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Carbon dioxide and carbon monoxide emission rates from an alkaline intra-plate volcano: Mt. Erebus, Antarctica

L.J. Wardell[a,*], P.R. Kyle[b], C. Chaffin[c]

[a] Department of Earth and Planetary Sciences, McGill University, 3450 University Street, Montreal, QC, Canada H3A 2A7
[b] Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, USA
[c] Aerosurvey Inc., P.O. Box 1163, Manhattan, KS 66502, USA

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Abstract

This is the first report of CO and CO_2 flux from Mt. Erebus, Antarctica, an alkaline intra-plate volcano with a convecting lava lake. The CO_2 flux from the Mt. Erebus plume was measured by in-plume infrared analysis during December 1997, December 1999 and January 2001. The CO_2 emission rates were consistently close to the average of 22.3 kg/s (1930 Mg/day) for the three measurements conducted over a 4-year period even though the third measurement (January 2001) was conducted at a time of elevated activity. As CO_2 is considered a good indicator of eruptive activity a more frequent type of monitoring system may be necessary to detect changes related to activity at Mt. Erebus. Increased CO_2 emissions lost via Strombolian eruptions in the lava lake were not accounted for in our airborne measurements. Carbon monoxide flux, determined by Fourier transform infrared spectroscopy in December 1995, yielded a rate of 1.74 kg/s (150 Mg/day) and a high CO:CO_2 ratio of 0.12.

Keywords: Mt. Erebus; carbon dioxide; volcanic gas flux; carbon monoxide

1. Introduction

The emission rates of CO_2 from active volcanoes are not only important in assessing volcanic hazards but are needed to understand the role of magmatic CO_2 in the biogeochemical carbon cycle (Brantley and Koepenick, 1995; Gerlach et al., 1997). Volcanism has been credited with the formation of our atmosphere, with causing past climatic events, and even keeping the carbon cycle in balance. However, the volcanic/magmatic input of carbon species to the carbon cycle has yet to be accurately assessed (Gerlach, 1991a; Brantley and Koepenick, 1995; Arthur, 2000; Mörner and Etiope, 2002). Quantifying the rate of CO_2 degassing from magmatic activity has been the most difficult problem in modeling the carbon geochemical cycle (Berner and Lasaga, 1989; Williams et al., 1992; Brantley and Koepenick, 1995; Gerlach et al., 1997; Kerrick, 2001). To acquire a better estimate of the contribution of CO_2 from subaerial volcanism, it would be beneficial to use direct measurements for degassing

* Corresponding author.
E-mail address: wardell@eps.mcgill.ca (L.J. Wardell).

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rates as much as possible in future carbon budget estimates (Berner, 1990; Gerlach, 1991a).

Carbon dioxide is one of the more important gas species for forecasting the eruptive activity of a volcano (Giggenbach, 1983). It is the most abundant gas phase after water in parental magma. Carbon dioxide is likely to be completely exsolved from its magma by the time it can be monitored at the surface (Giggenbach, 1996). Due to its low solubility in magma, efflux of CO_2 can reflect changes deep within the system. Therefore, an increase in volcanic CO_2 emissions can be an early indicator of magma ascent (Bruno et al., 2001). Carbon dioxide is considered a 'conservative' component in that any changes in relative proportions of other chemical species relative to CO_2 actually reflect processes that are affecting that species rather than the CO_2 (Giggenbach, 1996). Compared to the other volatile species in magmas, CO_2 is less likely to be scrubbed out by migration through groundwater systems, which is another important aspect of a chemical indicator (Symonds et al., 1994, 2001). Despite the significance of CO_2 as an indicator for volcanic activity or as a predictive tool, only a few flux measurements have been reported (Harris and Rose, 1996).

Mt. Erebus, Antarctica, the southernmost active volcano, is of particular interest due to its potential effect on the pristine Antarctic environment. This intra-plate volcano is currently the only known active volcano with anorthoclase phonolite magma, and one of the few volcanoes known to have a convecting persistent lava lake (Kyle, 1994). This lava lake serves as an 'open window' to the long-lived near-summit magma reservoir (Aster et al., 2003) and is the source of a persistent gas plume that is the focus of this study. Because of the alkalic nature of the Erebus magma, the emitted gases should be CO_2-rich (Gerlach, 1982; Williams et al., 1992). Furthermore, phonolite has been shown to maintain a high CO_2 solubility at all temperatures in experimental studies (Blank and Brooker, 1994). Measurement of the CO_2 contents in melt inclusions from olivine in the basanite (4000–7300 ppm) which is considered parental to the Erebus phonolite have some of the highest CO_2 concentrations measured to date (Eschenbacher, 1998).

Mt. Etna in Italy is alkalic and was found to be the highest CO_2-producing volcano in the world implying that alkalic volcanoes may, by nature, all be high CO_2 producers (Gerlach, 1991a,b). High CO_2 emission rates found at Mt. Etna (Gerlach, 1991b) and at Oldoinyo Lengai in Tanzania (Koepenick et al., 1996) also suggested that intraplate degassing could be significantly large and efforts should be made to represent the emissions from this type of volcano in global geochemical carbon cycle models (Gerlach, 1991a,b Koepenick et al., 1996; Mörner and Etiope, 2002). It was therefore of much interest to make direct measurements of CO_2 emissions from Mt. Erebus.

2. Methods

Carbon dioxide measurements were made with a portable infrared CO_2 analyzer (model LI-COR 6262 made by LI-COR, Lincoln, NE, USA). The LI-COR analyzer has a reported accuracy of ± 1 μmol/mol. The inlet hose for the analyzer was attached to the horizontal antenna extending from the front of an AS350 A-Star helicopter. The antenna extends over 2 m in front of the aircraft. Airborne sampling using an inlet on the nose antenna of helicopters has been used routinely in other studies (Cofer et al., 1998). Sampling is not affected by rotor downwash if the aircraft is operated at speeds above 65 km/h (18 m/s) (Landgrebe et al., 1982; Cofer et al., 1990, 1998). Helicopter speeds in excess of 110 km/h (31 m/s) were used during airborne sampling at Mt. Erebus. The sampling inlet hose was passed through a side window to the back seat of the aircraft where it was attached to the CO_2 analyzer. A flow controller unit was adjusted to give a sample rate of 0.03 l/s (2 l/min). The analyzer was equipped with both temperature and pressure transducers to adjust for changes in these variables. The analyzer yielded real-time measurements of CO_2 in μmol/mol/ at 1-s intervals.

During plume measurements a pair of Trimble 4000 GPS receivers were used to provide location data on the helicopter. A base station was located at permanent GPS monuments located at McMurdo Station or the Lower Erebus Hut. The

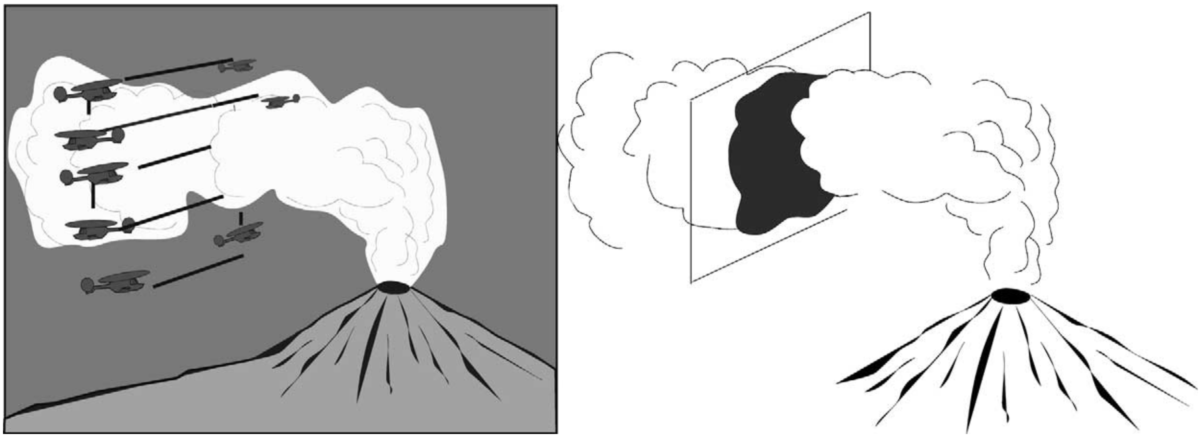
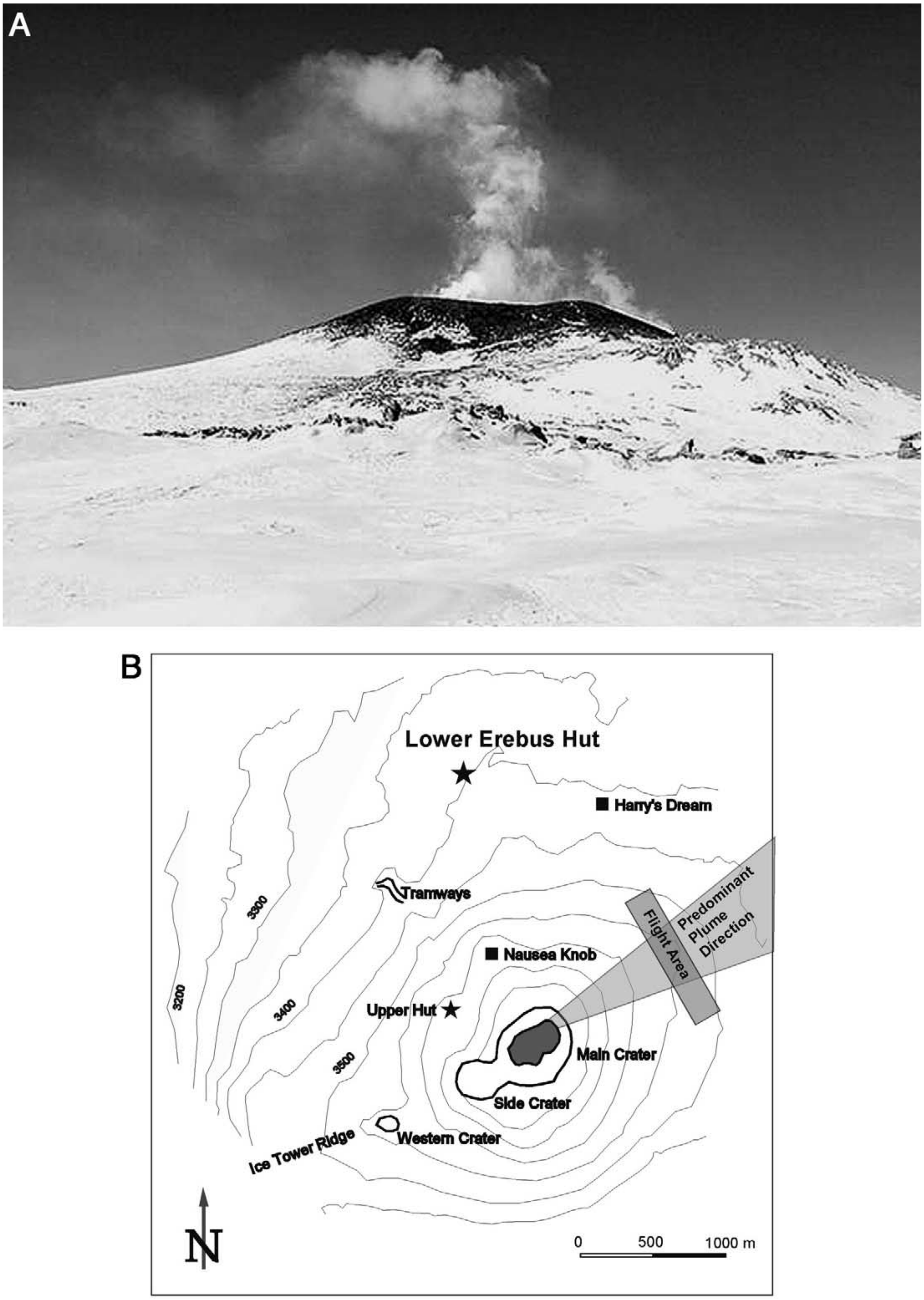


Fig. 1. The ladder technique is the flight path originating below the plume and making a transect across the plume perpendicular to the wind direction. The aircraft will then move up, usually at 30-m intervals, and turn 180° and fly another transect through the plume. This pattern is repeated until the top of the plume is reached. The goal is to obtain data to construct the CO_2 concentration in a cross-section or 'thin slice' of the plume. Theoretically, the ladder technique is designed to take numerous measurements in a plane normal to the plume, but as the plume is moving, the plume is assumed to remain uniform during the measurement period. It is the total CO_2 in this cross-section, multiplied by the wind speed that yields the CO_2 flux.

antenna for the roving unit was placed on the dashboard inside the helicopter. Position data were acquired at 1-s intervals and had an accuracy of less than 1 m.

A 'ladder survey' was conducted by flying the helicopter at a constant speed in transects perpendicular to the plume's wind direction (Fig. 1). The first transect began below the visible plume and in each sequential transect the altitude was ~30 m higher. Ten to 16 transects were usually required to reach the top of the visible plume. The flight pattern was performed ~1 km from the crater rim. The procedures followed those reported by Gerlach et al. (1997) and Koepenick et al. (1996). Wind velocity was measured by flying the helicopter at a constant velocity along the axis of the plume in the downwind and upwind directions. Wind speed was calculated from the difference in ground speeds as reported by the GPS navigation system on the aircraft.

The 1-s CO_2 observations were coordinated with and combined with the 1-s GPS position data to produce a plot of the CO_2 concentration in the plume cross-section. The plots were made using SURFER software (Golden Software, Golden, CO, USA) with the Kriging algorithm. After the background ambient CO_2 was subtracted, the plume CO_2 flux was calculated by multiplying the area of each contour by its corresponding CO_2 concentration, and the sum of these contour segments was then multiplied by the wind speed. Ideal plume geometry, which is dependent mainly on wind conditions, is needed to perform the measurements. The most advantageous factors include minimal cloud and low humidity, so that the plume is visible, and moderate wind speeds so the plume has good geometry (Fig. 2A). Low wind conditions caused the plume to disperse radially around the volcano so that a linear plume was not formed. High wind speeds sheared the plume so a turbulent flow caused the plume to hug the ground making it impossible to fly beneath the plume. Measurements were sometimes conducted under marginal atmospheric conditions that resulted in poor plume geometry. These resulted in cross-sections that did not adequately capture the plume concentrations or the data looked so diffuse that a plume structure could not be singled out. On 9 January 2001, wind conditions stagnated during the flight so that the plume started rising upward and the top of the plume was never reached, even at 4850 m. Poor plume geometry is the most common problem followed by poor data recovery from instruments. The GPS unit would sometimes have trouble regaining its full satellite lock after a


A
B
Lower Erebus Hut
Harry's Dream
Tramways
3300
3200
3400
3500
Nausea Knob
Upper Hut
Predominant Plume Direction
Flight Area
Main Crater
Side Crater
Western Crater
Ice Tower Ridge
N
0
500
1000 m

sharp turn by the helicopter. The most complete plume cross-section was chosen from each of the three seasons rather than incorporating data with obvious deficiencies. Flux values were then calculated only after the poor cross-sections had been rejected. The major contribution to uncertainty of calculated flux is associated with determination of the wind speed and identifying the background CO_2 levels. Other sources of uncertainty such as from instrumentation, data processing, atmospheric effects, pilot skill, etc., were considered to be significantly smaller than the major error sources. The standard errors determined by Gerlach et al. (1997) also assumed that uncertainty from sources such as instrumentation was trivial compared to the natural variances.

Carbon monoxide measurements were performed using Fourier transform infrared (FTIR) techniques during 9, 13 and 14 December 1995 at the crater rim of Mt. Erebus (Wardell et al., 1999). Spectra were collected with a Midac M2401-C spectrometer mounted to a Midac 10″ collection telescope (MIDAC Corporation, Costa Mesa, CA, USA). Source radiation was provided by a Midac field source assembly incorporating a SiC glower. Dual-beam absorbance spectra were created by arbitrarily choosing a single-beam spectrum as a background with all other spectra collected over the same path then used as sample spectra. The files displaying the least amount of spectral contributions from the volcanic plume were used as backgrounds. The spectral signatures of CO and SO_2 were quantitatively measured via comparison to reference spectra from a commercial spectral library (QASOFT by Infrared Analysis, Anaheim, CA, USA). The FTIR system was operated over path lengths of approximately 200 m and provided spectral response between approximately 650 and 3500 cm^{-1}. The relative levels of the analytes were calculated and reported as a CO:SO_2 ratio. The CO flux is then calculated by the corresponding SO_2 flux measured by a correlation spectrometer (COSPEC, Barringer Research, Mississauga, ON, Canada).

3. Results

The volcanic gas plume flowed predominately to the east for the majority of the plume flights (Fig. 2B). The 1997 measurement (Fig. 3A) yields a plume concentration cross-section that shows some atmospheric mixing with a large hole appearing in the center. Small portions of the plume appear to have escaped the cross-section that partially spanned an area of 1000×300 m. Maximum concentrations in the plume reached 25 ppm CO_2 above ambient with a wind speed of 3.1 m/s. The 1999 measurement (Fig. 3B) showed that a more uniform cross-section was formed with a lower wind speed. Plume dimensions reached approximately 800×300 m, with the highest CO_2 concentrations reaching 25 ppm above ambient. Although this plume had the lowest wind speed (2.0 m/s), it exhibited the largest average CO_2 concentration from being more uniform and thus yielding a comparable flux value to the other plume measurements. The 1999 plume showed good geometry even though a portion of the plume appeared to have escaped measurement on one end (Fig. 3B). The 2001 plume measurement shows a flat elongated cross-section (Fig. 3C) due to higher wind speeds (6.7 m/s). The plume covers about 2000×200 m and was the only plume measurement that captured the whole plume in the cross-section. The highest concentration was 29 ppm CO_2 above ambient but is overall a more dilute plume. This plume also maintained good geometric integrity unlike the 1997 plume that showed non-uniform atmospheric mixing.

Results show similar CO_2 emissions of 21.4,

Fig. 2. (A) Photograph of the summit of Mt. Erebus and the gas plume. This is a view of the summit as seen from Lower Erebus Hut, looking south, in December 1999. The plume is traveling easterly, in the predominant plume direction as indicated in (B). Low wind conditions allow the plume to rise above the crater before moving in the easterly direction. (B) Summit map of Mt. Erebus, Antarctica. The shaded area indicates the predominate location of the plume. The location of the perpendicular flight transects is also indicated.

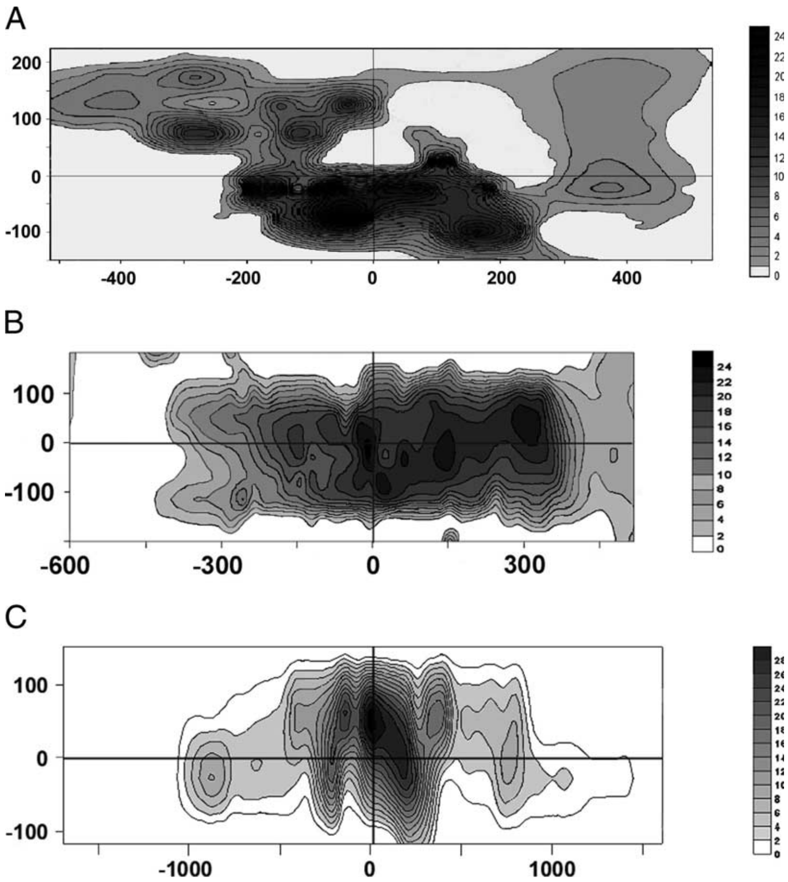


Fig. 3. (A) Cross-section of CO_2 concentration in Mt. Erebus plume measured normal to its westward direction on 18 December, 1997. Wind speed was measured to be 3.1 m/s with 16 transects used to accumulate the data set. This cross-section yields a CO_2 flux of 21.4 kg/s. (B) Cross-section of Mt. Erebus plume measured on 17 December 1999. This plume exhibited a lower wind speed of 2.0 m/s allowing the formation of a taller cross-section but yielding a similar CO_2 flux to the other two measurements. The CO_2 flux calculated from this cross-section is 23.3 kg/s. (C) Cross-section of Mt. Erebus plume measured on 16 January 2001. This plume exhibited the highest wind speed of 6.7 m/s, giving it a flatter configuration. The calculated flux is 22.2 kg/s.

23.3, and 22.2 kg/s for measurements conducted on 18 December 1997, 17 December 1999 and 16 January 2001, with respective wind speeds of 3.1, 2.0 and 6.7 m/s (Table 1). The average value for the three measurements is 22.3 ± 1.0 kg/s. The measurements agree within 4.3% based on the standard deviation expressed as percent of the mean and suggest a constant emission rate for Mt. Erebus during December 1997 through January 2001. Propagation error was calculated to be $\pm 23\%$. The estimated errors used to calculate the propagation error include a 5% error for the CO_2 concentration of each contour, 10% for calculated areas within the plume cross-section, and 20% for the measured wind speed during the airborne measurements.

Results from the FTIR measurements (December 1995) yield a range for the $CO{:}SO_2$ molar ratio from 2.51 to 3.28 (Table 2) with an average of 2.96. Using corresponding SO_2 flux from Mt. Erebus as measured by COSPEC of 0.58 kg/s (50 Mg/day) (Philip Kyle, unpublished data), the CO flux is 1.74 kg/s (150 Mg/day). The overall standard deviation from the average of the sample sets (column 4, Table 2) expressed as a percent of the mean is 10.9%.

Table 1
Data from the direct airborne measurement sessions at Mt. Erebus

Flight session	Number of passes	Aircraft speed (m/s)	GPS base station	Min/max elevation (m)	Flight time (min)	Wind direction (°)	Wind speed (m/s)	Max CO_2 (ppm)	Background CO_2 (ppm)	CO_2 flux (kg/s)
18 Dec 1997	12	31	LEH	3930/4270	28	086	3.1	425	392	21.4 (1850 tons/day)
17 Dec 1999	16	36	LEH	4080/4710	56	081	2	405	380	23.3 (2013 tons/day)
16 Jan 2001	14	36	McM	3870/4180	21	099	6.7	375	350	22.2 (1915 tons/day)

The number of passes refers to the airborne transects normal to the plume at varying elevations. Flight time is the total time required to complete the total number of passes for that session. The flight time is dependent on the number of passes, plume geometry, atmospheric conditions and pilot experience. LEH refers to the GPS station location at the base camp known as Lower Erebus Hut and McM is located at McMurdo Station, Antarctica.

4. Discussion

Results from Mt. Erebus fortunately spanned a phase of activity that was considered typically stable to a stage of elevated activity. Measurements of CO_2 flux from Mt. Erebus varied little in magnitude over the December 1997–January 2001 study period. For several years prior to 1997 and through 1999, Mt. Erebus had exhibited steady and constant activity consisting of a persistent gas plume exiting from the lava lake in the Main Crater and several small Strombolian eruptions per day, thus the CO_2 emission rate was expected to remain stable. Months before the January 2001 measurement, activity at Mt. Erebus increased and changes in eruption intensity and frequency were observed during the December 2000–January 2001 field season. In addition, variation in the lava lake levels resulting in lava flows of tens of meters was also observed, as well as the formation of a new lava pond and formation of an ash vent (Wardell et al., submitted). Unusual plume characteristics were occasionally observed that season and included small dark ash clouds in the plume as well as a puffing behavior. Unusual episodes of harmonic tremor were recorded (Ruiz et al., 2002), and tiltmeter data correlated tilt changes with a rise in the lava lake levels (Kyle et al., 2001) suggesting that there was recharge into the inner crater system from a larger underlying magma reservoir (Aster et al., 2003). Monitoring of trace element emissions showed a change in As:S in 2000 compared to previous seasons of 1997 and 1999, suggesting a correlation with activity (Wardell et al., submitted). However, CO_2 plume flux measured on 16 January 2001 was similar to the two earlier measurements in 1997 and 1999 and did not reflect this change in activity.

As CO_2 should be a good indicator of eruptive activity, it is possible that emissions could be changing intermittently without being detected by a single biennial sampling event. During the airborne measurement of the CO_2 flux on 16 January 2001, a puff of gas was observed exiting the main crater and traveled along the plume's axis. We traversed through the puff with our instrumentation and observed the highest anomalous

Table 2
The $CO:SO_2$ molar ratios from 1995 open-path FTIR measurements of Mt. Erebus

Day (1995)	Time period monitored	Number of data points	Average of sample set	Standard deviation
Dec 9	16:26 to 17:50	61	2.51	0.31
Dec 9	21:01 to 22:07	42	2.74	0.28
Dec 13	11:30 to 11:39	10	3.28	0.27
Dec 13	15:14 to 16:35	21	3.15	0.53
Dec 14	15:43 to 16:28	15	3.12	0.23

value within the plume to be 102 ppm CO_2 above background. This compares to our highest value of 28 ppm CO_2 above background for all other plume measurements that we performed on Mt. Erebus over the three seasons. The flux within the puff was not quantified as we were only able to accomplish this one traverse before the puff dissipated into the plume and could no longer be visually located. The traverse was repeated so the cross-section would not be affected by this anomaly. Therefore, it is likely that CO_2 fluxes were elevated with increased puffing and bubble bursting in the lava lake.

The configuration of the degassing system may also give insight into why the CO_2 emission rate appears stable. The lava lake eruption model proposed by Aster et al. (2003) suggests that large slugs of gas are formed in a summit magma reservoir before they ascend to the surface of the lava lake, resulting in a Strombolian-style eruption (Fig. 4). The injection of fresh magma into the summit reservoir may not have been large

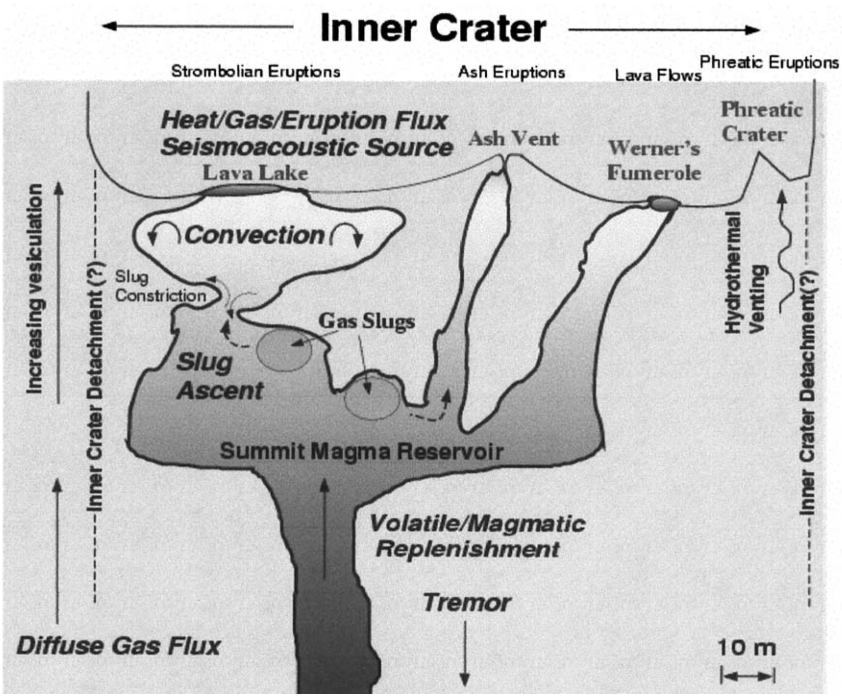


Fig. 4. Conceptual model of the Erebus summit magmatic system taken from Aster et al. (2003). The Inner Crater is underlain by a near-summit magma reservoir of comparable dimension. The differing character for the three presently active vents, which are linked to the summit magma reservoir at shallow depths, is modulated by the geometry of the shallow magmatic plumbing system. Lava lake explosions arise from the intact delivery of large (>5 m diameter) simple gas slugs via the lava lake vent.

enough to change the CO_2 flux contributed by outgassing via convection through the lava lake. However, additional CO_2 loss through expulsion of volcanic gases via gas slug formation and bubble bursting in the lava lake may have increased during this period of elevated activity inside the main crater. Therefore increases in eruptive activity may coincide with intermittent increases in CO_2 emissions via gas bubble formation and the gases from these slugs are not accounted for in our measuring technique, if the overall CO_2 efflux is indeed changing. Intermittent increases in CO_2 emissions were observed at Popocatèpetl with short-lived (0.5–3.0 h) elevations in the CO_2:SO_2, rising to 30 times the normal ratio (Goff et al., 2001). Goff et al. (2001) suspect that this intermittent behavior may be occurring at other sites, particularly volcanoes that are underlain by carbonate.

The overall stability of the CO_2 flux as suggested by our airborne measurements may result from continuous degassing occurring deep (>13 km) within the system and not from the shallow magma chamber. Melt inclusion work by Eschenbacher (1998) found that a CO_2-rich fluid (~ 90 mol%) is degassed from basanite parent magmas at pressures corresponding to depths of 8–13 km and that the theoretical CO_2 flux is much smaller than what was observed with the airborne measurements. Although such excesses in observed volatile flux can occur through magma convection in a conduit (Kazahaya et al., 1994) as exists at Mt. Erebus, Eschenbacher (1998) found this to be unlikely and attributes the source of excess CO_2 emission to be from basanite magma at depths in the system beyond what is recorded by the melt inclusions (~ 4.5 kbar) and suggests the possibility of a separate CO_2-rich fluid phase emanating from below 13 km in this open system. This may possibly explain why the measured CO_2 flux from Mt. Erebus did not change even though there was increased activity in the shallow part of the system.

In general, sources of error in the airborne measurements of CO_2 in volcanic plumes tend to result in underestimation of the actual flux. Gerlach et al. (1997) noted that in the time of 0.5–1.5 h needed to perform the measurements, the plume conditions could change significantly. Measurements on Mt. Erebus normally required 20–60 min and on occasion the plume configuration did change in this time frame. Another source of error is from the difficulty in resolving the small concentrations of volcanic CO_2 against high ambient CO_2 on the margins of the plume that result from lateral spreading and dispersion. This is likely to result in an underestimate of the true flux (Gerlach et al., 1997). The contour plots (Fig. 3A–C) also reveal that small sections of the plume may have escaped measurement that may contribute to the deficiency in the total flux. Koepenick et al. (1996) concluded that CO_2 fluxes based on anomalies <10 ppm could be underestimating the flux by a factor of 2 when using this method. Although the highest readings for the Mt. Erebus cross-sections are above 20 ppm, the average generated across the entire plume cross-section (as done by Koepenick et al., 1996) would be less than 10 ppm for the measurements. Carbon dioxide concentrations measured in the plume of Popocatèpetl, Mexico have been additionally decreased due to dilution by the water vapor in the plume, but the magnitude of this effect is not known (Gerlach et al., 1997). The largest source of error comes from the uncertainty in wind speed (Koepenick et al., 1996; Gerlach et al., 1997; Wardell et al., 2001).

The airborne technique has proven to be an effective method of determining CO_2 flux in volcanic plumes following evaluations by both Koepenick et al. (1996) and Gerlach et al. (1997). Koepenick et al. (1996) reported the accuracy of this technique of measuring CO_2 flux to be within $\pm 10\%$ when evaluated at 1 and 2 km distance from a coal-burning power plant with a known emission rate. Gerlach et al. (1997) estimated the error to be at $\pm 20\%$ for a 95% confidence interval for their similar measurements at Popocatèpetl, Mexico. Carbon dioxide flux measurements at White Island volcano, New Zealand, using the same analyzer and procedure as at Mt. Erebus, found that two measurements taken on the same day agreed within 3% (Wardell et al., 2001). Estimated errors are assumed to be similar to those reported by Gerlach et al. (1997) and Koepenick et al. (1996) as the same equipment (differential

GPS and LI-COR analyzer) and similar techniques (contouring with SURFER) were used. The error of ±10% reported by Koepenick et al. (1996) is especially valuable as it is a direct measurement of the error rather than a calculation. Koepenick et al. (1996) estimated propagation error of their measurements at Oldoinyo Lengai to be ±30%. Our propagation error of ±23% was slightly lower as the Oldoinyo Lengai study used a ±2σ average for the CO_2 concentration over the entire plume cross-section, and we chose to sum the individual contours corresponding to a 2 ppm CO_2 increase. All three values reported for Mt. Erebus agreed within an error range of 10%, suggesting that the background CO_2 flux for Mt. Erebus was similar during our surveys. Direct airborne measurement techniques, such as the one employed in this study, are costly and time-consuming. However, until remote sensing techniques are further developed, direct measurements are needed to provide CO_2 flux data and will also assist in validating the remote methods under development (Gerlach et al., 1997). Other methods of monitoring are also needed to be able to quantify the increased CO_2 flux resulting from the Strombolian-style eruptions crated by the bubble bursts in the lava lake.

Diffuse flank degassing can sometimes provide insight into the subsurface characteristics of a magmatic system. The environmental conditions at Mt. Erebus are exceptional in that, due to the extreme cold, diffuse degassing on the flanks of the volcano is visible in the forms of steaming warm ground and fumarolic ice towers. Contribution by flank degassing was estimated to be only <2% of the emission measured in the plume at Mt. Erebus (Wardell et al., 2003) although it has been found to be a significant contributor of volcanic CO_2 on other volcanoes such as Mt. Etna (Allard et al., 1991), Kilauea (Gerlach and Graeber, 1985) and Vulcano (Chiodini et al., 1996). At Oldoinyo Lengai volcano, Tanzania, the small contribution of flank degassing (<2%) suggested a small magma chamber or the lack of a hydrogeologic system (Koepenick et al., 1996). Similar conditions may exist at Mt. Erebus with the mod-

Table 3
Summary of CO_2:CO molar ratios and $\Delta\log fO_2$ data from selected volcanoes

Hot spot	CO_2 (mol%)	CO (mol%)	CO:CO_2	fO_2 (bar)	Temperature (°C)	$\Delta\log fO_2$
Intra-plate						
Kilauea summit lake	33.36	1.07	0.03	−9.02	1135	0.07
Kilauea east rift	3.45	0.065	0.02	−10.87	983.5	0.37
Etna	25.51	0.535	0.02	−9.47	1075	0.41
Surtsey	5.5	0.38	0.07	−9.47	1125	−0.25
Ardoukoba	3.71	0.155	0.04	−10.17	1070	−0.22
Nyiragongo	42.45	2.43	0.06	−11.85	990	−0.71
Erta' Ale	14.9	0.635	0.04	−9.67	1103	−0.17
Erebus			0.12	−12.2	1000	−1.22
Convergent plate						
St. Augustine	1.57	0.0113	0.0072	−15	711.5	1.76
St. Helens	3.914	0.031	0.0079	−15.51	732.5	0.71
Showa-Shinzan	0.61	0.00645	0.0106	−14.01	801.5	0.61
Usu	2.169	0.00396	0.0018	−16.83	667	1.13
Momotombo	1.46	0.0056	0.0038	−15.04	739	1.02
Poas	0.7632	0.0066	0.0086	−10.09	1002.5	0.85
Merapi	5.41	0.09	0.0166	−13.68	841	0.11

The data, except for Mt. Erebus, are taken from Symonds et al. (1994) with only the median values being reported. Data are limited to this source as it is from quenched, restored, equilibrium values from high-temperature gas samples of consistent quality. The fO_2 for Mt. Erebus is from Kyle (1977), which was determined petrologically but assumed comparable to the other equilibrium values shown here, and the gas concentrations were taken from plume flux values in this work. The $\Delta\log fO_2$ is the deviation of the reported log fO_2 from the FMQ buffer (Frost, 1991).

el of a small summit reservoir (Aster et al., 2003) and absence of a hydrogeologic system (Wardell et al., 2003).

Carbon monoxide measurements by FTIR indicate that Mt. Erebus emits high levels of CO in the plume as illustrated by the high CO:CO_2 ratio (Table 3). However, since CO_2 values were not obtained by FTIR as it was for CO in 1995, the ratio is based using the average CO_2 flux obtained between 1997 and 2001. For Mt. Erebus, the high CO:CO_2 ratio is likely due, in part, to the low oxygen fugacity (fO_2) exhibited by the gas. Since fO_2 is highly dependent on temperature, it is difficult to directly compare the fO_2 for Mt. Erebus with reported fO_2 values in Table 3 that correspond to various temperatures. Therefore, by normalizing the fO_2 to the FMQ buffer ($\Delta\log fO_2$), the fO_2 values can be compared without regard to the variety in temperatures (Frost, 1991). These calculated values are found in the last column of Table 3. The $\Delta\log fO_2$ for Mt. Erebus (−1.22) is significantly greater than values for the other volcanoes listed in Table 3 and indicates a highly reduced system. This is further illustrated by plotting the $\Delta\log fO_2$ versus the CO:CO_2 ratios (Fig. 5). Two distinct trends are established by the two volcanic groups, illustrating the general difference in their oxidative environments. For the hot spot/intra-plate volcanoes, Mt. Erebus supports this trend but exhibits the most reduced environment of the data set. It is the high CO flux from Mt. Erebus that corresponds to the low fO_2 (and $\Delta\log fO_2$).

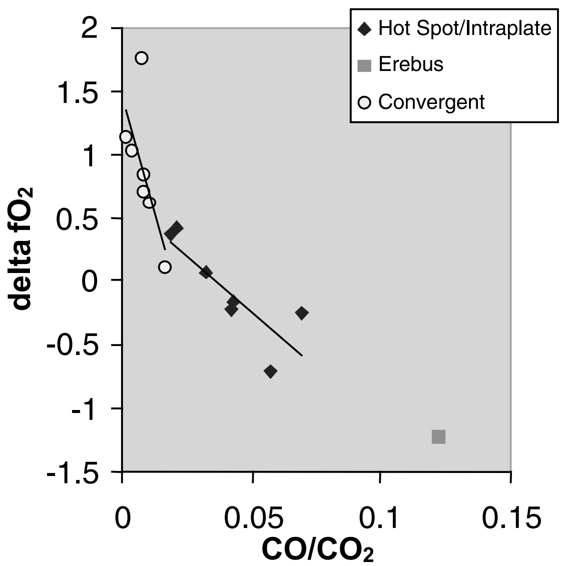


Fig. 5. The plot of the $\Delta\log fO_2$ versus the CO:CO_2 ratios. The data are also presented in Table 3. The hot spot/intra-plate volcanoes exhibit a trend distinct from the convergent plate volcanoes. Mt. Erebus, with its high CO flux, plots at the end of the hot spot/intra-plate trend.

5. Conclusion

The flux of CO_2 from Mt. Erebus was not found to be as exceptionally high as that found at Mt. Etna, despite the general similarities of their alkalic nature and intra-plate characteristics. Although indicators such as high CO_2 in melt inclusions and high CO flux would also suggest the potential for an exceptionally high CO_2 flux, the CO_2 emission rate for Mt. Erebus is more comparable to other active volcanoes such as Redoubt, Alaska and White Island, New Zealand. Although CO_2 is considered a strong geochemical indicator of eruptive activity, few studies presently exist, and multi-year studies of CO_2 flux are rare. The three direct airborne measurements spanning a 4-year period suggest a background emission rate of 22.3 kg/s (1930 Mg/day) despite the observed increase in activity during the 2000 monitoring period. Any increased CO_2 emissions lost via Strombolian explosions in the lava lake due to surfacing of gas slugs could not be accounted for in our airborne measurements. Degassing of CO_2 from deep within the system is likely the controlling factor for maintaining the consistent level of the measured CO_2 flux at Mt. Erebus.

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