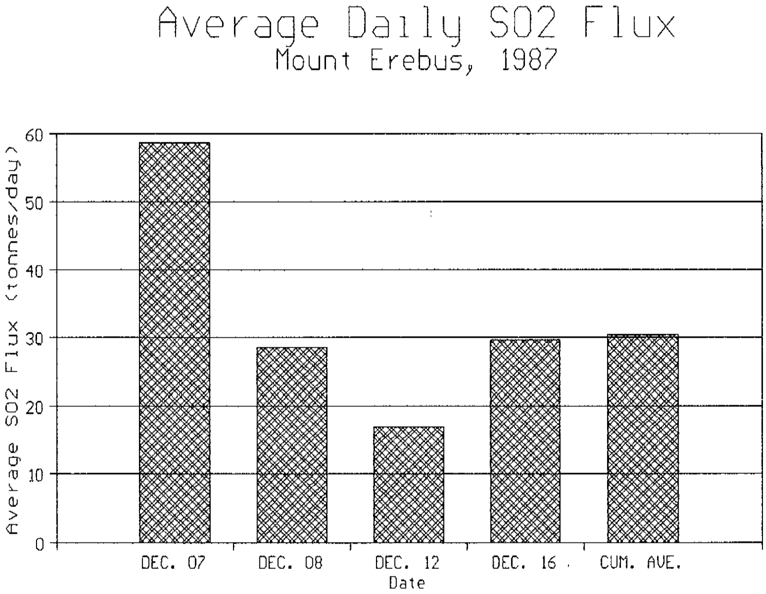

Figure 19: Bar graph depicting the daily average SO_2 fluxes for Mount Erebus during the 1987 field season.

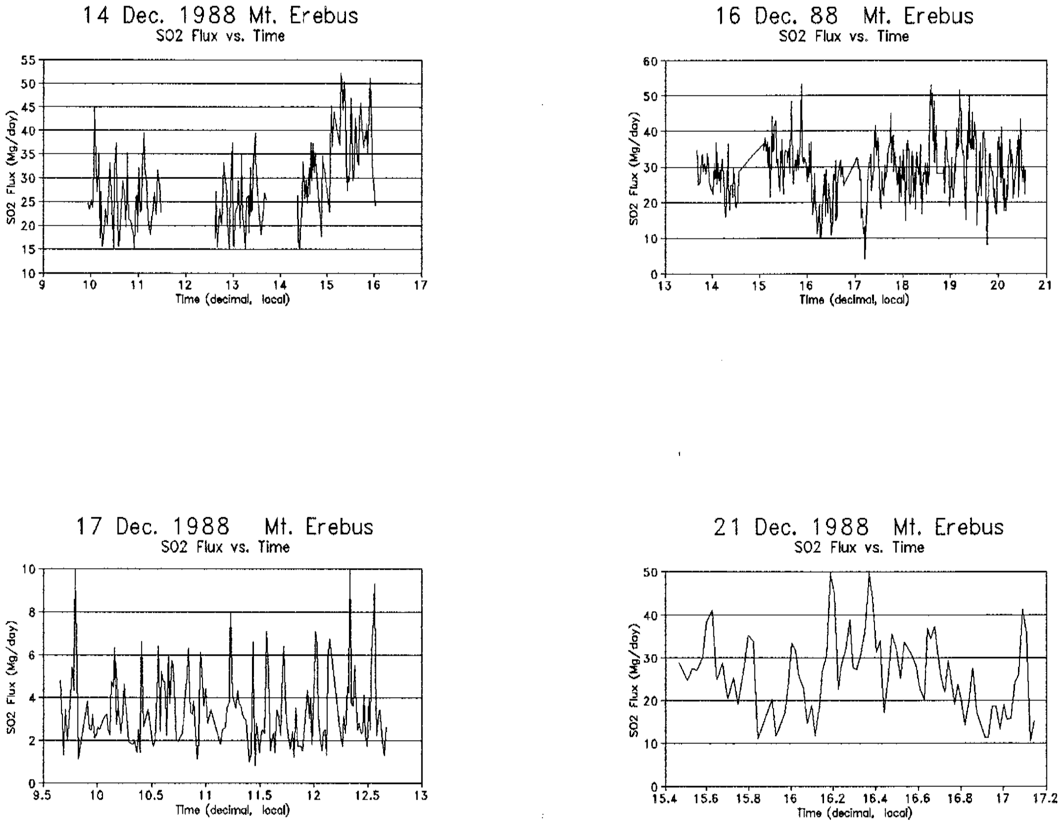

Figure 20: Graphical depiction SO_2 emissions measured at Mt. Erebus during 1988. Note the variation in both horizontal and vertical scale in each diagram.

Table 8: Average SO_2 Outputs for Mount Erebus: 1988

	DEC 14	DEC 16	DEC 17	DEC 21	CUMULATE
	9.55- 20.37	1.67- 9.09	10.66- 12.67	3.47- 5.15	
ave.=	28.22	26.92	3.44	25.88	27.32
std	7.66	10.33	1.80	9.13	9.25
n=	310	383	164	84	777
min.=	11.3	1.1	0.8	10.5	1.1
max.=	52.1	53.2	10.8	50.2	53.2

Note: The Cumulative average does not include measurements made on Dec. 17, 1988.

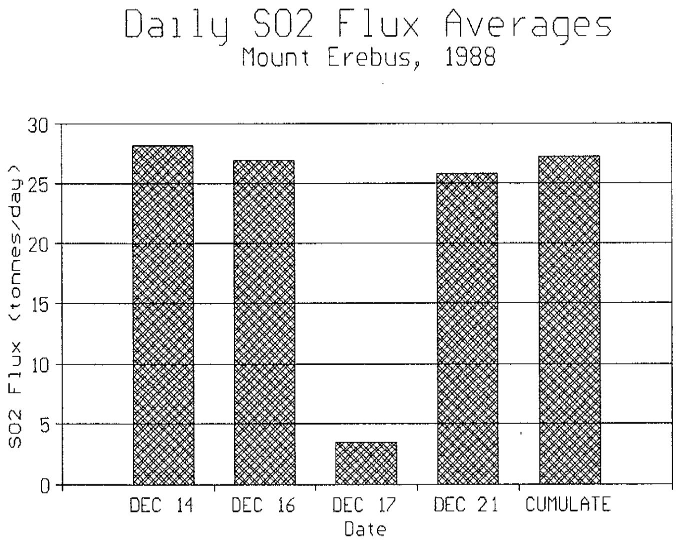

Figure 21: Bar graph showing daily average SO_2 emissions measured at Mount Erebus during 1988.

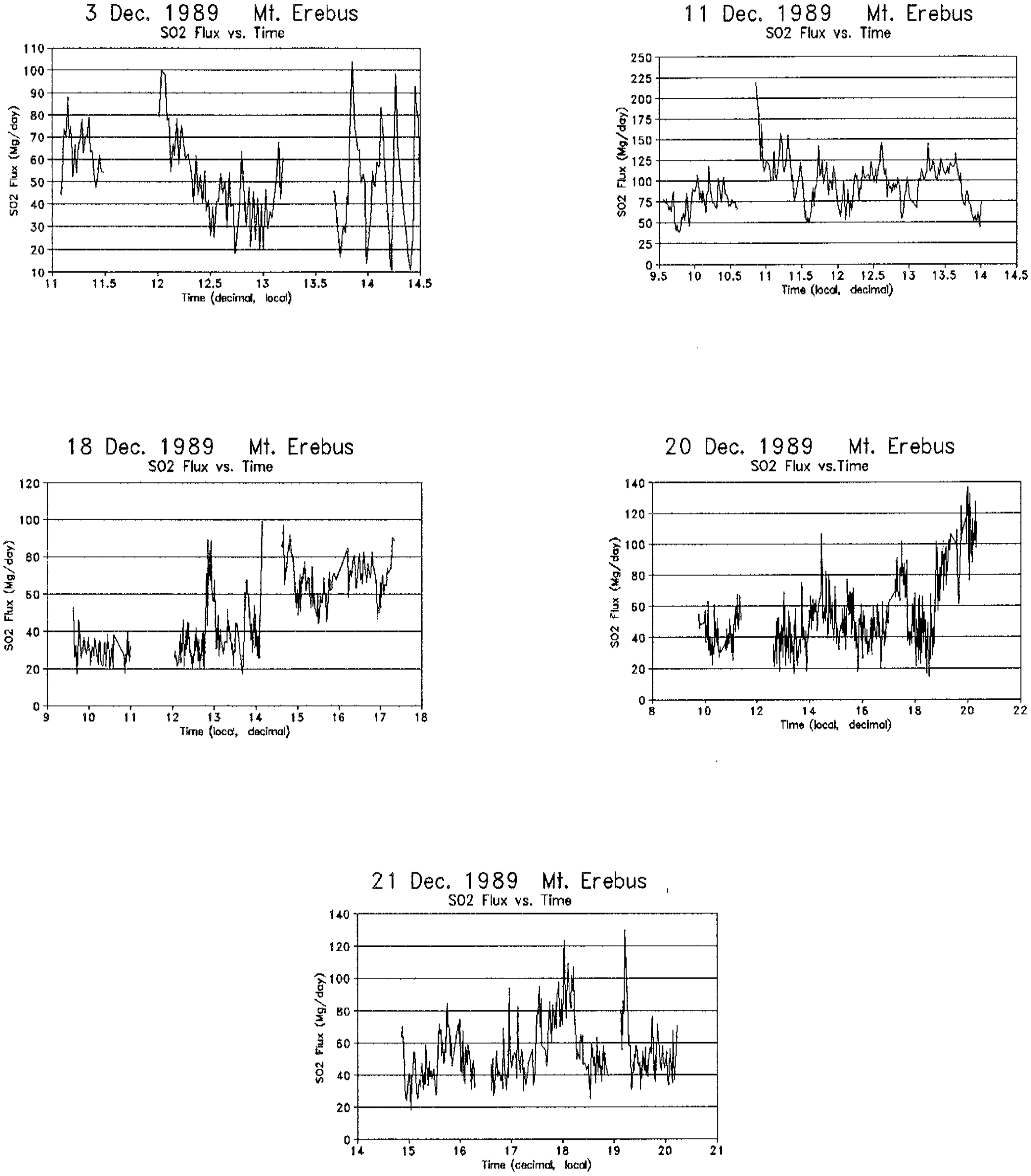

Figure 22: Graphical depiction of SO_2 emissions measured at Mt. Erebus during 1989. Note the variation in both the horizontal and vertical scales in each diagram.

Table 9: Average SO_2 Emission for Mount Erebus: 1989

	03 Dec.	11 Dec.	18 Dec.	20 Dec.	21 Dec.	cumulate
time	11.08- 14.5	9.55- 14.01	9.63- 17.34	9.78- 20.32	14.87- 20.23	
ave.=	51.70	93.22	47.93	54.18	54.28	52.50*
std=	20.62	27.01	20.14	23.03	18.68	20.62
n=	130	235	269	511	260	1405
min.=	10.7	38.2	17	14.7	18.2	10.7
max.=	103.6	218.1	99	136.6	130.2	218.1

*The 11 Dec. Measurements have not been included in this average.

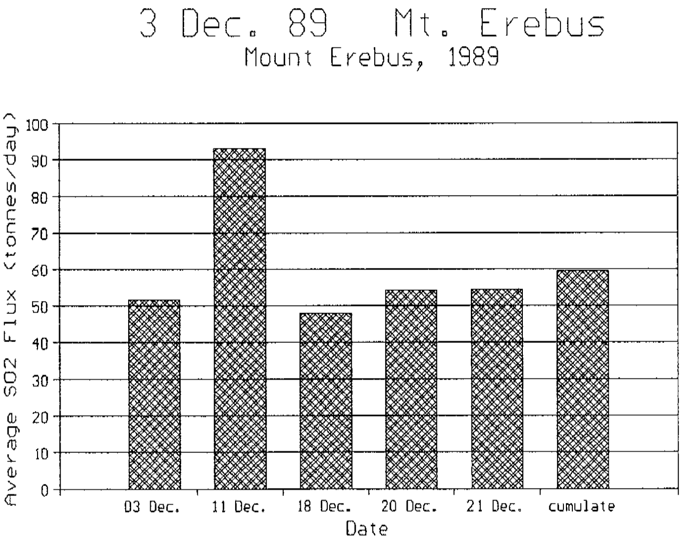

Figure 23: Bar graph showing average daily SO_2 emissions for Mount Erebus during the 1989 field season.

Trends in the Daily Data

Mount Erebus is similar to the Pu'u O'o vent in its tendency to emit volatiles in discrete bursts, or "puff". This puffing characteristic is not well understood, and may be the result of any number of physical circumstances. The measurements collected at Mount Erebus reflect the puffing phenomenon by being highly variable, thus giving averages that have high standard deviations. The data collected over time intervals greater than four or five hours shows other periodic behavior of longer period than seen in the puffs.

Periodicities on the order of 1.5 to 2.0 hours have been observed qualitatively in previous studies (Meeker, 1988). Using the greater quantities of data and the longer continuous terms of measurement afforded by the automatic scanning head, it was hoped that these longer periodicities could be quantified.

The Fast Fourier Transform algorithm was employed to isolate any consistent periodic behavior that exists in the data. Qualitative observations of the data were also used to show fluctuations that appear periodic and deserve mention, but were not brought out by the Fourier Transform.

The use of Fourier Transforms to isolate high amplitude frequencies in data sets is limited to those periods shorter in length than one-half of the total temporal length of the data set (see Appendix E). In addition, the transform is limited to regularly sinusoidal cycles. A data set may show periodic or semi-periodic trends that may not be discovered by the FFT Algorithm. For this reason, qualitative examinations of the data set for periodic trends was prudent.

The periodicities that appear in the SO_2 emission data are always more apparent on days when the SO_2 output from the vent is great, simply because the amplitude associated with the period is higher. This observation is apparent by examining the 1988 SO_2 emissions from Mount Erebus, where relatively few strong periodicities occur. The 1988 periods that did show from FFT analysis show agreement with the 1987 and 1989 data to the extent that the data is available. The 1987 and 1989 periodicity analysis show reasonable similarity.

Other than the strong, high frequency periodicity due to volcanic puffing, the data from each year shows relatively strong cyclical behavior that lasts between 10 and 15 minutes (Figs. 24-26). Other strong signals are noted for cycles with frequency of 20 minutes (seen on each day during the 1987 and 1989 seasons) (Figs. 24, 26), 30 minutes (seen every day during 1989) (Fig. 26), and 40 minutes (seen four out of five days during 1988 and 3 of five days during 1989) (Figs. 25, 26). Strong cyclicities also appear right around 100 minutes on three of the four data sets during 1987 (Fig. 24), and between 80 and 100 minutes for four of the five data sets collected during 1988 (Fig. 26). No conspicuously strong cyclicities that last that long are obvious in the FFT Data for 1989.

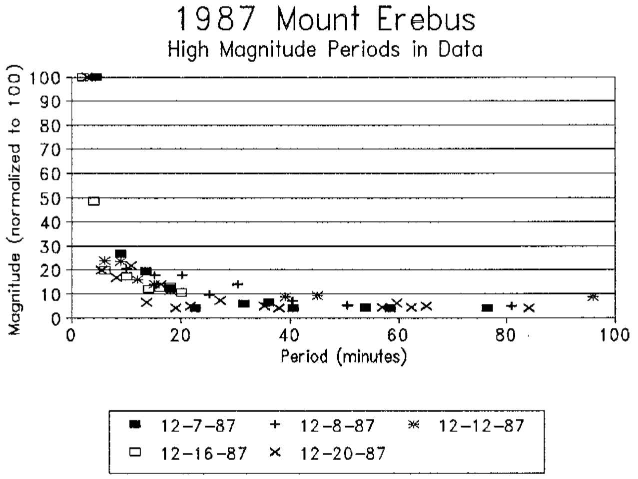

Figure 24: Strong cyclicities in SO_2 emissions during 1987. Cycles of 10 minute and 80 minute periods occurred in nearly every data set.

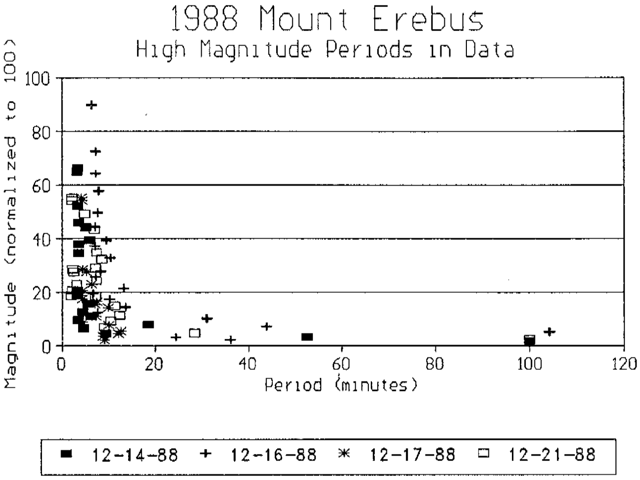

Figure 25 Strong cyclicities in SO_2 emissions during 1988. Periods that lasted about 10 minutes and 100 minutes were common to nearly all data sets. Longer periods were difficult to identify using FFT methods.

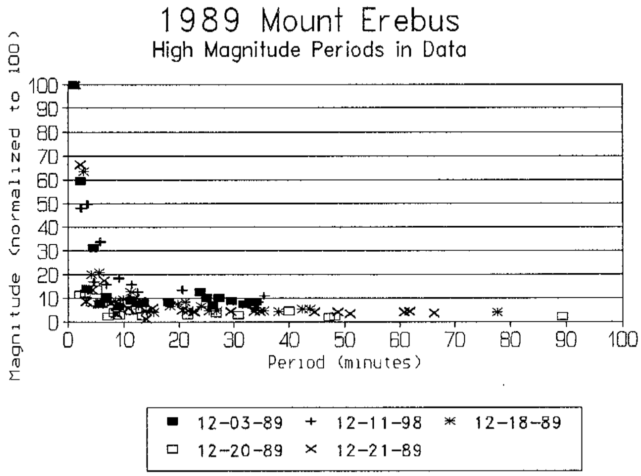

Figure 26: Strong cyclicities in SO_2 emission data during 1989. Periods of 10 minutes, 20 minutes, 30 minutes and 40 minutes are common to nearly all data sets.

Several of the data sets, particularly those from 1989, show strong periodic behavior that is not apparent in the FFT output for the data set. A fairly obvious cyclic pattern shows in the data collected between 11:30 A.M. and 2:00 P.M. (14:00) on 11 Dec. 1989 (Fig. 27). This appears to have a period of about 1 hour, although it does not appear in FFT data. Other similar periodicities apparent in 1989 data are shown in the graphical representations of the SO_2 emission data. Measurements made on 20 Dec. 1989 show a periodicity slightly greater than 1 hour, and a possible periodicity on the order of 2 hours (Fig. 28). Data sets from 21 Dec. 1989 have apparent cyclic behavior with 1.5 hour periods (Fig. 29). Once again, these cyclic patterns do not show up in the Fourier transforms of the data sets because the shape of their cycles is not well defined by a simple sine curve. They are only apparent by qualitative examination of the raw SO_2 emission data plotted against time.

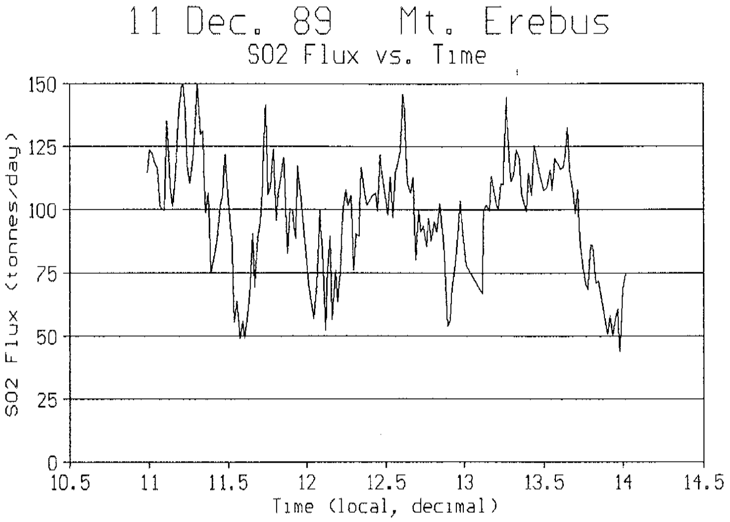

Figure 27: Raw SO_2 emission data from Mt. Erebus showing apparent cyclic behavior.

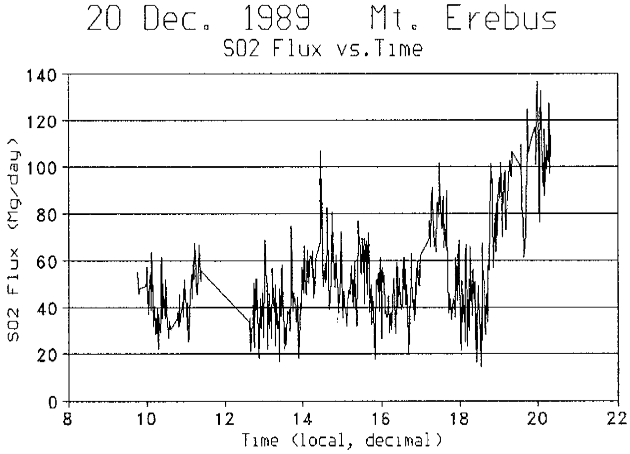

Figure 28: Raw SO_2 emission data from Mt. Erebus showing apparent cyclic behavior with periods on the order of 2 hours.

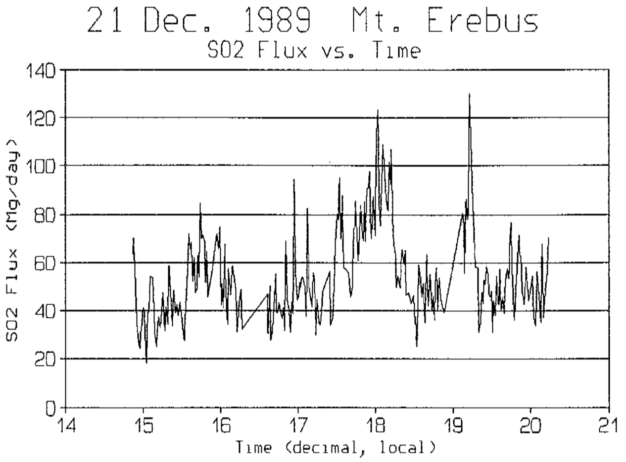

Figure 29: Raw SO_2 emission data from Mt. Erebus showing apparent cyclic behavior. Data collected on 21 Dec. 1989 has apparent period(s) between 1 and 2 hours .

These periodicities may be the result of any number of physical circumstances. The shorter periodicities (10 to 20 minutes) may be the result of bubble generation and growth in the magma. The bubbles are formed by the phase change associated with the exsolution of volatiles in the magma. After formation, they continue to grow by coagulation and expansion as the travel against gravity due to their buoyancy (Sparks, 1977). Once the bubbles are large enough to reach the surface, they escape from the lava lake.

The longer periods may be the result of the depletion of the surficial magmas. As the surface magma becomes depleted in volatiles, it is also being cooled by exposure to the atmosphere. The combination of at least these two things results in the magma's increasing in density, and its eventual sinking. Fresh, volatile rich magma replaces the depleted magma by convective overturn. The denser, cooled magma returns to the Erebus system and becomes replenished.

Judging from the apparent presence of longer periods in the SO_2 emission data (Figs. 27-29), the process of overturn takes from 1 to 3 hours. Longer overturn periods are possible, and even likely, but cannot be determined positively based on the data sets collected thus far (prior to 1990).

The Evolution of SO_2 Emission at Mount Erebus

The measurements made and presented in this study represent the continuation of a series of SO_2 emission measurements made at Mount Erebus. Of particular interest are measurements made since the large 1984 eruptive episode. The average SO_2 emission, measured prior to the 1984 eruption, was 230 ± 90 Mg SO_2/day (Rose, et al, 1985). This rate is considered characteristic of the SO_2 emissions from 1976 until the September 1984 eruption. Volcanic activity prior to the '84 eruption had reached a steady state of 2-6 moderate strombolian eruptions every day. The diameter of the Erebus' lava lake had remained at approximately 60 m during the period 1976-1984 (Dibble, et al, 1984). After the 1984 eruption, the diameter of the lava lake was greatly diminished, and SO_2 emissions decreased by an order of magnitude according to measurements made during the 1984 field season (Symonds, et al, 1985).

Since 1984, Mount Erebus has been experiencing a period of rejuvenation. SO_2 emissions rates were very low (averaging only 16 Mg/day) during the 1985 field season (Kyle, et al, 1985). Small but significant annual increases in gas emission and eruptive activity have been noted each year.

The average daily SO_2 emission measured during for 1987 (Table 9) is 44 Mg SO_2/day and represents an increase of +120% relative to the daily average for 1986 (20 Mg/day). The 1988 daily average dipped to 27 Mg SO_2/day, showing a decrease from 1987. The 1989 average emissions increased to 52.5 Mg/day, an increase of +218% over the 1988 average.

The decreases in average emission rates seen in 1985 (Kyle, et al, 1990) and 1988 (Table 10) probably represent temporary setbacks in Erebus' restoration of previous levels of activity. Examination of the bar graph showing annual average output rates supports this contention (Fig. 30).

The early stages of rejuvenation (1984-1988) have relatively constant SO_2 emissions averaging just under 30 Mg/day (Table 10). The 1989 measurements represent an increase of nearly 100%, to nearly 25% of the pre-1984 levels. This significant increase may indicate a physical change in the mechanism that brings magma to the surface of the lava lake, or in the rate at which magma is supplied to the Erebus system. There has been no evidence of any physical change to the actual geometry of the conduit system beneath Erebus.

Over the past several years, researchers have noted that the amount of SO_2 emitted from the summit vents of Mount Erebus has been approximately proportional to the area of the lava lake (Kyle, et al, 1990). The areas of the lava lake for the study period during each year are put forth in Table 10 (Kyle, personal communication, 1990). The ratio of SO_2 output (Mg/day) to unit area of the lake (m^2) was about 10, except in 1986, when it may have been 3 times as much. This relationship may imply that sulfur exsolution does not occur in the magma until it reaches the physical conditions found in shallow depths of the lava lake. In order to continue the emission of sulfur gas at a quasi-steady rate, once the magma at the surface of the lava lake becomes depleted in volatiles, it would have to be re-integrated into the conduit system. This process may be accomplished by convective overturn of cooled, depleted surface magmas and subsequent replacement by fresh, volatile rich magma from within the Erebus system. This process is directly linked to the periodic trends in the volatile emission rates discussed above.

Table 10: Annual average emission rates from Mount Erebus

year	SO2 Output (Mg/day)	Area of Lava Lake (m^2)	Reference
1983	230	2800	Rose, et al, 1985
1984	25	200	Symonds, et al, 1985
1985	16	180	Kyle, et al, 1990
1986	20	300	ibid.
1987	44	380	this study
1988	27	240	this study
1989	52.5	630	this study

Annual SO_2 Budget of Mount Erebus

The short field season and often uncooperative weather conditions common at Mount Erebus, Antarctica, make consistent day to day measurements of SO_2 emission virtually unobtainable. Viable measurements taken over a period of only 4 or 5 days during an entire year comprise the basis for the entire year. Determination of which emission measurements that are typical and representative of the true activity at Erebus over the year's time are difficult judgements.

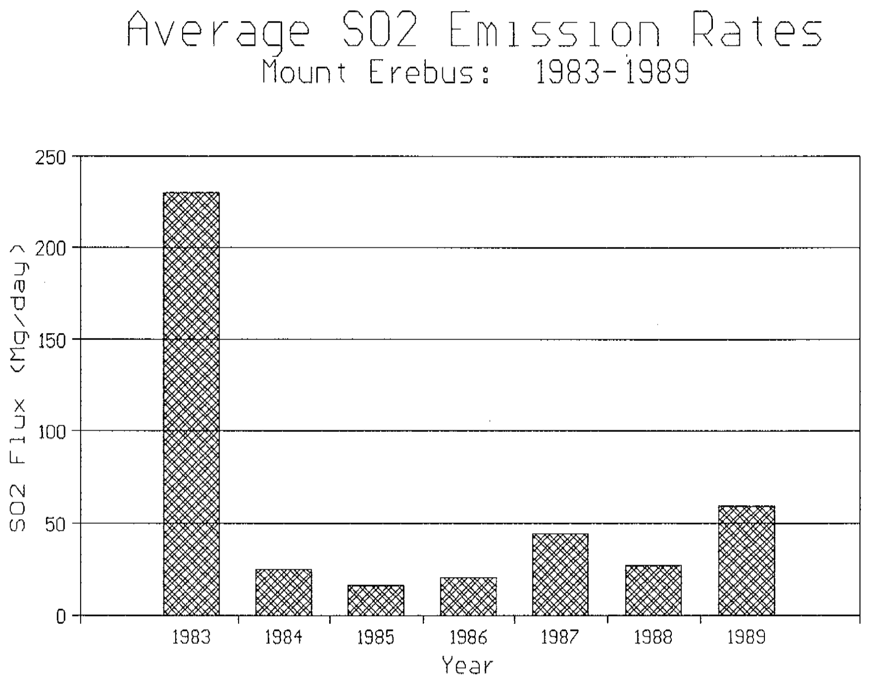

Figure 30: Daily SO_2 flux averages for Mount Erebus since 1983. The dramatic decrease in SO_2 flux seen in 1984 followed a major eruptive event. Since then, Erebus is apparently in a regenerative mode.

At Erebus, measurements are usually only taken under very specific plume conditions: The plume must be rising vertically; it cannot be sheared by the wind at heights such that plume swirling can artificially inflate emission measurements; clouds cannot exist between the COSPEC site and the summit of Erebus, or behind the summit, etc. With the exception of one low output day during 1988, no measurements made during times of low plume visibility are incorporated in the data presented here. Low plume visibility, however, is a common phenomenon. Although SO_2 gas in the plume is invisible to the eye, the volume of the visible plume generally correlates to the SO_2 discharge measured by the COSPEC. The daily averages for each year, as well as the annual sulfur budgets for the volcano should, therefore, be considered maximums for the time periods that they represent.

The data collected in 1987 show two days with averages 45 Mg SO_2/day. One day during 1987 (7 Dec.) shows an average output of 91 Mg/day, which appears to be anomalously high. Another day (12 Dec.) shows an anomalously low SO_2 output of only 26 Mg/day. The lows and highs in this case average out to 44 Mg/day and are therefore, in marginal agreement with the other three days. Using 44 Mg SO_2/day as an reasonable average leads to a emission of 0.016 Tg/year for 1987-1988.

1988 and 1989 data were measured over four and five days, respectively. 1988 displays one anomalously low output day (17 Dec.) whereas all other daily averages are between 25 and 30 Mg SO_2/day. 1989 data is made up of four days whose emissions average 52 Mg SO_2/day and one high output day averaging 93 Mg SO_2/day. Based on the average daily output, the annual SO_2 budgets are 0.009 Tg SO_2/year and 0.022 Tg SO_2/year for 1988 and 1989, respectively.

Based on the total global rate of SO_2 emission into the atmosphere each year (15.2 Tg/year; Berresheim and Jaeschke, 1983 or 18.7 Tg/year; Stoiber, et al, 1987), Mount Erebus emitted less than 0.6% of the total SO_2 prior to 1984. The emission rate immediately following the 1984 eruption was about one tenth of that. Erebus' SO_2 emissions have shown a general increase since 1984, and now are up to one-fourth of their previous levels. Still, Erebus emits less than 0.2% of the total global SO_2 output.

CHAPTER 5: SUMMARY AND CONCLUSIONS

The correlation spectrometer has been used to monitor and quantify volcanic SO_2 emissions since 1972. The quality of data gathered utilizing the COSPEC has been highly variable. Errors in the calculation of emission rates based on COSPEC measurements can occur at any stage from the actual collection of data all the way through the analytic processes involved in the reduction of the data. Careful attention must be paid to all details beginning with instrument calibration, meteorological conditions present during the data collection process and finally in the mathematical analysis of the raw data to calculate the actual emission measurements. Errors at any stage are propagated through the analysis and invalidate the study.

This study incorporates thousands of COSPEC measurements made in the stationary scan mode. Much of these data are accompanied by video tape footage of the plume taken simultaneously with the measurements. For all data accompanied by video footage, careful attention was taken to examine the video record that corresponded to each scan in order to determine the plume velocity as accurately as possible.

The advent of the automatic scanning head and computer interface for the COSPEC has brought a new level of precision to COSPEC data. This consistent data collection technique increases the credibility of COSPEC data by essentially eliminating operator error in data collection.

Measurements made at the Pu'u O'o vent, Kilauea volcano, Hawaii during March of 1989 and at Mount Erebus, Antarctica during the Austral summers of 1987, 1988 and 1989 have been examined using newly developed the video- and computer-aided analysis techniques.

The data collected at Pu'u O'o vent was gathered on four separate days over the course of one week. On two days (March 21 and 22), trade winds from the north prevailed and for most of the other two (March 18 and 19), Kona winds blew from the south. Windless conditions existed for a short period in the early morning of March 19.

No significant changes in plume or vent conditions were noted during the week, but emission averages during trade winds were greater than twice those made using measurements gathered during Kona winds. This factor led to the conclusion that, during trade wind conditions, the COSPEC was intercepting an additional SO_2 signal from the plume that rises off Kupaianaha lava pond, located a few kilometers beyond Pu'u O'o vent to the north west. The average emission rate for Pu'u O'o vent during the study period, therefore is most accurately portrayed by the data collected while Kona winds were blowing, 193 ± 84 Mg SO_2/day.

This average corresponds to only 13% of the measured emission rate along the entire ERZ (1503 Mg SO_2/day) based on automobile mounted COSPEC measurements made along the Chain of Craters Road during the study period. Pu'u O'o vent is visibly the largest emitter of SO_2 along the ERZ. Other sources of SO_2 along the rift are small vents, lava flows and the Kupaianaha lava pond.

The SO_2 emission rate for Pu'u O'o of 193 Mg/day corresponds to 0.07 Tg SO_2/year which is less than 0.5% of the total annual SO_2 emission into the atmosphere from all sources. The entire ERZ emits 0.55 Tg SO_2 into the atmosphere annually, or about 3% of the total.

The evolution of the volcanic system being studied can be monitored with the aid of SO_2 emission measurements taken regularly at the same site over long periods of time. SO_2 emissions at Pu'u O'o Vent have apparently decreased due to the absence of high fountaining events since the onset of eruptive episode 48B. However, the SO_2 emission rate along the entire ERZ has shown an increase since the commencement of episode 48B. This change in the ratio of Pu'u O'o vent emission to total ERZ emission is symptomatic of a physical change in the plumbing system beneath Pu'u O'o and the ERZ.

Emission rates measured at Mount Erebus, Antarctica based on data gathered for and presented in this study include four days of hand scan measurements made during 1987, four days of automated scan measurements made during

1988 and five days of automated scan measurements made during 1989.

The average daily emission rate based on data collected at Mount Erebus during 1987 range from a maximum 91 Mg SO_2/day on 7 December 1987 to a minimum of 26 Mg SO_2/day on 12 December 1987. The 1987 average for the study period based on four days' measurements was 44 Mg SO_2/day which corresponds to less than 0.1% of the total annual SO_2 emissions into the atmosphere.

Data were collected over four days in 1988, although the data collected on 17 December 1988 resulted in very low SO_2 emission rates and could not be brought into statistical agreement with the other three days' data. The average SO_2 emission rate for the study period, based on the measurement made on 14, 16 and 21 December 1988 is 27 Mg SO_2/day. This average corresponds to an annual emission rate of 0.01 Tg SO_2, or 0.05% of the total.

The average emission rate during 1989 based on four days' collected data is 52 Mg SO_2/day. A fifth day of data collection is included in this report, but the average of 93 Mg SO_2/day was outside of statistical agreement with the other four, and was therefore considered anomalous.

Mount Erebus has shown slight increases in the daily average SO_2 emission rate measured since the last major eruptive episode during the autumn of 1984. The most significant average increase occurs between the 1988 and

1989 field season. This increase may be due to some quasi-permanent change in the magma supply rate to the main vent on Erebus. Based on measurements made during 1984, just prior to the eruption, the SO_2 emission rate is believed to have been approximately constant at a rate of about 230 Mg SO_2/day (Rose, et al, 1985). It is reasonable, at this point, to assume that Mount Erebus will eventually regain this previous level of eruptive activity and SO_2 emission within the next few years, barring any major volcanic event.

Periodic behavior is apparent in the SO_2 emission data sets for both Pu'u O'o and Mount Erebus. The strongest periodic behavior in both cases occurs with periods between two and four minutes and is a result of the still poorly understood phenomenon of puffing seen at both these volcanoes. Other longer period cyclical behavior occurs in all data sets. These longer cycles probably hold an important key regarding the dynamics of magma convection and the geometry of the conduit system in the volcanic conduit systems.

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Appendix A: The Sulfur Cycle

The sulfur cycle models the sources and sinks of sulfur in the earth's atmosphere (Fig. A1). The main sulfur species involved in the sulfur cycle are hydrogen sulfide (H_2S), sulfur dioxide (SO_2), sulfur trioxide (SO_3), and sulfates (XSO_4, where X denotes a cation). Globally, most sulfur gases enter the atmosphere through human activities. Estimates of 65 terragrams (Tg) of sulfur gas enter the atmosphere every year from anthropogenic sources, primarily the burning of fossil fuels (Manahan, 1984). Non-anthropogenic sulfur gases (products of biologic or geologic activity) are also responsible for significant annual sulfur gas emission. These sources of sulfur gas include decomposition of organic matter, sea spray and volcanic activity (Kellogg, et al, 1972).

The residence time of a sulfur compound in the atmosphere is the most important aspect determining its atmospheric affect. The average residence time for most inorganic sulfur species in the lower atmosphere is between one and five days, depending on the climate of the region in question (Whelpdale, 1978). In humid climates, the lifetime is short, due to rapid chemical reaction with water. At this scale the main concerns involving these pollutants are the damages caused by acidic sulfur deposition on the earth's surface.

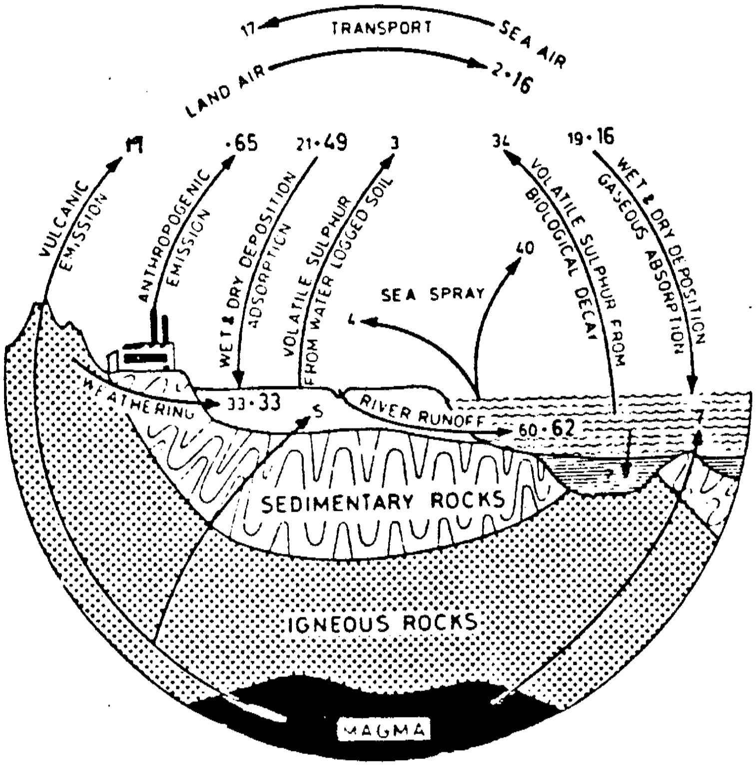

FIGURE A1: The Atmospheric Sulfur Cycle.

Most sulfur gases undergo many physical and chemical changes while they are airborne. Hydrogen sulfide, the most reduced sulfur gas species commonly found in the atmosphere, can undergo oxidation through a number of reactions that involve hydroxide (OH), molecular oxygen (O_2) and ozone (O_3):

$$H_2S + OH \rightharpoonup SO_2 + H_2O$$
$$2H_2S(g) + 3O_2(g) \rightharpoonup 2SO_2(g) + 2H_2O(l)$$
$$H_2S + O_3 \rightharpoonup SO_2 + H_2O$$

The third reaction is very slow unless particulate matter is present to provide surfaces on which the reaction may take place (Kellogg, 1972). The oxidation of H_2S in aqueous solution may be rapid due to the fact that H_2S, O_2 and O_3 are all soluble in water (Kellogg, 1972). The effects of the aqueous reaction is not well known under atmospheric conditions.

Many homogeneous (gas-phase) and heterogeneous (liquid-solid) reactions are responsible for the oxidation of sulfur dioxide to sulfate under atmospheric conditions (Whelpdale, 1978). The rates of SO_2 oxidation are determined by the ambient temperature, the amount of sunlight and the concentrations of other substances present, especially water and aerosols. When SO_2 is entrapped by water droplets in a cloud or in fog, it undergoes a rapid reaction with the water to become sulfurous acid (H_2SO_3). Sulfurous acid reacts further with dissolved O_2 in the water to become sulfuric acid (H_2SO_4).

Another common oxidation mechanism for SO_2 is a three-body reaction described as follows:

$$SO_2+O+M \rightleftharpoons SO_3+M$$

where M is a molecule, usually O_2 or N_2, that absorbs the energy given off in the reaction, thereby preventing the immediate reversal of it (Kellogg, et al, 1972). The sulfates formed by this reaction are probably the main component of the layer of H_2SO_4 found between 18 and 30 km elevation in the stratosphere (Kellogg, et al, 1972).

The Stratospheric Aerosol Layer

Direct sampling by Junge, et al, (1961) confirmed the presence of a globally distributed stratospheric aerosol layer. It was established that sulfur is the predominant elemental constituent of the large size fraction of the aerosols. Moreover, most investigators believe that stratospheric aerosols are impure sulfuric acid droplets. Crystalline nitrogen-sulfate compounds, traces of halogens, tropospheric constituents and meteoric debris are contained in these droplets in small amounts (Toon and Farlow, 1981).

The sulfate particles are probably generated in situ by photo-oxidation of sulfur containing gases (Junge, et al, 1961). Particle size distribution is unimodal and log-normal with maximums at radii between 0.01 and 0.1 μm (Toon and Farlow, 1981). Measurements of stratospheric concentrations of sulfate made during periods of volcanic quiescence exhibit low and nearly constant sulfate mass mixing ratios (Sedlacek, et al, 1983). Using these measurements, an average "background" value for sulfate in the unperturbed stratospheric mass mixing ratio is estimated to be 0.36 parts per billion (mass) (ppbm). A steady increase in the background sulfate concentration since 1973 is due to the ever-increasing anthropogenic contributions of sulfur compounds into the atmosphere.

Transport Processes in the Sulfur Cycle

Once in the atmosphere, sulfur gases are transported by wind and mixed into the mean atmosphere by turbulent fluctuations. Wind speed increases and drag due to surface roughness decreases with height above the earth. The distance the gases travel from their source, therefore is a function of height (Whelpdale, 1978).

Mixing of gaseous compounds between layers in the upper and lower atmosphere occurs by physical processes such as air current - surface interactions and thermal turbulence. Changes in altitude or the relative roughness of the ground surface give rise to physical mixing of atmospheric compounds while diurnal temperature changes of the earth's surface cause mixing by convection of air masses (Whelpdale, 1978).

SO_2 and other sulfur gases may be injected into the stratosphere during volcanic activity. On the other hand, SO_2 or any of its oxidized products may get transported into the stratosphere by current upwelling or diffusion. Once in the stratosphere, SO_2 becomes oxidized to sulfate and incorporated into the stratospheric aerosol layer (Baldwin, et al, 1976). If a plume is emitted into a stable atmospheric layer, it may travel hundreds of kilometers away from its source before getting diffused into the stratosphere or incorporated into a cloud and removed by wet or dry depositional processes (Kellogg, et al, 1972). Wet deposition (precipitation) incorporates sulfates in two ways: In-cloud scavenging (rainout) and below-cloud scavenging (washout) (Kellogg, et al, 1972). Washout incorporates diffusional uptake of SO_2 followed by the interception of the particles by falling water droplets. Rainout involves several important microphysical processes, including:

Nucleation: Generation of new ultra-fine particles from a super-saturated vapor.

Condensation: Growth of a particle by collision and incorporation of other particles.

Coagulation (four mechanisms): 1) Brownian coagulation occurs when particles impinge during random thermal motions. 2) Gravitational coagulation results from particles with large fall velocities overtaking and engulfing slower particles. 3) Turbulent diffusive and inertial coagulation occur when particles come together during turbulent movements. 4) Electrostatic aggregation occurs due to attractive electrostatic forces between fine silicate particles (Rose, et al, 1983).

Water Vapor Growth: The change in size and/or composition of a particle as a response to a local increase in humidity or change in temperature (Turco, et al, 1982).

Dry depositional processes dominate in less humid circumstances, and include gravitational sedimentation, surface adsorption and impaction (Whelpdale, 1978). In addition to climatic conditions the preference toward wet or dry depositional processes depends on the chemical and physical properties of the pollutant. Sulfate particles are often in the sub-micron size range. Their small size makes gravitational sedimentation relatively unimportant, and rainout and washout the significant depositional modes. High particle concentrations in near source regions favor dry depositional processes.

Dry deposition is a continuous process. Wet deposition requires humid conditions and precipitation, and therefore is not usually a continuous process.

Appendix B: Analytical Techniques for COSPEC Data

The COSPEC measures the atmospheric burden of SO_2, which is measured in parts per million - meters (ppm-m). The actual output of the COSPEC is in millivolt - seconds. This section outlines the method used to get from millivolt - seconds to ppm-m, and how the burden in turn is converted to SO_2 output in Mg/day. A typical scan, together with a calibration reading of the COSPEC is shown in figure 1B. The initial step in the reduction of this data is calculating the SO_2 concentration to peak height ratio. This is done first by finding the area inscribed by the SO_2 scan curve above a baseline (defined by the sides of the curve unaffected by the SO_2 plume). The algorithm is as follows:

$$\frac{peak\ area(mvolt\text{-}sec) * cal.\ conc.(ppm\text{-}m)}{peak\ width\ (sec) * cal.\ ht.\ (mvolt)} = SO_2\ burden(ppm\text{-}m)$$

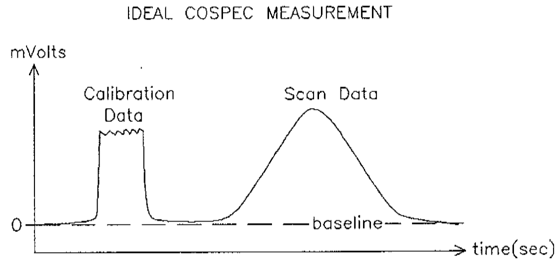

FIGURE B1: An example of a typical calibration and plume scan output from the COSPEC.

Plume width:

The plume width is calculated individually for each scan. The scan rate is recorded, as is the distance from the COSPEC site to the plume, at the time of measurement.

Using this information:

$$plume\ wd(m) = 2 * plume\ dist(m) * \tan\left(\frac{\frac{1}{2} * peak\ wd(\text{sec})}{scan\ rate\ (rad./\text{sec})}\right)$$

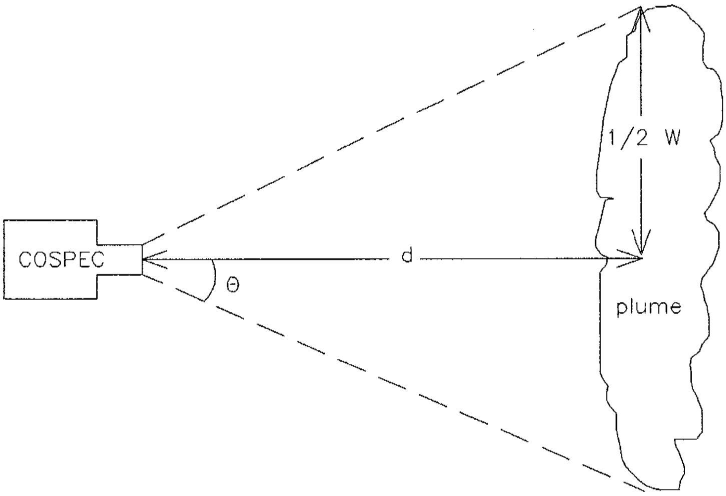

FIGURE B2: Plan view of the dimensions used in COSPEC flux calculations.

SO_2 Emission Rate:

Once the atmospheric burden, and the plume width are calculated, the SO_2 emission rate is easily determined:

$$flux\left(\frac{ppm\text{-}m^3}{\text{sec}}\right) = burden(ppm\text{-}m) * plume\ wd(m) * rise\ rate(m/\text{sec})$$

The conversion from ppm-m^3/second to Mg/day is just a matter of dimensional analysis. Using $2.86 * 10^{-3}$ grams/m^3 as the density of SO_2 gas at STP, and converting back to 0° C for standardization purposes:

$$\frac{86400\ \mathrm{sec}}{1\ day} * \frac{2.86*10^{-3}\ g\ SO_2}{ppm\text{-}m^3\ SO_2} * \frac{1\ Mg}{10^6\ g} * \frac{273^o}{293^o} = 0.00023\,\frac{Mg\ \mathrm{sec}}{ppm\text{-}m^3\ day}$$

Thus, the SO_2 emission:

$$flux = burden(ppm\text{-}m) * plume\ wd(m) * rise\ rate(m/\mathrm{sec}) * 0.00023\,\frac{Mg\ \mathrm{sec}}{ppm\text{-}m^3\ day}$$

Uncertainties in COSPEC Measurements

COSPEC measurements have inherent uncertainties even though careful considerations are always made on site to reduce error. The main quantifiable sources of uncertainty include: 1) Windspeed determination; 2) Distance from the site to the plume; 3) Scan rate; and 4) Error in data reduction.

Windspeed calculations are the most difficult to make with great accuracy. Using the videos of the plume and anemometer measurements taken on site at Pu'u O'o, the windspeed measurements are generally within ±15%. At Erebus the rise rate was measured for each puff and each scan, so the error, ideally may be as low as ±5% when good video is available, and ±10% when averages are used in the absence of video data.

The wind direction at Pu'u O'o varies the distance from the plume to the COSPEC site. The variation in site to plume distance may be as great as ±75 m (±10%) due to wind direction. At Erebus, this error is also less, due to the permanence of the COSPEC site, and to the fact that measurements are only taken on days when the plume is rising vertically.

The mechanical scanning head produces scan rates accurate to less than ±2%. Data reduction using the computer program ASPEC results in a reproducibility of within 2%.

Appendix C: Data Acquisition and Reduction Codes

The computer codes COSPEC and ASPEC were written to collect and reduce data, respectively. They were written specifically for use with an automated COSPEC as described above. These codes were written by Bill McIntosh and modified by the author.

```
'********************************************************************
'*                                                                  *
'*    COSPEC.BAS - - - - - COSPEC LOGGING PROGRAM FOR DAS-8         *
'*                                                                  *
'* Modified from MetraByte DISKLOG8.BAS program for QB 4.00  10-12-88 *
'*                                                                  *
'********************************************************************
   DIM di%(7)                                  'set up channel data array
   DIM sig(8)
   DIM tim$(8)
   DIM pix%(600)

   COMMON SHARED di%()
   DECLARE SUB DAS8 (mode%, BYVAL dummy%, flag%)

   '
   '----------- Description of Program --------------------------------
   '      This program logs data from a COSPEC and automated scanner with a
   'DAS8 board using 4 analog channels (COSPEC signal and AGC; scanner pan
   'and tilt) and 2 digital inputs (COSPEC low and high calibration). The
   'program acquires data and logs it to a random access data files on disk
   'at intervals of 0.1 second up. Options are provided for subsequent
   'on-screen viewing or printing out of the data files.
   '    Individual 20-byte data records are grouped into "sets",
   'representing data from single scans or calibration peaks.
   '
   '
   'subroutines:Setup
   '            InputScanParameters
   '            AcquireData
   '            DetermineScanParameters
   '            StoreData
   '            Delay
   '            TestKey
   '            RetrieveData
   '            DisplayGraphicHeadings
   '            SetGraphicScale
   '            DisplayGraphicData
   '            SetStripChartScale
   '            GraphLine
   '            PrintFirstLines
   '            PrintEndLine
   '
   '
MainMenu: 'display main menu options
     '
     GOSUB Setup
     '
     'Start chosen option.
     ON choice% GOTO 1000, 2000, 3000, 4000, 5000
     '
     '-------------------------------------------------------------------
1000 '----- <Option1> Log data to disk ------------------------------------
     '-------------------------------------------------------------------
     '
     GOSUB InputRunParameters
```

```
     '
     GOSUB DisplayGraphicHeadings
     '
1100 '---- start data logging loop ---------
     '
     GOSUB AcquireData
     '
     GOSUB DisplayGraphicData
     '
     GOSUB StoreData
     '
     IF NR < 32767 THEN GOTO 1200
     LOCATE 12, 17: PRINT "File has reached maximum size of 32767 records"
     LOCATE 13, 18: PRINT "Press any key to continue"
1150 a$ = INKEY$: IF a$ = "" THEN GOTO 1150
     CLOSE #1: GOTO MainMenu
     '
1200 GOSUB TestKey
     IF restart > 0 THEN GOTO MainMenu
     '
     GOSUB delay
     IF restart > 0 THEN GOTO MainMenu
     '
     GOTO 1100 'loop back for next data record
     '
     '-----------------------------------------------------------------
2000 '-------<Option 2> Display data file on screen in graphic format--------
     '-----------------------------------------------------------------
     '
2005 CLS 0
2010 PRINT "Option to display file data in graphic format on screen"
2015 PRINT
2020 PRINT "File = "; file$
2030 PRINT
2040 INPUT "Enter first data set for display (return=first):", a$
2050 IF a$ = "" THEN firstdataset% = 1 ELSE firstdataset% = VAL(a$)
2070 INPUT "Enter last data set for display (return=last):", a$
2080 IF a$ = "" THEN lastdataset% = 20000 ELSE lastdataset% = VAL(a$)
2090 IF lastdataset% = 0 THEN lastdataset% = 20000
     CLS 0
     NR = 1
     GOSUB RetrieveData   'get run parameters
     GOSUB DisplayGraphicHeadings
     '
2100 NR = NR + 1'begin display loop
2110 GOSUB RetrieveData
2125 IF scanang < .1 THEN scanparam$ = "none"
     IF EF = 1 THEN
       CLOSE #1
       PRINT "End of file"
       PRINT "Number of records = "; INT(NR - 1);
2180   LOCATE 23, 1: PRINT "Press any key to leave program"
2190   a$ = INKEY$: IF a$ = "" GOTO 2190
       CLOSE #1: GOTO MainMenu
     END IF
2300 IF dataset% < firstdataset% - 2 THEN NR = NR + 20: GOTO 2110
2305 IF dataset% < firstdataset% THEN GOTO 2100
2310 IF dataset% > lastdataset% THEN GOTO 2180
     GOSUB DisplayGraphicData
     GOSUB TestKey
     IF restart > 0 THEN GOTO MainMenu
     IF x% < 614 THEN 2100
     LOCATE 23, 1:  PRINT " - Press any key to continue display - ";
2400 a$ = INKEY$: IF a$ = "" GOTO 2400 ELSE GOTO 2500
2500 IF ASC(a$) = 27 THEN CLOSE #1: GOTO MainMenu
     LOCATE 23, 1: PRINT SPC(38); : GOTO 2100
     '
     '-----------------------------------------------------------------
3000 '-------<Option 3> Display data file on screen in tabular format--------
     '-----------------------------------------------------------------
3005 CLS 0
3010 PRINT "Option to display file data in tabular format on screen"
3015 PRINT
3020 PRINT "File = "; file$
3030 PRINT
3040 INPUT "Enter first data set for display (return=first):", a$
3050 IF a$ = "" THEN firstdataset% = 1 ELSE firstdataset% = VAL(a$)
3070 INPUT "Enter last data set for display (return=last):", a$
```

```
3080 IF a$ = "" THEN lastdataset% = 20000 ELSE lastdataset% = VAL(a$)
3090 IF lastdataset% = 0 THEN lastdataset% = 20000
3100 row = 5                                                    'count of lines on
screen
3110 CLS 0            'clear screen and print header
3120 NR = 1: GOSUB RetrieveData  'fetch data from record 1
3125 IF scanang < .1 THEN scanparam$ = "none"
3130 LOCATE 1, 1: PRINT "File: "; file$; "   Date: "; dat$; "   Scan Ang: "; scanang; "
Sample int: "; si
3140 LOCATE 3, 1
3145 PRINT "  Record  Set    Time       SO2     AGC      Pan   Tilt   Scan    LoCal HiCal"
3150 PRINT "  ------  ---  --------     -----   -----    -----  -----  ----    ----- -----"
3160 '
3200 NR = NR + 1
3205 GOSUB RetrieveData    'fetch data from record # NR
3210 IF EF <> 1 THEN GOTO 3300
3220 CLOSE #1
3230 PRINT "End of file": PRINT "Number of records = "; INT(NR - 1)
3240 PRINT "Press any key to return to main menu"
3250 a$ = INKEY$: IF a$ = "" GOTO 3250
3260 CLOSE #1: GOTO MainMenu
3300 IF dataset% < firstdataset% - 2 THEN NR = NR + 20: GOTO 3205
3305 IF dataset% < firstdataset% THEN GOTO 3200
3310 IF dataset% > lastdataset% THEN GOTO 3240
3395 LOCATE row, 1
3400 PRINT USING "  ##### ####   \          \ #####    #####    #####  #####    \     \    #
#"; NR; dataset%; ti$; di%(0); di%(1); di%(4); di%(5); scanparam$; lcal%; hcal%;
3410 row = row + 1
3420 IF row < 24 GOTO 3200 'pause to scroll next screen of data
3430 LOCATE 25, 1:  PRINT " - Press any key to continue display - "; :  PRINT "    <ESC>
to exit";
3440 a$ = INKEY$: IF a$ = "" GOTO 3440
3450 IF ASC(a$) = 27 THEN CLOSE #1: GOTO MainMenu
3460 row = 5: GOTO 3200

     '----------------------------------------------------------------------
4000 '-------<Option 4> Print data file in tabular format------------------
     '----------------------------------------------------------------------

4001 sht% = 1          'page count for headers
4005 CLS 0
4010 PRINT "Option to print out file data in tabular format"
4015 PRINT
4020 PRINT "File = "; file$
4030 PRINT
4040 INPUT "Enter first data set for display (return=first):", a$
4050 IF a$ = "" THEN firstdataset% = 1 ELSE firstdataset% = VAL(a$)
4070 INPUT "Enter last data set for display (return=last):", a$
4080 IF a$ = "" THEN lastdataset% = 20000 ELSE lastdataset% = VAL(a$)
4090 IF lastdataset% = 0 THEN lastdataset% = 20000
4092 PRINT : PRINT "Now printing - press <ESC> to abandon printing"
4100 NR = 1: GOSUB RetrieveData  'fetch data from record 1
4102 IF scanang < .1 THEN scanparam$ = "none"
4105 ' print page header
4110 row = 6                                                    'count of lines on
screen
4120 LPRINT "SHEET "; sht%; " OF FILE "; file$
4130 LPRINT "  Date: "; dat$; "   Scan Ang: "; scanang; "   Sample int: "; si
4135 LPRINT
4140 LPRINT "  Record  Set    Time       SO2     AGC      Pan   Tilt   Scan    LoCal
HiCal"
4150 LPRINT "  ------  ---  --------     -----   -----    -----  -----  ----    -----
-----"
4160 '
4200 NR = NR + 1
4201 GOSUB RetrieveData    'fetch data from record # NR
4202 a$ = INKEY$: IF a$ = "" THEN GOTO 4210
4204 IF ASC(a$) = 27 THEN CLOSE #1: LPRINT "Printout cancelled": LPRINT CHR$(12): GOTO
MainMenu
4210 IF EF <> 1 THEN GOTO 4300
4220 CLOSE #1
4230 LPRINT "End of file";
4240 LPRINT "Number of records = "; INT(NR - 1)
4250 LPRINT CHR$(12)
4260 CLOSE #1: GOTO MainMenu
4300 IF dataset% < firstdataset% - 2 THEN NR = NR + 20: GOTO 4201
4305 IF dataset% < firstdataset% THEN GOTO 4200
4310 IF dataset% > lastdataset% THEN GOTO 4240
```

```
4400 LPRINT USING "  ##### ####    \            \  #####    #####    #####  #####    \     \     #
 #"; NR; dataset%; ti$; di%(0); di%(1); di%(4); di%(5); scanparam$; lcal%; hcal%
4410 row = row + 1
4420 IF row < 61 GOTO 4200 'print next data line
4430 LPRINT CHR$(12): sht% = sht% + 1: GOTO 4110  'advance page and print header

     '-----------------------------------------------------------------
5000 '-------<Option 5> Print data file in strip chart format-------------
     '-----------------------------------------------------------------
5005 CLS 0
     WIDTH LPRINT 255
     LPRINT CHR$(27); "@"; CHR$(27); "A"; CHR$(8); 'reset printer, set 8/in
5010 PRINT "Option to print file data in strip chart format"
5015 PRINT
5020 PRINT "File = "; file$
5030 PRINT
5040 INPUT "Enter first data set for display (return=first):", a$
5050 IF a$ = "" THEN firstdataset% = 1 ELSE firstdataset% = VAL(a$)
5070 INPUT "Enter last data set for display (return=last):", a$
5080 IF a$ = "" THEN lastdataset% = 20000 ELSE lastdataset% = VAL(a$)
5090 IF lastdataset% = 0 THEN lastdataset% = 20000
     LOCATE 13, 1: PRINT "Press <ESC> to stop printing";
     firstrecord = 0
     zeroline = 1
     pixcount = 0
     linenumber = 1
     mark = 1
     olddataset% = firstdataset%
     oldmark% = -1
     recordchange% = 0
     ticmark% = 0
     timestring$ = "      "
     dotcharratio = 4.5
     NR = 1
     GOSUB RetrieveData   'get run parameters
     GOSUB SetStripChartScale
     LOCATE 19, 1: PRINT "sigmax="; sigmax; "    sigmin="; sigmin; "   sigrange=";
sigrange;
     '
5100 NR = NR + 1'begin display loop
5110 GOSUB RetrieveData
     LOCATE 10, 1: PRINT "Reading record "; NR;
5125 IF scanang < .1 THEN scanparam$ = "none"
     IF EF = 1 THEN
       CLOSE #1
       PRINT "End of file"
       PRINT "Number of records = "; INT(NR - 1);
5180   GOSUB PrintEndLine
       LOCATE 23, 1: PRINT "Press any key to leave program"
5190   a$ = INKEY$: IF a$ = "" GOTO 5190
       LPRINT CHR$(27); "@"; : CLOSE #1: GOTO MainMenu
     END IF
5300 IF dataset% < firstdataset% - 2 THEN NR = NR + 20: GOTO 5110
5305 IF dataset% < firstdataset% THEN GOTO 5100
5310 IF dataset% > lastdataset% THEN GOTO 5180
     IF firstrecord = 0 THEN oldminute% = VAL(MID$(ti$, 4, 2)): firstrecord = 1
     pixcount = pixcount + 1
     sig(pixcount) = di%(0)
     tim$(pixcount) = ti$
     IF dataset% > olddataset% THEN recordchange% = pixcount: olddataset% = dataset%
     tsecond% = VAL(RIGHT$(ti$, 2))
     IF (tsecond% MOD 10 = 0) AND tsecond% <> oldmark% THEN ticmark% = pixcount'10 sec tic
marks
     tminute% = VAL(MID$(ti$, 4, 2)) 'label minutes
     IF tminute% <> oldminute% THEN timestring$ = LEFT$(ti$, 5) + " ": oldminute% =
tminute%
     IF pixcount = 8 THEN GOSUB GraphLine: pixcount = 0
     GOSUB TestKey
     IF restart > 0 THEN
      GOSUB PrintEndLine
      LPRINT "Strip chart printout terminated"; CHR$(12)
      LPRINT CHR$(27); "@";
      GOTO MainMenu
     END IF
     GOTO 5100
```

```
'===========================================================================
'======= SUBROUTINES =======================================================
'===========================================================================


Setup:  'setup subroutine
    CLS 0
    NR = 1   'initial record number
    horiztoggle% = 1: horizhalf% = 1' initial horizontal scaling factors
    olddataset% = 1
    '
    SCREEN 2: CLS
    BASADR% = &H300
    'Do Mode 0 initialization of DAS-8
    flag% = 0                                'and CALL parameters
    MD% = 0
    CALL DAS8(MD%, VARPTR(BASADR%), flag%)           'run initialization
    IF flag% <> 0 THEN LOCATE 24, 1: PRINT "DAS8 INSTALLATION ERROR, Data acquisition not
possible"' DAS8 board not found
    '
    '---------- Display menu with setup options -----------------------
    LOCATE 1, 1: PRINT "Choose from following options:-"
    LOCATE 3, 5: PRINT "<1> - Display and log data to disk"
    LOCATE 5, 5: PRINT "<2> - Display disk data file, graphic format"
    LOCATE 7, 5: PRINT "<3> - Display disk data file, tabular format"
    LOCATE 9, 5: PRINT "<4> - Print disk data file, tabular format"
    LOCATE 11, 5: PRINT "<5> - Print disk data file, strip chart format"
    LOCATE 13, 5: PRINT "<6> or <ESC> - Exit program"
730 LOCATE 15, 2:      PRINT "Choose option (1-6): ";
740 a$ = INKEY$: IF a$ = "" GOTO 740
    IF a$ = "6" OR ASC(a$) = 27 THEN END
    PRINT a$                     'echo response to screen
    choice% = VAL(a$)
    IF choice% >= 1 AND choice% <= 5 GOTO 790'check for valid response
    LOCATE 16, 1
    PRINT "["; a$; "] is not a valid response. Re-enter"
    LOCATE 15, 1: PRINT SPC(79); : GOTO 730
790 LOCATE 16, 1: PRINT SPC(79);
    '


    '-------  Get name of user's data file ---- ------------------------
    '
830 LOCATE 17, 1: INPUT "Name of data file (e.g. B:MYFILE.DAT) "; file$
    IF LEN(file$) < 1 THEN GOTO 830
    IF choice% > 1 THEN 870
840 '
    '-------- Open random access file with records as follows:-
    '
    ON ERROR GOTO 869
    OPEN file$ FOR INPUT AS #1
    CLOSE #1:  PRINT " File "; file$; " already exists.  Overwrite (Y/N)?";
865 a$ = INKEY$: IF a$ = "" THEN 865
    IF a$ = "Y" OR a$ = "y" THEN 868
    LOCATE 17, 1: PRINT SPACE$(79): GOTO 830
868 PRINT " Y": GOTO 870
869 RESUME 870
870 OPEN file$ FOR RANDOM AS #1 LEN = 20
    FIELD #1, 2 AS set0$, 10 AS dt$, 4 AS sang$, 4 AS sint$
    FIELD #1, 2 AS set$, 8 AS TM$, 2 AS CH0$, 2 AS CH1$, 2 AS CH4$, 2 AS CH5$, 2 AS DIG$
    '
    'DATA is stored in random access file with the following structure:
    '
    'Record 1 : set0$, 2 bytes - data set number = 0
    '           dt$ ,10 bytes  - date, string
    '           sang$, 4 bytes - scan angle, floating point
    '           sint$, 4 bytes - sample interval, floating points
    '           remaining fields = 0
    'Record>1 : set$, 2 bytes - data set number, integer
    '           TM$,  8 bytes - time, string
    '           CH0$, 2 bytes - DAS8 ch.0, COSPEC signal, integer
    '           CH1$, 2 bytes - DAS8 ch.1, COSPEC AGC, integer
    '           CH4$, 2 bytes - DAS8 ch.4, scanner pan, integer
    '           CH5$, 2 bytes - DAS8 ch.5, scanner tilt, integer
    '           DIG$, 2 bytes - DAS8 digital inp., COSPEC cal., integer
    '
    'A/D data is stored as integers (-2048 to +2047) converted to strings
    'using MICROSOFT random access file format.
```

```
     'Disk usage depends on sample interval.  A 0.5 second sample interval
     'fills about 5K of disk space per minute, yield 2 hours 24 minutes of
     'data storage per 720K disk.
     '
     RETURN

InputRunParameters:  'subroutine to input and save run parameters
     '
     'Input sample interval (si) and scan angle (scanang)
1020 LOCATE 19, 1: INPUT "Sample interval (seconds) "; si
     PRINT SPC(79);
     IF si < .1 THEN LOCATE 20, 1: PRINT "Minimum interval is 0.1 second. Re-enter":
LOCATE 16, 1: PRINT SPC(79); : GOTO 1020
     stoplimit = 2.5 / si 'specifies maximum stop time at end of data set
     LOCATE 21, 1: INPUT "Scan angle (degrees, 0 for no scanner) "; scanang
     'save sample interval and scan angle in dataset 0
     dataset% = 0
     LSET set0$ = MKI$(dataset%)
     LSET dt$ = dat$
     LSET sang$ = MKS$(scanang)
     LSET sint$ = MKS$(si)
     PUT #1, NR
     NR = NR + 1
     dataset% = 1
     oldscanparam$ = "stop"
     stopcount% = 0
     Pan$ = " "
     Tilt$ = " "
     panrate% = 0
     tiltrate% = 0
     '
     RETURN


AcquireData:   'data acquistion subroutine


     '------ Fetch A/D data from channels 0 thru 5 and return in DI%(*) ----
     DEF SEG = SG
     '
     'Start on channel 0
     MD% = 2: CH% = 0
     CALL DAS8(MD%, VARPTR(CH%), flag%)        'set start channel
     MD% = 4
     FOR i = 0 TO 5
     CALL DAS8(MD%, VARPTR(di%(i)), flag%)     'convert & get each channel data
     NEXT i
     'Fetch DAS-8 digital data from inputs IP1-3
     MD% = 13: dg% = 0
     CALL DAS8(MD%, VARPTR(dg%), flag%)
     '
     'mask digital data
     IF (dg% AND 2) = 2 THEN hcal% = 1 ELSE hcal% = 0
     IF (dg% AND 1) = 1 THEN lcal% = 1 ELSE lcal% = 0
     '
     'Lock time
     ti$ = TIME$
     '
     IF scanang > .1 THEN GOSUB DetermineScanParameters
     '
1420 RETURN

DetermineScanParameters: 'subroutine to interpret analog scanner data
     IF (di%(4) > 10) THEN GOTO 1403 ELSE Pan$ = " ": panrate% = 0: GOTO 1405
1403 IF (di%(4) > 250) THEN GOTO 1404 ELSE Pan$ = "R": panrate% = INT(100 * (di%(4) /
204)): GOTO 1405
1404 Pan$ = "L": panrate% = INT(100 * (di%(4) / 2047))
1405 IF (di%(5) > 10) THEN GOTO 1406 ELSE Tilt$ = " ": tiltrate% = 0: GOTO 1409
1406 IF (di%(5) > 250) THEN GOTO 1407 ELSE Tilt$ = "D": tiltrate% = INT(100 * (di%(5) /
204)): GOTO 1409
1407 Tilt$ = "U": tiltrate% = INT(100 * (di%(5) / 2047))
1409 IF Pan$ <> " " THEN scanparam$ = Pan$ ELSE IF Tilt$ <> " " THEN scanparam$ = Tilt$
ELSE scanparam$ = "stop"
     '
     'increment scan data set number where required
     IF choice% > 1 THEN GOTO 1418
     IF scanparam$ = oldscanparam$ THEN GOTO 1418
     IF scanparam$ = "stop" THEN stopcount% = stopcount% + 1 ELSE GOTO 1417
```

```
     IF stopcount% < stoplimit THEN GOTO 1418
1417 dataset% = dataset% + 1: oldscanparam$ = scanparam$: stopcount% = 0
1418 RETURN


StoreData:     'subroutine to store one record on disk
     LSET set$ = MKI$(dataset%)
     LSET TM$ = ti$
     LSET CH0$ = MKI$(di%(0))
     LSET CH1$ = MKI$(di%(1))
     REM - LSET CH2$ = MKI$(di%(2)) <secondary COSPEC AGC>
     REM - LSET CH3$ = MKI$(di%(3)) <tertiary COSPEC AGC>
     LSET CH4$ = MKI$(di%(4))
     LSET CH5$ = MKI$(di%(5))
     LSET DIG$ = MKI$(dg%)
     PUT #1, NR
     NR = NR + 1                  'increment record number
     '
     RETURN


delay:     'delay loop subroutine
     '
     DEF SEG = &H40
1650 TNOW = PEEK(&H6C) + 256! * PEEK(&H6D)     'read clock jiffies
     TNOW = TNOW * 65536! / 1193180!          'turn into seconds
     GOSUB TestKey
     IF restart > 0 THEN RETURN
     IF TNOW <= (TSL - .06) THEN TSL = TNOW    'clock rolled over?
     IF TNOW - TSL < (si - 1 / 18.2) THEN GOTO 1650 ELSE TSL = TNOW
     DEF SEG = SG
     RETURN


TestKey:  'subroutine to act on key choices
     restart = 0
     a$ = INKEY$
     IF a$ = "" THEN
       RETURN
       '
     ELSEIF ASC(a$) = 27 THEN   '<ESC> to terminate log
       LOCATE 24, 1:  PRINT " TERMINATED "; SPC(60);
       LOCATE 22, 1: CLOSE #1: restart = 1: RETURN
       '
     ELSEIF ASC(a$) = 32 THEN   'SPACE to pause
       LOCATE 23, 2: PRINT "Program halted, press any key to continue";
1800   a$ = INKEY$: IF a$ = "" THEN GOTO 1800
       LOCATE 23, 2: PRINT SPC(42);
     ELSEIF ASC(a$) = 49 THEN   '1 to change vertical scale
       vertscale = vertscale + 1: IF vertscale = 4 THEN vertscale = 0
       GOSUB SetGraphicScale
       '
     ELSEIF ASC(a$) = 50 THEN   '2 to change horizontal scale
       horizhalf% = horizhalf% * -1
       '
     ELSEIF ASC(a$) = 82 OR ASC(a$) = 114 THEN 'manually increment data set
       dataset% = dataset% + 1
       oldscanparam$ = scanparam$
       stopcount% = 0
       '
     END IF
     RETURN

RetrieveData:  'subroutine to retrieve one record from disk
     EF = 0        'end of file flag
     'Get record
     GET #1, NR
     IF NR = 1 THEN
       dataset% = CVI(set0$)
       dat$ = dt$
       scanang = CVS(sang$)
       si = CVS(sint$)
     ELSE
       dataset% = CVI(set$)
       ti$ = TM$                'time
       di%(0) = CVI(CH0$)            'COSPEC signal
       di%(1) = CVI(CH1$)       'COSPEC AGC
       REM - di%(2) = CVI(CH2$) <secondary COSPEC ACG>
```

```
       REM - di%(3) = CVI(CH3$) <tertiary COSPEC AGC>
       di%(4) = CVI(CH4$)       'scanner pan
       di%(5) = CVI(CH5$)       'scanner tilt
       dg% = CVI(DIG$)          'COSPEC calibration
       'Check for last record
       IF ASC(MID$(ti$, 3, 1)) = 0 THEN EF = 1
       IF (dg% AND 2) = 2 THEN hcal% = 1 ELSE hcal% = 0
       IF (dg% AND 1) = 1 THEN lcal% = 1 ELSE lcal% = 0
       IF scanang > .1 THEN GOSUB DetermineScanParameters
     END IF
     '
     RETURN

DisplayGraphicHeadings:   'subroutine to set up for graphic data on screen
     '
     CLS 0 'clear screen for logging mode and display title
     VIEW (24, 40)-(638, 174)
     vertscale = 1
     GOSUB SetGraphicScale
     LOCATE 23, 64: PRINT "10 sec. tic marks";
     LOCATE 1, 1: PRINT "COSPEC/DAS-8 data logger";
     LOCATE 2, 2: PRINT "file = "; file$;
     LOCATE 25, 1: PRINT "<ESC>=quit, SPACE=pause, 1=change vert, 2=change horiz,
r=increment data set";
     LOCATE 1, 60: PRINT "Interval   = "; : PRINT USING "#.##"; si; : PRINT " sec";
     LOCATE 2, 60: PRINT "Scan angle= "; : PRINT USING "##.#"; scanang; : PRINT "  deg";
     LOCATE 3, 16: PRINT "           COSPEC  data          Scanner:"
     LOCATE 4, 1: PRINT "  Date        Time  Data Set  Signal   AGC     Pan      Tilt"
     LOCATE 3, 64: PRINT "  Calibration:"
     LOCATE 4, 64: PRINT "   Hi      Low"
     x% = 5 'sets initial horizontal offset for stripchart
     '
     RETURN


SetGraphicScale:
     IF vertscale = 3 THEN maxy = 720 ELSE IF vertscale = 2 THEN maxy = 480 ELSE IF
vertscale = 1 THEN maxy = 240 ELSE maxy = 120
     IF vertscale > 0 THEN miny = -80 ELSE miny = -40
     rangey = maxy - miny
     pixel = .0075 * rangey
     WINDOW (0, miny)-(614, maxy)
     LINE (4, miny)-(614, maxy), , B 'draw box
     'clear x-axis labels
     FOR row = 6 TO 22
      LOCATE row, 1: PRINT "    "
     NEXT row
     'clear tic marks
     FOR column = 0 TO 3
     LINE (column, maxy)-(column, miny), 0
     NEXT column
     'V for volts
     LOCATE 6, 2: PRINT "V"
     'add tic marks and labels
     FOR tic% = 0 TO INT(maxy / 96.1)
     LINE (0, 96 * tic%)-(4, 96 * tic%)
     IF tic% MOD 2 = 0 OR vertscale < 3 THEN
       LOCATE 6 + INT(((17 * maxy) - (tic% * 1632)) / rangey), 1
       PRINT USING "#.#"; .2 * tic%
     END IF
     NEXT tic%

     RETURN


DisplayGraphicData:     'subroutine to display graphic data on screen
     IF NR = 2 THEN starttime = 60 * VAL(MID$(ti$, 4, 2)) + VAL(RIGHT$(ti$, 2)): LOCATE 1,
1
     horiztoggle% = horiztoggle% * horizhalf% ' optional half horizontal scale
     IF horiztoggle% = -1 AND horizhalf% = -1 THEN RETURN
     top = maxy - pixel
     bottom = miny + pixel
     LOCATE 5, 1: PRINT USING "\        \  \      \  ######  ###### ###### "; dat$; ti$;
dataset%; di%(0); di%(1);
     LOCATE 5, 47: PRINT USING "!#####   !#####"; Pan$; panrate%; Tilt$; tiltrate%
     LOCATE 5, 64: PRINT USING "    #       # "; hcal%; lcal%
     '
     'move cursor
```

```
     IF x% = 614 THEN x% = 5
     LINE (x% + 1, bottom)-(x% + 1, -pixel): LINE (x% + 1, pixel)-(x% + 1, top)'plot
cursor line
     LINE (x%, bottom)-(x%, -pixel), 0: LINE (x%, pixel)-(x%, top), 0'remove previous
cursor
     '
     'plot zero line
     IF x% MOD 16 < 9 THEN PSET (x%, 0) ELSE PRESET (x%, 0)

     'plot data
     IF VAL(RIGHT$(ti$, 2)) MOD 10 <> 0 THEN
       mark = 1
     ELSE
       IF mark = 1 THEN
         LINE (x%, bottom + .03 * rangey)-(x%, bottom)
         mark = 0
       END IF
     END IF
     IF x% = 5 THEN GOTO 1445
     LINE (x% - 1, diprev%)-(x%, di%(0))
     ' delineate new data set
     IF dataset% <> olddataset% THEN
       datasetxpos% = INT(x% / 8 + 4 - LEN(STR$(dataset% - 1)))
       IF datasetxpos% < 1 THEN datasetxpos% = 1
       LOCATE 7, datasetxpos%: PRINT dataset% - 1;
       LINE (x% - 1, bottom + 3 * pixel)-(x% - 1, top - 3 * pixel), , , &HFF00
       finishtime = 60 * VAL(MID$(ti$, 4, 2)) + VAL(RIGHT$(ti$, 2))
       scantime% = INT(finishtime - starttime)
       IF scantime% < 0 THEN scantime% = scantime% + 3600
       IF scantime% = 0 THEN GOTO 1440
       scanrate = scanang / scantime%
       LOCATE 1, 30: PRINT "Scan Time = "; scantime%; " sec";
       LOCATE 2, 30: PRINT "Scan Rate = "; : PRINT USING "#.##"; scanrate; : PRINT "
o/sec";
1440   starttime = finishtime
       olddataset% = dataset%
     END IF
1445 x% = x% + 1
     diprev% = di%(0)
     '
     RETURN

SetStripChartScale:
     sigmin = 20000
     sigmax = -20000
     NR = 10
     FOR i = 1 TO 200
      GOSUB RetrieveData
      LOCATE 19, 1: IF i MOD 50 > 25 THEN PRINT "Setting scale now";  ELSE PRINT
SPACE$(17);
      IF EF = 1 THEN GOTO done
      IF di%(0) > sigmax THEN sigmax = di%(0)
      IF di%(0) < sigmin THEN sigmin = di%(0)
      NR = NR + 10
     NEXT i
     IF sigmin > 5 THEN sigmin = 5
done: sigrange = sigmax - sigmin
      LOCATE 19, 1: PRINT "                   ";
      scaleticmax% = INT((sigmax + 20) / 48.05)
      NR = 1
     RETURN


GraphLine:

     stripwidth = 256:
     IF linenumber = 1 THEN GOSUB PrintFirstLines
     FOR i = 1 TO stripwidth: pix%(i) = 0: NEXT i 'reset line array

     FOR j = 1 TO pixcount 'set line array
      IF j = recordchange% THEN
        FOR K = 0 TO 31
         FOR L = 1 TO 4
          pix%((8 * K) + L) = pix%((8 * K) + L) + 2 ^ (8 - j)
         NEXT L
        NEXT K
       ELSE
        pixsub% = CINT((sig(j) - sigmin + 10) / (sigrange + 20) * stripwidth)
```

```
         IF pixsub% < 1 THEN pixsub% = 1
         IF pixsub% > stripwidth THEN pixsub% = stripwidth
         pix%(pixsub%) = pix%(pixsub%) + 2 ^ (8 - j)
        END IF
        IF j = ticmark% THEN
         FOR K = 1 TO 4
          pix%(K) = pix%(K) OR (2 ^ (8 - j))
         NEXT K
         oldmark% = tsecond%
         ticmark% = 0
        END IF
      NEXT j

      IF zeroline = 1 THEN pix%(CINT((-sigmin + 10) / (sigrange + 20) * stripwidth)) = 255

      IF linenumber > 1 THEN GOTO PrintLine
       FOR i = 1 TO scaleticmax%
        pixsub% = CINT((48.05 * i - sigmin + 10) / (sigrange + 20) * stripwidth)
        IF pixsub% < 1 THEN pixsub% = 1
        IF pixsub% > stripwidth THEN pixsub% = stripwidth
        pix%(pixsub%) = pix%(pixsub%) OR 248
       NEXT i


PrintLine:
      LPRINT timestring$;
      timestring$ = "      "
      LPRINT CHR$(27); "K";
      LPRINT CHR$(2); CHR$(1);

      LPRINT CHR$(255);
      FOR K = 1 TO stripwidth:  LPRINT CHR$(pix%(K)); : NEXT K
      LPRINT CHR$(255);
      IF datasetchange% > 0 THEN LPRINT "  "; datasetchange%; : datasetchange% = 0
      LPRINT
      IF recordchange% > 0 THEN datasetchange% = dataset%: recordchange% = 0

      IF linenumber = 105 THEN
       GOSUB PrintEndLine
       LPRINT CHR$(12);
       linenumber = 1
       zeroline = 1
       RETURN
      END IF
      linenumber = linenumber + 1
      zeroline = zeroline * -1
      RETURN

PrintFirstLines:
      LPRINT CHR$(27); "@";   ' reset printer
      LPRINT "      "; "file: "; file$; "    "; dat$

      LPRINT CHR$(27); "A"; CHR$(8); "      "; CHR$(15); 'set condensed print, 8 ln/"
       zerospace = CINT(((-sigmin + 10) / (dotcharratio * (sigrange + 20)) * stripwidth) -
1.5)
       IF zerospace < 0 THEN zerospace = 0
       ticspace = CINT((106 / (dotcharratio * (sigrange + 20)) * stripwidth) - 3)
       IF ticspace < 0 THEN ticspace = 0

      FOR i = 0 TO 2 * INT(scaleticmax% / 2) STEP 2
       IF i = 0 THEN
        LPRINT SPACE$(zerospace); "0.0";
       ELSE
        LPRINT SPACE$(ticspace); : LPRINT USING "#.#"; (.1 * i);
       END IF
      NEXT i
      LPRINT " V";
      LPRINT

      LPRINT CHR$(27); "@"; CHR$(27); "A"; CHR$(8); 'reset printer, set 8/in

      LPRINT "      ";
      LPRINT CHR$(27); "K";
      LPRINT CHR$(2); CHR$(1);

      FOR i = 1 TO stripwidth + 2: LPRINT CHR$(1); : NEXT i
      LPRINT
```

```
     RETURN


PrintEndLine:
     LPRINT "      ";
     LPRINT CHR$(27); "K";
     LPRINT CHR$(2); CHR$(1);

     FOR i = 1 TO stripwidth + 2: LPRINT CHR$(128); : NEXT i
     LPRINT

     RETURN
```

```
'*********************************************************************
'*                                                                   *
'*    ASPEC.BAS - - - - - COSPEC/DAS8 DATA ANALYSIS PROGRAM 16-1-90  *
'*                                                                   *
'*********************************************************************

    '
    '----------- Description of Program ----------------------------------
    '      This program helps analyze data logged from a COSPEC, DAS-8 board,
    ' and automated scanner using the program COSPEC.BAS.
    '
    'DATA is retrieved from random access file with the following structure:
    '
    'Record 1 : set0$, 2 bytes - scan number = 0
    '           dt$ ,10 bytes  - date, string
    '           sang$, 4 bytes - scan angle, floating point
    '           sint$, 4 bytes - sample interval, floating point
    '           remaining fields = 0
    'Record>1 : set$, 2 bytes - scan number, integer
    '           TM$,  8 bytes - time, string
    '           CH0$, 2 bytes - DAS8 ch.0, COSPEC signal, integer
    '           CH1$, 2 bytes - DAS8 ch.1, COSPEC AGC, integer
    '           CH4$, 2 bytes - DAS8 ch.4, scanner pan, integer
    '           CH5$, 2 bytes - DAS8 ch.5, scanner tilt, integer
    '           DIG$, 2 bytes - DAS8 digital inp., COSPEC, integer
    '
    'A/D data is stored as integers (-2048 to +2047) converted to strings
    'using MICROSOFT random access file format.
    '
    'Each group of data records is referred to as a "set"
    '      the two varieties of sets are termed "calibration sets"
    '                                      and "peak sets"
    '
    '
    '
    '
    '
    'subroutines:Setup
    '            SetVolcanoParameters
    '            ChooseFirstDataSet
    '            SetUpCalibrationFile
    '            SetUpPeakFile
    '            GetHeaderRecord
    '            ChooseCalibrationMethod
    '            GetCalibration
    '            GetDataSet
    '            DisplayGraphicHeadings
    '            SetGraphicScale
    '            DisplayDataSet
    '            ChooseInflectionPoints
    '            Cross
    '            CalculateCalibrationData
    '            CalculatePeakData
    '            StoreCalibrationData
    '            StorePeakData
    '
BEGIN:
    CLEAR
    CLS 0
    GOSUB Setup
    '
    IF beginagain <> 0 THEN GOTO BEGIN
    '
    'Start chosen option.
    ON choice% GOTO 1000, 2000
    '
    'error handling
    '
10  RESUME 850
20  RESUME 245
30  RESUME 545
40  RESUME 8400
50  RESUME 8350
     '
     '
     '---------------------------------------------------------------------
1000 '----- <Option1> Measure and file calibration heights-----------------
     '---------------------------------------------------------------------
```

```
     '
     GOSUB SetUpCalibrationFile
     '
     GOSUB ChooseFirstDataSet
     '
     GOSUB GetHeaderRecord
     '
     CLS 0 ' clear screen
     '
     calibrationnumber = 0

1100 '-----start calibration set loop-----
     '
     GOSUB GetDataSet
     '
     IF beginagain <> 0 THEN GOTO BEGIN
     IF datarec% < 20 THEN GOTO 1200
     '
     calibrationnumber = calibrationnumber + 1
     '
1140 GOSUB DisplayGraphicHeadings
     '
     GOSUB DisplayDataSet
     '
     GOSUB ChooseInflectionPoints
     '
     IF newpeak% = 1 THEN GOTO 1100
     IF beginagain <> 0 THEN GOTO BEGIN
     '
     GOSUB CalculateCalibrationData
     '
     ON choice2% GOTO 1150, 1140, 1150, 1100, 1200

     '
1150 GOSUB StoreCalData
     '
     IF choice2% = 3 GOTO 1140
     '
1200 IF EF = 1 THEN
       LOCATE 12, 40: PRINT "end of file"; : GOTO BEGIN
     ELSEIF choice2% = 5 THEN
       CLS 0
       GOTO BEGIN
     END IF
     '
     GOSUB TestKey
     IF beginagain <> 0 THEN GOTO BEGIN
     '
     GOTO 1100 'loop back for next calibration data set
     '
     '-------------------------------------------------------------------
2000 '-------<Option 2> Measure and file peak heights ---------------------
     '-------------------------------------------------------------------
     GOSUB SetUpPeakFile
     '
     GOSUB GetHeaderRecord
     '
      GOSUB SetVolcanoParameters
     '
     GOSUB ChooseFirstDataSet
     '
     CLS 0 ' clear screen
     '
     GOSUB ChooseCalibrationMethod
     '
     IF beginagain <> 0 THEN GOTO BEGIN
     '
     peaknumber = 0

2100 '-----start peak set loop-----
     '
     GOSUB GetDataSet
     '
     IF beginagain <> 0 THEN GOTO BEGIN
     IF choice4% > 1 THEN GOSUB GetCalibration
     IF datarec% < 20 THEN GOTO 2200
     '
     peaknumber = peaknumber + 1
```

```
     '
2140 GOSUB DisplayGraphicHeadings
     '
     GOSUB DisplayDataSet
     '
     GOSUB ChooseInflectionPoints
     '
     IF newpeak% = 1 THEN GOTO 2100
     IF beginagain <> 0 THEN GOTO BEGIN
     '
     GOSUB CalculatePeakData
     '
     ON choice2% GOTO 2150, 2140, 2150, 2100, 2200
     '
2150 GOSUB StorePeakData
     '
     IF choice2% = 3 THEN GOTO 2140
     '
2200 IF EF = 1 THEN
       LOCATE 12, 40: PRINT "end of file"; : GOTO BEGIN
     ELSEIF choice2% = 5 THEN
       CLS 0
       GOTO BEGIN
     END IF
     '
     GOSUB TestKey
     IF beginagain <> 0 THEN GOTO BEGIN
     '
     GOTO 2100 'loop back for next peak data set
     '
'============================================================================
'======= SUBROUTINES ========================================================
'============================================================================

Setup:  'setup subroutine
    RESET 'closes any open files
    DIM ti$(850), sig%(850), di%(5)
    DIM caltime#(100), calAGC(100), calheight(100)
    readrecord% = 2   'initial record number
    pagecount% = 1
    horiztoggle% = 1: horizhalf% = 1' initial horizontal scaling factors
    olddataset% = 0
    beginagain% = 0
    '
    'define function to convert time strings to seconds
    '
    DEF fntimecon# (timestr$)
      hrs = VAL(LEFT$(timestr$, 2))
      min = VAL(MID$(timestr$, 4, 2))
      sec = VAL(RIGHT$(timestr$, 2))
      totalsecs# = 3600 * hrs + 60 * min + sec
      fntimecon# = totalsecs#
    END DEF
    '
    SCREEN 2: CLS 0
    '---------- Display menu with setup options -----------------------
    LOCATE 1, 1: PRINT "Choose from following options:-";
    LOCATE 3, 5: PRINT "       <1> - Measure and file calibration heights";
    LOCATE 5, 5: PRINT "       <2> - Measure and file peak heights";
    LOCATE 7, 5: PRINT "<3 or ESC> - Exit program";
730 LOCATE 12, 2:  PRINT "Choose option (1 to 3): ";
740 a$ = INKEY$: IF a$ = "" GOTO 740
    PRINT a$                         'echo response to screen
    IF a$ = CHR$(27) THEN
     choice% = 3
     GOTO 790
    END IF
    choice% = VAL(a$)
    IF choice% >= 1 AND choice% <= 3 GOTO 790'check for valid response
    LOCATE 14, 1: PRINT "["; a$; "] is not a valid response. Re-enter": LOCATE 12, 1:
PRINT SPACE$(79); : GOTO 730
790 LOCATE 14, 1: PRINT SPACE$(79);
    IF choice% = 3 THEN CLS 0: END
    outputchoice% = 2
    LOCATE 14, 1: PRINT "Hard copy desired (y or n) ? ";
725 a$ = INKEY$: IF a$ = "" GOTO 725
    PRINT a$
    IF ASC(a$) = 78 OR ASC(a$) = 110 THEN outputchoice% = 3
```

```
    '
    '--------  Get name of user's data file ---- ------------------------
    '
830 LOCATE 16, 1: INPUT "Name of data file (e.g. B:MYFILE.DAT) "; file$
    IF LEN(file$) = 0 THEN GOTO 830
840 '
    '--------- Open random access file with records as follows:-
    '

    ON ERROR GOTO 10
    OPEN file$ FOR INPUT AS #1
    ON ERROR GOTO 0
    CLOSE #1: OPEN file$ FOR RANDOM AS #1 LEN = 20
    FIELD #1, 2 AS set0$, 10 AS dt$, 4 AS sang$, 4 AS sint$
    FIELD #1, 2 AS set$, 8 AS tm$, 2 AS ch0$, 2 AS ch1$, 2 AS ch4$, 2 AS ch5$, 2 AS dig$
    GOTO 880
850 ON ERROR GOTO 0
    PRINT " File "; file$; " not found.  Try another (Y/N)?";
865 a$ = INKEY$: IF a$ = "" THEN 865
    IF a$ <> "Y" AND a$ <> "y" THEN beginagain = 1: RETURN
    LOCATE 16, 1: PRINT SPACE$(50): LOCATE 17, 1: PRINT SPACE$(50): GOTO 830
    '
880 IF outputchoice% = 2 THEN OPEN "LPT1" FOR OUTPUT AS #2
    RETURN



ChooseFirstDataSet:
    startset% = 0
    PRINT
    LOCATE 23, 1: INPUT "Start at beginning of file (Y or N)"; q$
    IF q$ <> "N" AND q$ <> "n" THEN RETURN
    LOCATE 24, 1: INPUT "Input starting data set number"; startset%
    RETURN


SetUpCalibrationFile:
    filec$ = file$ + "c"
230 ON ERROR GOTO 20
    OPEN filec$ FOR INPUT AS #3
    ON ERROR GOTO 0
    CLOSE #3:
    LOCATE 17, 1: PRINT "Calibration file "; filec$; " already exists."
240 LOCATE 18, 1: INPUT "  Overwrite, Append, or New file (O,A, or N)"; q$
    IF q$ = "O" OR q$ = "o" THEN
      choice3% = 1
    ELSEIF q$ = "A" OR q$ = "a" THEN
      choice3% = 2
    ELSEIF q$ = "N" OR q$ = "n" THEN
      choice3% = 3
    ELSE
      LOCATE 18, 1: PRINT SPACE$(65);
      GOTO 240
    END IF
    ON choice3% GOTO 250, 260, 270
245 ON ERROR GOTO 0
250 OPEN filec$ FOR OUTPUT AS #3: GOTO 300
260 OPEN filec$ FOR APPEND AS #3: GOTO 300
270 LOCATE 19, 1: INPUT "New calibration file name "; filec$: GOTO 230
300 LOCATE 20, 1: PRINT "Calibration data will be be written to file "; filec$;
    RETURN

SetVolcanoParameters:
    IF scanang > .1 THEN PRINT : INPUT "Distance to plume (meters) "; distance#
    PRINT
    INPUT "Rise-rate or wind-speed (meters/second) "; riserate#
    PRINT
    RETURN



SetUpPeakFile:
    filep$ = file$ + "p"
530 ON ERROR GOTO 30
    OPEN filep$ FOR INPUT AS #3
    ON ERROR GOTO 0
    CLOSE #3:
    LOCATE 17, 1: PRINT "Peak file "; filep$; " already exists."
```

```
540 LOCATE 18, 1: INPUT "  Overwrite, Append, or New file (O,A, or N)"; q$
    IF q$ = "O" OR q$ = "o" THEN
      choice3% = 1
    ELSEIF q$ = "A" OR q$ = "a" THEN
      choice3% = 2
    ELSEIF q$ = "N" OR q$ = "n" THEN
      choice3% = 3
    ELSE
      LOCATE 18, 1: PRINT SPACE$(65);
      GOTO 540
    END IF
    ON choice3% GOTO 550, 560, 570
545 ON ERROR GOTO 0
550 OPEN filep$ FOR OUTPUT AS #3: GOTO 600
560 OPEN filep$ FOR APPEND AS #3: GOTO 600
570 LOCATE 19, 1: INPUT "New calibration file name "; filep$: GOTO 530
600 LOCATE 20, 1: PRINT "  Peak data will be written to file "; filep$
    RETURN


GetHeaderRecord:  'get first record with run parameters
     GET #1, 1
     dataset% = CVI(set0$)
     dat$ = dt$
     scanang = CVS(sang$)
     IF choice% = 1 THEN RETURN
     PRINT
     PRINT "Scan angle = "; scanang
     PRINT "RETURN if OK, or enter new scan angle";
     INPUT ; newscanang$
     PRINT
     IF newscanang$ <> "" THEN scanang = VAL(newscanang$)
     IF scanang < .1 AND choice% > 1 THEN PRINT : INPUT "Enter air-speed/ground-speed
(meters/second) "; airspeed#
     si = CVS(sint$)
     RETURN

ChooseCalibrationMethod:  'subroutine to get calibrations for peak analysis
8000 LOCATE 1, 1: PRINT "Choose calibration option"
     LOCATE 3, 1: PRINT "  1) User input, uniform throughout file";
     LOCATE 4, 1: PRINT "  2) User input for each peak";
     LOCATE 5, 1: PRINT "  3) Data file, time interpolation";
     LOCATE 6, 1: PRINT "  4) Data file, AGC interpolation";
     LOCATE 7, 1: PRINT "  5) Return to main menu";
8050 LOCATE 8, 1: INPUT " Choose option 1-5: "; choice4%
     IF choice4% < 1 OR choice4% > 5 THEN
       LOCATE 8, 1
       PRINT SPACE$(60)
       GOTO 8050
     END IF
     ON choice4% GOTO 8100, 8500, 8200, 8200, 8600
8100 LOCATE 10, 1: INPUT "Input calibration for entire file (volts) ", cal: GOTO 8500
8200 'get calibration data from file
     filec$ = file$ + "c"
8300 ON ERROR GOTO 40
     OPEN filec$ FOR INPUT AS #4
     ON ERROR GOTO 50
     'put calibration data from file into array
     FOR i = 1 TO 100
8310 INPUT #4, fileline$
     colonpos = INSTR(fileline$, ":")
     IF colonpos = 0 OR MID$(fileline$, colonpos + 1, 1) = " " THEN
       IF EOF(4) THEN calmax = i - 1: GOTO 8340
       IF i = 1 THEN GOTO 8310 ELSE calmax = i - 1: GOTO 8340
     END IF
     caltime#(i) = fntimecon#(MID$(fileline$, colonpos - 2, 8))
     calAGC(i) = VAL(MID$(fileline$, colonpos + 23, 5))
     calheight(i) = VAL(MID$(fileline$, colonpos + 48, 6))
     IF EOF(4) THEN calmax = i: GOTO 8340
     NEXT i
8340 LOCATE 10, 1
     PRINT "Total of "; calmax; " calibration sets found in file "; filec$
     IF calmax = 0 THEN GOTO 8000
     GOSUB Delay1
     ON ERROR GOTO 0
     GOTO 8500
8350 ON ERROR GOTO 0  'calibration file data error
     LOCATE 11, 1: PRINT "Error in calibration data file";
```

```
     GOTO 8000
8400 ON ERROR GOTO 0
     LOCATE 11, 1: PRINT "Calibration file "; filec$; " not found";
     LOCATE 12, 1: INPUT "  Input name of calibration file or RETURN for options: ",
filec$
     IF filec$ = "" THEN CLS 0: GOTO 8000
     GOTO 8300
8500 CLS 0
     RETURN
8600 CLS 0: beginagain = 1: RETURN

Delay1:  'subroutine to generate short delay
     FOR i = 1 TO 7000
       sqrt2 = SQR(2)
     NEXT i
     RETURN

GetCalibration:
     ON choice4% GOTO 9500, 9100, 9200, 9200
9100 LOCATE 3, 5: PRINT "Input calibration for data set "; dataset%;
     INPUT ; ": ", cal
     GOTO 9500
9200 'find calibrations on either side of peak
     midtime# = fntimecon#(ti$(CINT((peakmax% - peakmin%) / 2)))
     FOR i = 1 TO calmax
     IF caltime#(i) > midtime# THEN GOTO 9210
     NEXT i
     cal = calheight(i)
     GOTO 9500
9210 IF i = 1 THEN cal = calheight(1): GOTO 9500
     IF choice4% = 3 THEN 'use time to interpolate calibration
       caltimediff = caltime#(i) - caltime#(i - 1)
       IF caltimediff = 0 THEN
         timefraction = 0
       ELSE
         timefraction = (midtime# - caltime#(i - 1)) / caltimediff
       END IF
       cal = calheight(i - 1) + timefraction * (calheight(i) - calheight(i - 1))
     ELSE  'use AGC to interpolate calibration
       calAGCdiff = calAGC(i) - calAGC(i)
       IF calAGCdiff = 0 THEN
         AGCfraction = 0
       ELSE
         AGCfraction = (meanAGC - calAGC(i - 1)) / calAGCdiff
       END IF
       cal = calheight(i - 1) + AGCfraction * (calheight(i) - calheight(i - 1))
     END IF
9500 RETURN

GetDataSet: 'subroutine to find cal or peak data set and put in array
     EF = 0       'end of file flag
     olddataset% = -1
     maxsig% = 0
     datastep1 = 1  'fine initial search for peaks
     IF choice% = 1 THEN datastep1 = 8  'coarse initial search for calibration

restart:
     totalAGC# = 0
     datastep = datastep1     'initial number of records skipped in search
     datarec% = 0   'number of records in data set

getrecord:
     LOCATE 19, 30: PRINT USING "& #####"; "Reading record "; readrecord%;
     GOSUB TestKey
     IF beginagain <> 0 THEN RETURN
     GET #1, readrecord%
     dcal% = CVI(dig$) AND 3
     readrecord% = readrecord% + datastep
     '
     'test for end of file
     '
     IF ASC(MID$(tm$, 3, 1)) = 0 THEN
       EF = 1
       IF datarec% < 21 THEN RETURN
       readrecord% = readrecord% - 1
       datarec% = datarec% - 1
       totalAGC# = totalAGC# - AGC / 480
       GOTO endgetdataset
```

```
     END IF
     '
     IF datarec% > 0 THEN GOTO readremainingrecords

identifyfirstrecord:
     dataset% = CVI(set$)
     IF dataset% < startset% THEN GOTO getrecord 'data set before minimum
     IF choice% > 1 THEN IF dataset% = olddataset% THEN GOTO getrecord'not new data set
     LOCATE 20, 30: PRINT USING "& ###"; "Data Set =  "; dataset%;
     IF choice% = 1 AND dcal% > 0 THEN GOTO firstcalrecordfound
     IF choice% > 1 THEN GOTO firstdatarecordfound
     olddataset% = dataset%
     GOTO getrecord

       '
firstcalrecordfound:
     IF dcal% = 2 THEN caltype$ = "High" ELSE caltype$ = "Low"
     readrecord% = readrecord% - datastep
     datastep = 1
     FOR i = 1 TO 400
      readrecord% = readrecord% - 1
      GET #1, readrecord%
      IF readrecord% = 1 OR CVI(set$) < dataset% THEN GOTO previousdatasetfound
     NEXT i
     LOCATE 20, 50
     PRINT "Big trouble with this cal set"
     GOTO restart
previousdatasetfound:
     GET #1, readrecord% + 1
     readrecord% = readrecord% + 2
     GOTO readremainingrecords

firstdatarecordfound:
     di%(4) = CVI(ch4$)
     di%(5) = CVI(ch5$)
     GOSUB DetermineScanParameters

readremainingrecords:
     IF CVI(set$) > dataset% THEN
       IF datarec% < 20 THEN
         GOTO restart
       ELSE
         GOTO endgetdataset
       END IF
     END IF
     datarec% = datarec% + 1
     IF choice% = 1 THEN
       LOCATE 21, 30: PRINT USING "& #####"; "Cal. records = "; datarec%;
     ELSE
       LOCATE 21, 30: PRINT USING "& #####"; "Data records = "; datarec%;
       IF dcal% > 0 THEN olddataset% = dataset%: GOTO restart
     END IF
     ti$(datarec%) = tm$                'time
     sig%(datarec%) = CVI(ch0$)  'COSPEC signal
     AGC = CVI(ch1$)
     totalAGC# = totalAGC# + AGC / 480
     IF sig%(datarec%) > maxsig% THEN maxsig% = sig%(datarec%)
     GOTO getrecord

endgetdataset:
     GOSUB GetBorderPeaks 'exit with usable data set
     meanAGC = totalAGC# / datarec%
     RETURN' display and process data


GetBorderPeaks:
     maxx% = 395
     IF datarec% > 394 THEN
       LOCATE 14, 10: PRINT "Data set "; detaset%; " is "; datarec%; " records long";
       LOCATE 15, 10: PRINT "  400 records is maximum";
1113   LOCATE 16, 10: PRINT "  Analyze data set starting at which of "; datarec%;
       INPUT " records"; startrec%
       IF startrec% < 1 OR startrec% > datarec% - 1 THEN LOCATE 16, 10: PRINT SPACE$(69);
: GOTO 1113
       IF datarec% - startrec% > 394 THEN peakmax% = 395 ELSE peakmax% = datarec% -
startrec%
       FOR i = 1 TO peakmax%
         ti$(i) = ti$(startrec% + i - 1)
```

```
         sig%(i) = sig%(startrec% + i - 1)
       NEXT i


       peakmin% = 1
       LOCATE 16, 30: PRINT SPACE$(49);
       IF peakmax% < 395 THEN GOTO 1111 ELSE RETURN
     END IF
     peakmin% = INT((395 - datarec%) / 2)
     peakmax% = peakmin% + datarec% - 1
     IF peakmax% > readrecord% THEN
       peakmax% = readrecord% - 1
       peakmin% = peakmax% - datarec% + 1
     END IF
     FOR i = peakmax% TO peakmin% STEP -1
       ti$(i) = ti$(i - peakmin% + 1)
       sig%(i) = sig%(i - peakmin% + 1)
     NEXT i
     'get data preceeding analyzed peak
     FOR i = 1 TO peakmin% - 1
       readrecord1% = readrecord% - datarec% - peakmin% + i
       GET #1, readrecord1%
       sig%(i) = CVI(ch0$)
       ti$(i) = tm$
     NEXT i
     'get data following analyzed peak
1111 FOR i = peakmax% TO 395
       readrecord1% = readrecord% - peakmax% + i
       GET #1, readrecord1%
       IF ASC(MID$(tm$, 3, 1)) = 0 THEN 'test for end of file
         EF = 1
         maxx% = i - 1
         RETURN
       END IF
       sig%(i) = CVI(ch0$)
       ti$(i) = tm$
     NEXT i
     RETURN




DisplayGraphicHeadings:   'subroutine to set up for graphic data on screen
     '
     CLS 1 'clear graphics viewport
     VIEW (24, 9)-(424, 175)
     vertscale = 1
     GOSUB SetGraphicScale
     LOCATE 23, 24: PRINT "10 sec. tic marks";
     LOCATE 23, 44: PRINT "P.K.Co";
     starttime# = fntimecon#(ti$(peakmin%))
     finishtime# = fntimecon#(ti$(peakmax%))
     scantime% = CINT(finishtime# - starttime#)
     IF scantime% > 0 THEN scanrate = scanang / scantime% ELSE scanrate = 0
     IF choice% = 1 THEN
       LOCATE 1, 5: PRINT "Calibration Height Measurement - file "; file$;
       LOCATE 1, 55: PRINT caltype$; " Cal. Peak Number "; calibrationnumber;
       LOCATE 3, 56: PRINT "Data Set = "; dataset%;
       LOCATE 4, 56: PRINT USING "& #.## &"; "Interval   = "; si; " sec";
       LOCATE 5, 56: PRINT "Start Time = "; ti$(peakmin%);
       LOCATE 6, 56: PRINT "Data Set Time = "; scantime%; " sec";
       LOCATE 7, 56: PRINT "Data points = "; datarec%;
       LOCATE 8, 56: PRINT USING "& #.### &"; "meanAGC = "; meanAGC; "V";
     ELSEIF scanang > .1 THEN
       LOCATE 1, 5: PRINT "Data Peak Area Measurement - file "; file$;
       LOCATE 1, 55: PRINT "Data Peak Number "; peaknumber;
       LOCATE 3, 56: PRINT "Data Set = "; dataset%;
       LOCATE 4, 56: PRINT USING "& #.## &"; "Interval = "; si; " sec";
       LOCATE 5, 56: PRINT USING "& ##.# &"; "Scan angle="; scanang; " deg";
       LOCATE 6, 56: PRINT USING "& ##.## &"; "Scan Rate="; scanrate; "deg/sec";
       LOCATE 7, 56: PRINT "Start Time = "; ti$(peakmin%);
       LOCATE 8, 56: PRINT "Data Set Time = "; scantime%; " sec";
       LOCATE 9, 56: PRINT "Data points = "; datarec%;
       LOCATE 10, 56: PRINT "Scan Dir = "; scanparam$;
       LOCATE 11, 56: PRINT USING "& ###.# &"; "Rise Rate = "; riserate#; "m/s"
       LOCATE 12, 56: PRINT USING "& #.### &"; "MeanAGC = "; meanAGC; "V";
       LOCATE 13, 56: PRINT USING "& #.### &"; "Calibration="; cal; "V";
     ELSE
```

```
    LOCATE 1, 5: PRINT "Data Peak Area Measurement - file "; file$;
    LOCATE 1, 55: PRINT "Data Peak Number "; peaknumber;
    LOCATE 3, 56: PRINT "Data Set = "; dataset%;
    LOCATE 7, 56: PRINT "Start Time = "; ti$(peakmin%);
    LOCATE 8, 56: PRINT "Data Set Time = "; scantime%; " sec";
    LOCATE 9, 56: PRINT "Data points = "; datarec%;
    LOCATE 10, 56: PRINT USING "& #### &"; "Air Speed = "; airspeed#; "m/s";
    LOCATE 11, 56: PRINT USING "& ###.# &"; "Rise Rate = "; riserate#; "m/s";
    LOCATE 12, 56: PRINT USING "& #.### &"; "MeanAGC = "; meanAGC; "V";
    LOCATE 13, 56: PRINT USING "& #.### &"; "Calibration="; cal; "V";
  END IF
  RETURN


SetGraphicScale:
  IF choice% < 3 THEN
    maxy = 1.25 * maxsig%
  ELSE
    IF vertscale = 3 THEN maxy = 720 ELSE IF vertscale = 2 THEN maxy = 480 ELSE IF
vertscale = 1 THEN maxy = 240 ELSE maxy = 120
  END IF
  IF maxy > 240 THEN miny = -80 ELSE miny = -40
  rangey = maxy - miny
  pixel = .0075 * rangey
  WINDOW (0, miny)-(400, maxy)
  LINE (4, miny)-(400, maxy), , B 'draw box
  'clear x-axis labels
  FOR row = 1 TO 23
   LOCATE row, 1: PRINT "   "
  NEXT row
  'clear tic marks
  FOR column = 0 TO 3
  LINE (column, maxy)-(column, miny), 0
  NEXT column
  'V for volts
  LOCATE 1, 2: PRINT "V"
  'add tic marks and labels
  FOR tic% = 0 TO INT(maxy / 48!)
  LINE (0, 48 * tic%)-(4, 48 * tic%)
  IF maxy < 250 OR maxy < 400 AND tic% MOD 2 = 0 OR tic% MOD 4 = 0 THEN
    IF rangey = 0 THEN
      labelrow% = 0
    ELSE
      labelrow% = 2 + INT(((21 * maxy) - (tic% * 1008)) / rangey)
    END IF
    IF labelrow% > 1 AND labelrow% < 23 THEN
      LOCATE labelrow%, 1
      PRINT USING "#.#"; .1 * tic%
    END IF
  END IF
  NEXT tic%

  RETURN



DisplayDataSet:
  '
  FOR i = 2 TO maxx%
  x% = i + 4
  top = maxy - pixel
  bottom = miny + pixel
  '
  'plot strip chart of data
  '
  'move cursor
  LINE (x% + 1, bottom)-(x% + 1, -pixel): LINE (x% + 1, pixel)-(x% + 1, top)'plot
cursor line
  LINE (x%, bottom)-(x%, -pixel), 0: LINE (x%, pixel)-(x%, top), 0'remove previous
cursor

  '
  'plot zero line
  IF x% MOD 16 < 9 THEN PSET (x%, 0) ELSE PRESET (x%, 0)
  '
  'delineate data set with dashed lines
  IF i = peakmin% AND peakmin% > 1 THEN LINE (x% - 1, bottom + 3 * pixel)-(x% - 1, top
- 3 * pixel), , , &HFF00
```

```
     '
     IF i = peakmax% OR (i < peakmax% AND i = maxx%) THEN
       LINE (x% - 1, bottom + 3 * pixel)-(x% - 1, top - 3 * pixel), , , &HFF00
       LOCATE 4, INT(x% / 8): PRINT dataset%
     END IF
     'plot data
     IF VAL(RIGHT$(ti$(i), 2)) MOD 10 <> 0 THEN
       MARK = 1
     ELSE
       IF MARK = 1 THEN
         LINE (x%, bottom + .03 * rangey)-(x%, bottom)
         MARK = 0
       END IF
     END IF
     IF x% = 5 THEN GOTO 1446
     LINE (x% - 1, diprev%)-(x%, sig%(i))
1446 diprev% = sig%(i)
     '
     NEXT i
     '
     RETURN


ChooseInflectionPoints:
     newpeak% = 0
     peakcenter% = INT(peakmin% + (peakmax% - peakmin%) / 2)
     LOCATE 25, 1: PRINT SPACE$(80);
     IF choice% > 1 THEN
       LOCATE 25, 1: PRINT "Move cursor as required and <ENTER>, 1=next peak, 2=change
speeds, ESC=quit";
     ELSE
       LOCATE 25, 1: PRINT "Move cursor as required and <ENTER>, 1=next peak, ESC=quit";
     END IF
     LOCATE 3, 34: PRINT "Mark left baseline  ";
     cxo = peakcenter%: cyo = 4 * pixel: cx = peakcenter%: cy = 4 * pixel
cr1: GOSUB Cross: lbx% = cx: lby% = cy
     IF newpeak% = 1 THEN GOTO 333
     IF newpeak% = 2 THEN GOSUB ChangeParameters: newpeak% = 0: GOTO cr1
     IF beginagain <> 0 THEN RETURN
     LOCATE 3, 34: PRINT "Mark right baseline ";
     cxo = peakcenter%:  cx = peakcenter%
cr2: GOSUB Cross: rbx% = cx: rby% = cy
     IF newpeak% = 1 THEN GOTO 333
     IF newpeak% = 2 THEN GOSUB ChangeParameters: newpeak% = 0: GOTO cr2
     IF beginagain <> 0 THEN RETURN
     IF lbx% > rbx% THEN
       SWAP lbx%, rbx%
       SWAP lby%, rby%
     END IF
     LINE (lbx%, lby%)-(rbx%, rby%)
     IF choice% = 1 THEN 'mark peak edges for cal option
       LOCATE 3, 34: PRINT "Mark left peak edge ";
       cxo = peakcenter%: cyo = 40 * pixel: cx = peakcenter%: cy = 40 * pixel
cr3:   GOSUB Cross: lpx% = cx: lpy% = cy
       IF newpeak% = 1 THEN GOTO 333
       IF beginagain <> 0 THEN RETURN
       LOCATE 3, 34: PRINT "Mark right peak edge";
       cxo = peakcenter%: cx = peakcenter%
cr4:   GOSUB Cross: rpx% = cx: rpy% = cy
       IF newpeak% = 1 THEN GOTO 333
       IF beginagain <> 0 THEN RETURN
       IF lpx% > rpx% THEN
         SWAP lpx%, rpx%
         SWAP lpy%, rpy%
       END IF
     END IF
333  LOCATE 3, 34: PRINT SPACE$(20);
     RETURN

ChangeParameters: ' subroutine to change windspeed, etc.
334  LOCATE 25, 1: PRINT SPACE$(80);
     LOCATE 25, 1: PRINT "Input new rise-rate/wind-speed (meters/second) ";
     inputstring$ = ""
335  a$ = INKEY$: IF a$ = "" THEN GOTO 335 ELSE IF ASC(a$) <> 13 THEN inputstring$ =
inputstring$ + a$: GOTO 335
     riserate# = VAL(inputstring$)
     IF riserate# < .001 THEN GOTO 334
     LOCATE 25, 53: PRINT riserate#;
```

```
     LOCATE 11, 56: PRINT USING "& ###.# &"; "Rise Rate = "; riserate#; "m/s"
     FOR i = 1 TO 5000: NEXT i'  pause
     IF scanang < .1 THEN
336    LOCATE 25, 1: PRINT SPACE$(80);
       LOCATE 25, 1: PRINT "Input new air-speed/ground-speed (meters/second) "
       inputstring$ = ""
337    a$ = INKEY$: IF a$ = "" THEN GOTO 337 ELSE IF ASC(a$) <> 13 THEN inputstring$ =
inputstring$ + a$: GOTO 337
       airspeed# = VAL(inputstring$)
       IF airspeed# < .001 THEN GOTO 334
       LOCATE 25, 53: PRINT airspeed#;
       LOCATE 10, 56: PRINT USING "& #### &"; "Air Speed = "; airspeed#; "m/s"
     FOR i = 1 TO 5000: NEXT i'  pause
     END IF
     LOCATE 25, 1: PRINT SPACE$(80);
     LOCATE 25, 1: PRINT "Move cursor as required and <ENTER>, 1=next peak, 2=change
speeds, ESC=quit";
     RETURN


Cross: 'movable cursor subroutine
      '
7000 LINE (cxo - 3, CINT(cyo))-(cxo + 3, CINT(cyo)), 0
     LINE (cxo, CINT(cyo - 2 * pixel))-(cxo, CINT(cyo + 2 * pixel)), 0
     LINE (cx - 3, CINT(cy))-(cx + 3, CINT(cy))
     LINE (cx, CINT(cy - 2 * pixel))-(cx, CINT(cy + 2 * pixel))
     IF cx - 4 >= 5 THEN replotmin% = cx - 4 ELSE replotmin% = 5
     IF cx + 4 <= 399 THEN replotmax% = cx + 4 ELSE replotmax% = 399
     FOR i = replotmin% TO replotmax% + 2
      LINE (i - 1, sig%(i - 5))-(i, sig%(i - 4))
      IF i MOD 16 < 9 THEN PSET (i, 0)
     NEXT i
7010 a$ = INKEY$: IF a$ = "" GOTO 7010
     a2 = ASC(RIGHT$(a$, 1))
     IF a2 = 27 THEN CLS 0: beginagain = 1: RETURN ELSE IF a2 = 49 THEN newpeak% = 1:
RETURN ELSE IF a2 = 50 THEN newpeak% = 2: RETURN
     cyo = cy: cxo = cx
     IF a2 = 72 THEN
       IF cy < maxy - pixel THEN cy = cy + pixel ELSE BEEP
     ELSEIF a2 = 80 THEN
       IF cy > miny + pixel THEN cy = cy - pixel ELSE BEEP
     ELSEIF a2 = 77 THEN
       IF cx < 400 THEN cx = cx + 1 ELSE BEEP
     ELSEIF a2 = 75 THEN
       IF cx > 1 THEN cx = cx - 1 ELSE BEEP
     ELSE RETURN
     END IF
     GOTO 7000
     RETURN

CalculateCalibrationData:
     baseline = ((lby% + rby%) / 2) / 480
     peakwidth = rpx% - lpx% + 1
     peaktotal! = 0
     FOR i = lpx% TO rpx%
     peaktotal! = peaktotal! + sig%(i - 4)
     NEXT i
     IF peakwidth = 0 THEN
       meanpeak = 0
     ELSE
       meanpeak = (peaktotal! / peakwidth) / 480
     END IF
     netpeakheight = meanpeak - baseline
     IF caltype$ = "High" THEN netpeakheight = netpeakheight * (180 / 590)
     LOCATE 11, 56: PRINT USING "& #.### &"; "Baseline = "; baseline; "V";
     LOCATE 12, 56: PRINT USING "& #.### &"; "Peak Height = "; meanpeak; "V";
     LOCATE 13, 56: PRINT USING "& #.### &"; "Net Height = "; netpeakheight; "V";
     GOSUB Checkkey
     RETURN
     '

CalculatePeakData:
     recordtime# = scantime% / datarec%
     LINE (lbx%, lby%)-(lbx%, sig%(lbx% - 4))
     LINE (rbx%, rby%)-(rbx%, sig%(rbx% - 4))
     PAINT ((lbx% + rbx%) / 2, (lby% + rby%) / 2 + 2 * pixel)
     baseline = ((lby% + rby%) / 2) / 480
     peakwidth = (rbx% - lbx% + 1) * recordtime#
```

```
     peakareatotal! = 0
     FOR i = lbx% TO rbx%
     IF rbx% = lbx% THEN
       localbaseline = baseline
     ELSE
       localbaseline = (lby% + ((i - lbx% + 1) / (rbx% - lbx%)) * (rby% - lby%)) / 480
     END IF
     peakareatotal! = peakareatotal! + (sig%(i - 4) / 480 - localbaseline) * recordtime#
     NEXT i
     LOCATE 14, 56: PRINT USING "& #.####"; "Baseline = "; baseline; " V";
     LOCATE 15, 56: PRINT USING "& #.###"; "Max Peak Ht = "; maxsig% / 480!; " V";
     LOCATE 16, 56: PRINT USING "& ####.#"; "Peak Width = "; peakwidth; " sec";
     LOCATE 17, 56: PRINT USING "& ###.#"; "           = "; peakwidth * scanrate; " deg";
     LOCATE 18, 56: PRINT USING "& ###.#"; "Peak Area = "; peakareatotal!; " Vsec"
     GOSUB Calcflux
     GOSUB Checkkey
     RETURN

Calcflux:
     IF cal = 0 THEN
       calconst# = 0
     ELSE
       calconst# = 180 / cal
     END IF
     tondayfactor# = .00023
     degperrad# = 57.2975
     IF peakwidth > 0 THEN
       burden# = (peakareatotal! / peakwidth) * calconst#
     ELSE
       burden# = 0
     END IF
     IF scanang > 0 THEN
      plumewidth# = 2 * TAN((½*peakwidth * scanrate) / degperrad#) * distance#
     ELSE
      plumewidth# = peakwidth * airspeed#
     END IF
     flux# = burden# * plumewidth# * riserate# * tondayfactor#
     LOCATE 20, 56: PRINT USING "& ####.# &"; "Plume Width ="; plumewidth#; "m";
     LOCATE 21, 56: PRINT USING "& ####.# &"; "Burden ="; burden#; "ppmm";
     LOCATE 22, 56: PRINT USING "& ###.## &"; "Flux ="; flux#; "tons/day";
     RETURN


Checkkey:  'subroutine to choose option at end of calculation
211  LOCATE 25, 1
     PRINT "Enter=store and continue, 1=redo, 2=repeat, 3=discard, ESC=quit";
212  a$ = INKEY$: IF a$ = "" THEN GOTO 212
     LOCATE 25, 1: PRINT SPACE$(80);
     a2% = ASC(a$)
     IF a2% = 13 OR a2% = 32 THEN
       choice2% = 1          'continue
     ELSEIF a2% = 49 THEN
       choice2% = 2          'redo
     ELSEIF a2% = 50 THEN
       choice2% = 3          'repeat
     ELSEIF a2% = 51 THEN
       choice2% = 4          'discard
     ELSEIF a2% = 27 THEN
       choice2% = 5          'quit
     ELSE GOTO 211
     END IF
     RETURN

StoreCalData:
     FOR i = outputchoice% TO 3
       IF pagecount% = 1 THEN
             PRINT #i, : PRINT #i, : PRINT #i,
             PRINT #i, "file: "; file$; "     "; dat$
             PRINT #i,
             PRINT #i, "data   start   scan   scan    mean     base    peak      net"
             PRINT #i, " set    time    time    ang    AGC      line    height   cal"
             PRINT #i, "                sec    deg      V        V        V        V "
             PRINT #i, "---- --------   ----- ------   -----   ------   ------  -----"
       END IF
       PRINT #i, USING "###  \      \   ###  ###.#   ##.##   ##.###   #.###    #.###";
dataset%; ti$(peakmin%); scantime%; scanang; meanAGC; baseline; meanpeak; netpeakheight
     NEXT i
     pagecount% = pagecount% + 1
```

```
     RETURN


StorePeakData:
     FOR i = outputchoice% TO 3
       IF pagecount% = 1 THEN
             PRINT #i, : PRINT #i, : PRINT #i,
             PRINT #i, "file: "; file$; "     "; dat$
             PRINT #i, "distance to plume = "; distance#; " m"
             PRINT #i,
             IF scanang > .1 THEN
              PRINT #i, "data start   scan  scan   scan  mean    cal    plume  peak
burden  rise  flux"
              PRINT #i, " set  time   time   ang   rate   AGC           width  area
 rate       "
              PRINT #i, "              sec   deg   o/sec   V      V       m    Vsec  ppmm
  m/s   t/d"
              PRINT #i, "--- --------  ---  -----  ----  ----- ------  ------  -----
------  ----  ------"
             ELSE
              PRINT #i, "data start   scan   airspeed/   mean    cal    plume  peak
burden  rise  flux"
              PRINT #i, " set  time   time  groundspeed   AGC           width  area
 rate       "
              PRINT #i, "              sec     m/sec       V      V       m    Vsec  ppmm
  m/s   t/d"
              PRINT #i, "--- --------  ---  -----------  ----- ------  ------  -----
------  ----  ------"
             END IF
       END IF
       IF scanang > .1 THEN
        PRINT #i, USING "### \      \  ###  ##.#   #.##  ##.## ##.###  ####.#  ##.##
####.#  ##.#  ####.#"; dataset%; ti$(peakmin%); scantime%; scanang; scanrate; meanAGC;
cal; plumewidth#; peakareatotal!; burden#; riserate#; flux#
       ELSE
        PRINT #i, USING "### \      \  ###     ####.#    ##.## ##.###  ####.#  ##.##
####.#  ##.#  ####.#"; dataset%; ti$(peakmin%); scantime%; airspeed#; meanAGC; cal;
plumewidth#; peakareatotal!; burden#; riserate#; flux#
       END IF
       NEXT i
     pagecount% = pagecount% + 1
     RETURN
     '

TestKey:  'subroutine to act on key choices
     a$ = INKEY$
     IF a$ = "" THEN
       RETURN
       '
     ELSEIF ASC(a$) = 27 THEN  '<ESC> to terminate log
       LOCATE 24, 1:  PRINT " TERMINATED "; SPACE$(60);
       LOCATE 22, 1: CLOSE #1: beginagain = 1: RETURN
       '
     ELSEIF ASC(a$) = 32 THEN  'SPACE to pause
       LOCATE 23, 2: PRINT "Program halted, press any key to continue";
1800   a$ = INKEY$: IF a$ = "" THEN GOTO 1800
       LOCATE 23, 2: PRINT SPACE$(42);
     ELSEIF ASC(a$) = 49 THEN  '1 to change vertical scale
       vertscale = vertscale + 1: IF vertscale = 4 THEN vertscale = 0
       GOSUB SetGraphicScale
       '
     ELSEIF ASC(a$) = 50 THEN  '2 to change horizontal scale
       horizhalf% = horizhalf% * -1
       '
     END IF
     RETURN

     '

DetermineScanParameters: 'subroutine to interpret analog scanner data
     IF (di%(4) > 10) THEN GOTO 1403 ELSE scanparam$ = "  ": GOTO 1405
1403 IF (di%(4) > 250) THEN GOTO 1404 ELSE scanparam$ = "Right": GOTO 1409
1404 scanparam$ = "Left ": GOTO 1409
1405 IF (di%(5) > 10) THEN GOTO 1406 ELSE scanparam$ = "  ": GOTO 1409
1406 IF (di%(5) > 250) THEN GOTO 1407 ELSE scamparam$ = "Down ": GOTO 1409
1407 tilt$ = "Up   "
1409 RETURN
```

Appendix D: SO_2 Emission Data

The following tables contain all the SO_2 emission data collected at Pu'u O'o Vent during March 1989 and at Mount Erebus, Antarctica during the 1987, 1988 and 1989 field seasons obtained and reduced for the purposes of this study:

Data is available on diskette (either in ASCII or lotus *.prn/Quattro Pro format. Requests should be sent to Dr. Philip Kyle, c/o Geoscience, New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801. (Phone: (505)-835-5995)

Appendix E: Time Series and the Fourier Transform

Time series, in their simplest form, are merely a collection of numerical observations arranged in a natural order (Bloomfield, 1976). Periodicities or cyclical behavior in time series occur when one or more random harmonic structure is incorporated to make up the time series (Shumway, 1988). Most statistical methods for harmonic analysis of time series depend upon the assumption that adjacent observations in a time series are independently made an identically distributed over time.

Two domains are common among periodic data: The time domain is bast thought of as a correlation among adjacent time series data explained in terms of a regression of the current value on past values. In the frequency domain, a time series is regarded as a sum or linear superposition of periodic sine and/or cosine waves of different periods or frequencies, in other words, events in these types of time series are generated by periodic phenomena (Shumway, 1988).

Fourier analysis of time series simply decomposes the series into a sum of sinusoidal components, the coefficients of which are known as the discrete Fourier transform of the series. Mathematically, the Fourier transform of a series of length N can be expressed:

$$f(t) \Leftrightarrow F(\nu)$$
$$f(t) = \frac{1}{2\pi}\sum F(2\pi\nu)\,e^{(-i2\pi\nu t)}$$
$$f(t) = \sum\left[a_k\cos(2\pi\nu_k t) + ib_k\sin(2\pi\nu_k t)\right]$$

where a_k and b_k represent the amplitudes of the wave functions for the k^{th} measurements; v_k is the frequency of the k^{th} wave function in cycles per unit time (this frequency is often expressed in radians per second, using the Greek character omega which equals 2π times the frequency in cycles per second).

The Fourier transform is a linear operation that converts the data from the time series (x as a function of time) to a frequency series the amplitude of F is a function of frequency).

Aliasing

All frequency units are non-negative when using Fourier analysis since cos (-x) = cos x and sin (-x) = -sin x. Any wave function of frequency -v can therefore be written:

$$a\cos(-2\pi\nu t) + b\sin(-2\pi\nu t) = a\cos(2\pi\nu t) - b\sin(2\pi\nu t)$$

The projection of the negative frequency onto the positive frequency is a known as aliasing. This is not the only form of aliasing that exists in time series analysis.

A continuous function f(t), discretely sampled at a sampling interval ▲, is band width limited to frequencies smaller in magnitude than the frequency equal to 1/2 times

the sampling period (the Nyquist critical frequency). In other words, if $F(v) = 0$ for all v such that $|v| >$ the Nyquist frequency, then the function $f(t)$ is completely determined by its samples, f_n.

In most cases, unfortunately, information is lost by taking a discrete sequence of observations over a continuous function. The loss of information manifests itself in another form of aliasing. The effect of sampling a function that is not band width limited to less than the Nyquist frequency is that all the power spectral density that lies outside the range $-v_c < 0 < v_c$ is projected onto that range.

Aliasing can be overcome be knowing the natural band width of the signal in advance or enforcing a known limit using an analog filter on the continuous signal; or by sampling at a rate rapid enough to give at least two points per cycle for the highest frequency present.

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This thesis is accepted on behalf of the faculty of the Institute by the following committee:

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4/29/91
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