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ERUPTIVE AND PASSIVE DEGASSING OF SULPHUR DIOXIDE AT NYIRAGONGO VOLCANO (D. R. CONGO): THE 17 JANUARY 2002 ERUPTION AND ITS AFTERMATH

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Abstract

The Total Ozone Mapping Spectrometer (TOMS) instrument aboard the Earth Probe (EP) satellite observed SO_2 emissions during the 17 January 2002 effusive eruption of Nyiragongo (D. R. Congo). A total of 9.3 ± 2.8 kilotons (kt) of SO_2 was measured by EP TOMS at 1108 local time on 17 January, in a plume that rose close to the tropopause (~14-17 km) according to brightness temperatures derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data. Available data indicate that the eruption onset and the start of plume emission were not coincident, supporting a regional tectonic trigger for the eruption. Eruptive SO_2 fluxes for the initial 2-3 hours of activity average ~850-1700 kg s^{-1}. Total SO_2 production for the $\leq$ 24 hours of eruptive activity is highly dependent on the duration of plume emission and the source of the SO_2, which are poorly constrained, but it is estimated to be 15-48 kt. Available evidence, while limited, suggests that degassing during the 2002 eruption did not differ substantially from that during the similar 10 January 1977 lava lake drainage event. Renewed, vigorous SO_2 emissions from Nyiragongo's rejuvenated lava lake were detected by EP TOMS beginning on 7 October 2002 and continuing until the time of writing. Between 7 October 2002 and 17 November 2003 EP TOMS detected a total of ~2 Mt SO_2 in plumes from the volcano that typically extended west across D. R. Congo. Extrapolation of this figure to account for data gaps indicates a possible total SO_2 emission of 6.9 ± 2.1 Megatons (Mt) at an average of ~16 kt day^{-1} (~185 kg s^{-1}). The sulphur content of magmas supplying the observed SO_2 flux is currently unknown, but reasonable bounds on the volume of magma degassed in this period are 0.4-3.4 km^3. Accommodation of this degassed magma in the fracture system developed during the January 2002 eruption seems likely, although the total fracture space ultimately available for endogenous intrusion is poorly known. Based on known eruptive gas compositions, fluxes of CO_2 and HF from Nyiragongo may be higher than the SO_2 flux.

Introduction

Nyiragongo (1.52°S, 29.25°E, elev. 3469 m), situated in the highly alkaline Virunga volcanic field of eastern Democratic Republic of Congo (D. R. Congo) in the western branch of the East African Rift, is renowned as one of the few volcanoes known to have hosted an active lava lake. The volcano was first described in 1894 (Le Guern 1987) and exhibits the morphology of a stratovolcano, unlike its close neighbour Nyamuragira (1.41°S, 29.2°E, elev. 3058 m) which has the profile of a typical shield volcano (Demant *et al.*, 1994). Nyiragongo's lava lake was reportedly discovered in 1948 (Tazieff 1949) but the precise chronology of its eruptive history varies in the literature (e.g., Tazieff 1984, Demant *et al.*, 1994). For example, Simkin and Siebert (1994) record Nyiragongo's first historic eruption in 1884 and the appearance of lava lakes in 1894, 1905, 1918 and 1927, whilst Tazieff (1977) reports «complete quietness» from 1894-1928. However, most reports concur that a lava lake persisted at Nyiragongo from at least 1928 until 10 January 1977, when fissures opened on the volcano's flank and catastrophic draining of the lake occurred, feeding lava flows that attained speeds of up to 60 km h^{-1} and caused many fatalities (Tazieff 1977, Hamaguchi *et al.*, 1992).

Renewed lava lake activity was observed at Nyiragongo in 1982-83 (Krafft and Krafft 1983, Tazieff 1984) and again in 1994-1995 (GVN, 1996), probably separated by periods of quiescence (Table 1). Civil war broke out in neighbouring Rwanda in 1994 and the ensuing unrest in D. R. Congo prohibited regular observations of activity at the Virunga volcanoes between 1994 and 2001. Nyamuragira erupted five times during this period (in 1994, 1996, 1998, 2000 and 2001), producing sulphur dioxide (SO_2) emissions measured via satellite remote sensing using the Total Ozone Mapping Spectrometer (TOMS) instrument (Carn and Bluth 2003 and Carn *et al.* 2003). Following the February 2001 eruption of Nyamuragira, anomalous regional seismicity (long-period events and tremor) was recorded until Nyiragongo erupted on 17 January 2002 (GVN, 2002a). The 2002 eruption was analogous to the 1977 event, involving draining of the lava lake through fissures, however in 2002 the fissures extended further from Nyiragongo and allowed the emitted lava flows to enter the city of Goma (~18 km south of the volcano).

This paper uses satellite remote sensing data, predominantly from the TOMS instrument, to examine degassing of SO_2 during the 17 January 2002 eruption of Nyiragongo and further refine existing models of the eruption's mechanism and chronology. Whilst significant eruptive SO_2 emissions have been recorded from Nyamuragira since 1980 using TOMS (Krueger *et al.* 1996, Carn and Bluth 2003, Carn *et al.*, 2003), the 2002 event was the first major eruption of Nyiragongo to be detected from space. Ground-based or airborne remote sensing measurements of SO_2 emissions are yet to be attempted at Nyiragongo, and hence the satellite data represent the only quantitative measurements of SO_2 output from the volcano. Such measurements are of value for assessing the atmospheric and environmental impacts of the activity at Nyiragongo. Furthermore, they offer an insight into gas discharge from a rare magma composition (melilite nephelenite; Demant *et al.*, 1994) and also provide constraints on petrological

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models of degassing. From October 2002 until the time of writing, TOMS has continued to detect discharge of SO_2 from the active lava lake established at Nyiragongo following the 17 January 2002 eruption, correlated with the emission of a vigorous plume from the volcano. The implications of over 1 year of continuous SO_2 emissions for magma supply at Nyiragongo are also discussed.

Volcanic sulphur dioxide measurements from space

TOMS is an ozone sensor but it can also measure SO_2 as both gases absorb at the ultraviolet (UV) wavelengths detected by the instrument. The first TOMS instrument was launched in 1978 but its ability to detect volcanic SO_2 was not realized until 1982 (Krueger 1983). Following this discovery, and with the launch of 3 further TOMS instruments, TOMS data for all major volcanic eruptions were analyzed to create the first long-term record of global volcanic SO_2 emissions (Bluth *et al.* 1993), which now covers the period from October 1978 onwards with the exception of a 18-month data gap in 1995-1996 (Carn *et al.* 2003). For the present paper the primary source of data was Earth Probe (EP) TOMS, which was launched in July 1996 and continues to operate at the time of writing, collecting data once per day at around local noon. EP TOMS does not provide complete daily coverage at the equatorial latitudes of Nyiragongo, and hence data gaps often cover the volcano on alternate days. However, the locations of the data gaps vary and daily coverage is achieved at certain times. The techniques used to retrieve SO_2 from TOMS data and calculate SO_2 burdens, along with an error analysis and the limitations of the TOMS measurements, are given in Krueger et al. (1995). A typical uncertainty on TOMS SO_2 cloud tonnage measurements is ± 30% (Krueger *et al.* 1995).

The minimum amount of SO_2 detectable by the TOMS sensor depends on eruption, background and meteorological conditions at the time of the measurement. The 35 across-track scan positions sampled by EP TOMS correspond to target areas of ~1550-12760 km^2 on the Earth's surface, with the minimum SO_2 mass considered above noise in one pixel varying from ~460-3820 tons. However, to produce an unambiguous SO_2 cloud that is easily separable from background noise a cluster of several pixels close to the volcano is normally required, giving a practical SO_2 cloud detection limit of ~4-32 kilotons (kt) depending on scan position. Cloud altitude is also a factor; TOMS was designed for stratospheric measurements and detection of tropospheric SO_2 is affected by weaker UV absorption by the SO_2 molecule at higher temperatures, increased UV scattering by the dense lower tropospheric atmosphere, and possible interference by UV-reflecting water clouds situated between the sensor and a low-level SO_2 cloud. Nevertheless, targets such as the SO_2 emissions from Nyiragongo from October 2002 onwards (discussed later) demonstrate that EP TOMS is eminently capable of detecting and quantifying lower tropospheric SO_2.

In addition to EP TOMS there are several other satellite sensors currently in orbit that are capable of measuring SO_2, including the Moderate Resolution Imaging Spectroradiometer (MODIS; on the EOS Terra and Aqua satellites), the High-resolution Infrared Radiation Sounder (HIRS/2; on NOAA polar-orbiting satellites) and the Atmospheric Infrared Sounder (AIRS; on EOS Aqua). These instruments exploit infrared (IR) SO_2 absorption features around 7.3 mm (e.g., Prata *et al.*, 2003) and 8.6 mm (e.g., Realmuto 2000) and provide greater temporal and spatial resolution (~2 images per day; ~1-20 km pixel size at nadir) than EP TOMS (1 image per day at the equator; 39 km pixel size at nadir). The relative performance of the various sensors is not elaborated on here (see Rose *et al.* [2003] for an example of a multi-sensor study of a volcanic eruption), but in the tropical environment of central Africa the IR sensors are generally less effective than the UV TOMS instrument for SO_2 measurements, largely due to high atmospheric water vapour loadings which interfere with SO_2 retrievals in the IR. Daily MODIS, HIRS/2 and AIRS data are available for the period of unrest at Nyiragongo discussed in this paper and future studies using these data may provide further insights into the degassing activity, although an initial scrutiny of MODIS and AIRS data for selected dates revealed no significant SO_2 signals. Hence all SO_2 measurements presented herein are derived from EP TOMS, with supplementary data on volcanic cloud characteristics obtained from MODIS data. Observations of SO_2 made by the Global Ozone Monitoring Experiment (GOME), a UV instrument on the European ERS-2 satellite, were also used to track degassing at Nyiragongo from October 2002 until mid-June 2003.

Historical activity and degassing at Nyiragongo

Whilst no prior remote sensing studies of gas emissions from Nyiragongo exist, the volcano has been visited or observed on a reasonably frequent basis throughout the period since its discovery. Table 1 provides a summary of historical observations of degassing at Nyiragongo. These are largely qualitative, derived from sporadic activity reports and examination of photographs in published works, but they help to place the 2002 eruption and the subsequent degassing crisis in context.

As would be expected, degassing vigour at Nyiragongo appears to correlate broadly with the activity of the lava lake, with increased degassing associated with more active, molten lakes and reduced emissions when the lake is crusted over (Table 1). Reviewing his numerous observations at Nyiragongo from 1948-1982, Tazieff (1994) notes «the difference between the thin, small fumes that usually drifted above the volcano's summit and the mighty plume towering high over it when a 'lava tempest' was developing». However, the often long periods between crater visits, coupled with the ability of the lava lake to fluctuate in size and level on short timescales (e.g., Tazieff 1994) and frequent cloud cover obscuring the volcano, preclude a full assessment of temporal trends in degassing at Nyiragongo. Prior to 2002-2003, a previous peak in gas emissions appears to have occurred in the early to mid-

TABLE 1. Historic observations related to degassing at Nyiragongo.

Date(s)	Observations	Reference(s)
11 Jun 1894	Clouds of vapour rose continuously from one of two pit craters in the summit caldera.	Tazieff (1979)
1908-1915	Vapour emitted.	Tazieff (1979)
1916-1924	Smoke emitted.	Tazieff (1979)
1928	Permanent emission of 'smoke' with 'reddish glow' begins.	Tazieff (1979)
Sep 1947?	Clouds of steam emitted from large central pit.	Tazieff (1979)
Jul 1948	Lava lake first observed within central pit. Vigorous degassing.	Tazieff (1977, 1994)
Aug 1953	Variable degassing from the lava lake (reduced in surface area and height since 1948); a diffuse, transparent plume alternating with a more vigorous, opaque plume. Fumarolic activity at lake edge.	Tazieff (1979)
Jul-Aug 1958	No distinct plume from summit; possibly diffuse emissions. Diffuse emissions visible within the caldera, though degassing of 'sulphurous fumes' from the lava lake surface within the pit crater appeared vigorous. Further reduction in surface area and height of lava lake since 1953.	Tazieff (1979)
Jul-Aug 1959	Diffuse emissions visible within the caldera. Further reduction in surface level and area of the lava lake since 1958. Lake appeared less active with only localized degassing from molten regions apparent, and fumarolic activity at the edge of the lake, producing a weak plume.	Tazieff (1979)
Feb 1966	Rise in level and increase in surface area of lava lake since 1959, though lake largely crusted over. Degassing appeared reduced and more sporadic yet 'powerful', from vents and fissures in the crusted lake surface.	Tazieff (1979)
Aug 1966	Similar activity to February 1966, though fewer active vents and more concentrated flow of gas.	Tazieff (1979)
May 1967	Rise in level of lava lake since 1966; otherwise similar activity.	Tazieff (1979)
Mid-1971 Apr 1972	Lava lake molten and began to rise within the central pit. Periods of calm (10-20 days) interspersed with eruptive phases (2-5 days) when lava lake level rose rapidly.	CSLP (1972); Tazieff (1979)
Apr 1972	Lava lake reaches highest level since discovery.	Tazieff (1977)
Aug 1972	Lava lake level fallen since April. Vigorous, opaque steam plume from central pit crater, largely sourced from incandescent vents on the lake surface. Plume 'visible from a considerable distance' in clear weather.	Tazieff (1979)
1974	Similar activity to 1972, though lava lake level had fallen; degassing less vigorous?	Tazieff (1977,1979)
Jul 1976-Jan 1977	Lava lake at similar level to April 1972.	Tazieff (1977)
10 Jan 1977	Lava lake drained in short effusive eruption. Ash-laden 'phreatomagmatic' mushroom cloud rose ~35.000 feet above volcano after old lava lake terraces within the crater collapsed. Fumarolic activity continued after the eruption.	SEAN (1977a, b); Tazieff (1977)
16 Jan 1977	Strong gas eruption from main crater ejected cloud to ~1 km above the volcano. End of major gas emission, though weak fumarolic activity persisted.	SEAN (1977b)
16 Jan 1977-21 Jun 1982	No lava lake activity. Weak fumarolic activity?	Tazieff (1984)
21 Jun-early Nov 1982	Lava fountaining from replenished lava lake, but 'degassing was several orders of magnitude less than that of usual fountains of a few years ago.' However, gas output was estimated as at the same order of magnitude as measured in 1972.	Kraffi & Kaffi (1983); Tazieff (1984, 1994)
Early Nov 1982-23 Jun 1994	No lava lake activity.	GVN (1994a)
23 Jun 1994	Reactivation of the lava lake. Volcanic 'smoke' and 'dust' reported near Goma, but possibly associated with simultaneous eruption of Nyamuragira.	GVN (1994a)
~14 Jul 1994	Dense steam and gas plume visible from Goma for 4 days around this date.	GVN (1994b)
20, 21, 24 Aug 1994	Moderate plume from active lava lake.	USGS photographs (J.P. Lockwood); see Oppenheimer (1998)
1996-17 Jan 2002	Weak fumarolic activity. Increase in fumarolic activity following seismic events on 7 Oct 2001 and 7 Jan 2002.	GVN (1996, 2001, 2002a)
17 Jan 2002	Lava lake drained in effusive eruption. Gas and steam plume rose to near tropopause (~16 km).	This study
17-18 May 2002	Renewed magmatic activity discovered in summit crater.	GVN (2002c)
16-17 Jul 2002	'White plume' reported exiting crater, and SO_2 odour noted near summit.	GVN (2002d)
29-30 Sep 2002	High-pressure degassing reported from vents within summit crater.	GVN (2002d)
7 Oct 2002 present	Near-continuous, vigorous degassing from active lava lake and lava fountains within summit crater, with SO_2 emissions detected by TOMS.	This study

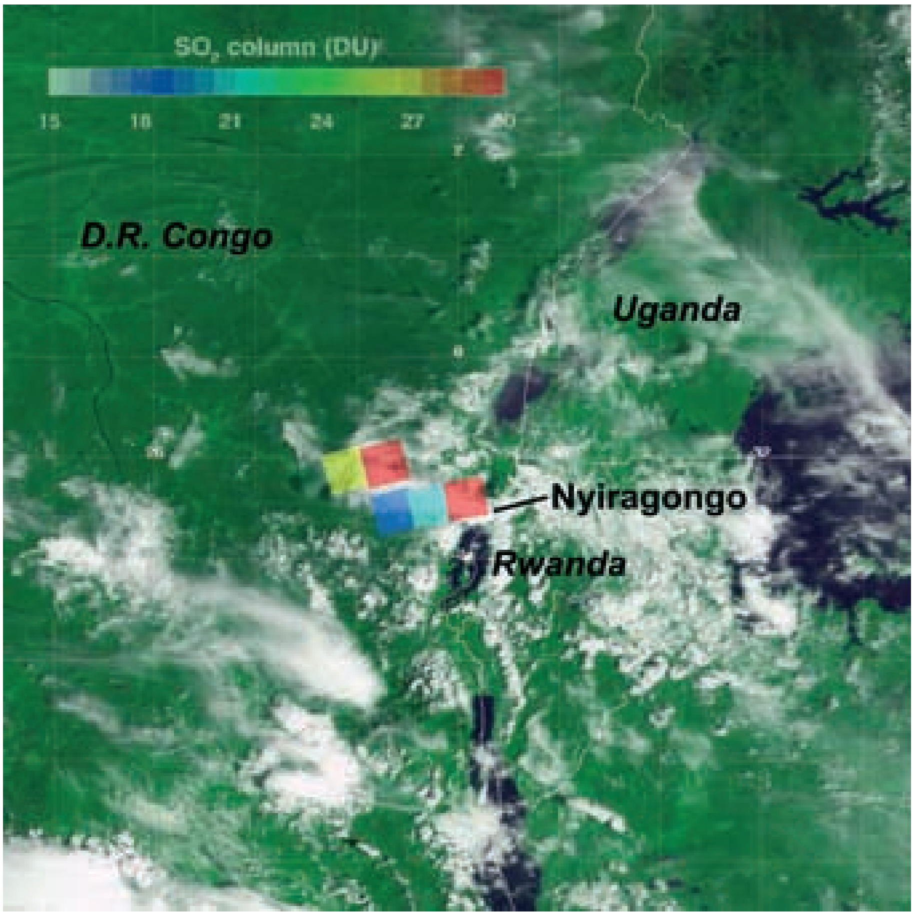

FIG. 1. EP TOMS and MODIS images of the eruption cloud emanating from Nyiragongo on 17 January 2002. Column SO$_2$ (milli atm cm or Dobson Units [DU]) from EP TOMS at 09:08 UT (39 × 39 km pixel size) is superimposed on a MODIS image from the EOS/Terra spacecraft collected at 08:50 UT (1 km spatial resolution; combination of channels 1 [0.65 mm], 2 [0.86 mm] and 4 [0.56 mm]).

1970s when the lava lake surface was above 3250 m a.s.l. (TABLE 1; Tazieff 1977).

Prior to the present study, Le Guern (1987) provides the only estimates of actual gas fluxes at Nyiragongo, with emission rates (in kilotons day^{-1}) of 5 for H_2O, 12 for CO_2 and 1 for SO_2 determined in 1959, and 77 for H_2O, 184 for CO_2 and 23 for SO_2 determined in 1972. These figures appear to have been derived by combining analyses of sampled gases with estimates of volumetric flow rates, the latter deduced from film footage and crater geometry. No error assessment is given by Le Guern (1987), so the data are used cautiously. It is also unclear whether the fluxes refer to a particular day or if they represent average emissions over a longer period but they indicate high levels of degassing in the early 1970s, consistent with the dense plume visible at that time (TABLE 1; Tazieff 1979).

During the 10 January 1977 eruption of Nyiragongo an ash-laden mushroom cloud developed over the volcano (TABLE 1). This was attributed to a phreatomagmatic event as old lava lake terraces containing groundwater collapsed into the axial region of the volcano and the water flashed to steam (Tazieff 1977). Observations documented in SEAN (1977b) indicate that «rapid draining of the lava lake caused a partial collapse of the terraces, where groundwater flashed to steam producing a dark grey cloud that rose more than 1 km» and moved in the direction of Goma. A photograph in Tazieff (1977) suggests that the cloud in fact reached a substantial altitude, estimated at ~11 km from a pilot report. A subsequent gas explosion on 16 January 1977 was followed by collapse of the remaining lava lake terraces, which ended major gas emissions (TABLE 1) presumably due to blockage of the conduit and/or withdrawal of the degassing magma body to greater depths.

Degassing during lava lake activity in 1982-1983 was apparently less vigorous than that associated with previous lakes, although gas output was estimated to be comparable to 1972 levels (TABLE 1). Entry of lava into the crater of Nyiragongo was preceded by allegedly phreatic explosions on 21 June 1982, followed by emission of «white vapour» (SEAN, 1982). The Nimbus-7 (N7) TOMS instrument was operational at the time of this activity but no SO_2 emissions were detected in the region of Nyiragongo; although the N7 TOMS sensor was less sensitive than the current EP TOMS. A dense plume was also reported during renewed activity in 1994 around 14 July (TABLE 1), but SO_2 emissions detected by Meteor-3 (M3) TOMS at this time were most likely from a contemporaneous eruption of Nyamuragira. The low spatial resolution of the TOMS sensor makes it impossible to resolve the actual source of SO_2 when the two vents are separated by <50 km. M3 TOMS also detected no emissions on 10-13 August 1994 when increased activity was reported at Nyiragongo (GVN 1994b).

Emitted gases from Nyiragongo have been sampled on a few occasions. Gerlach (1980) estimated the gas phase composition at the volcano's lava lake using samples obtained in 1959 at emission temperatures of 960-1020°C. A notable characteristic of the Nyiragongo gases, in addition to their very CO_2-rich compositions (36-49% CO_2), was a low total sulfur content (SO_2 + S_2 + H_2S + COS = ~4 mole %) compared to typical high temperature volcanic gases, despite relatively high S_2 fugacities and up to 0.5 wt% S in glasses from the lava lake, which may have been the result of low O_2 fugacity in the melt (Gerlach 1980). Gas samples obtained at Nyiragongo in 1972 were found to have similar compositions to the 1959 samples (49% H_2O, 47% CO_2 and 4% SO_2; Le Guern *et al.*, 1977). The very CO_2-rich nature of the Nyiragongo gases is not unusual given the highly alkaline melilite-leucite nephelinite composition of lavas erupted during the volcano's current phase of activity (Demant *et al.*, 1994). Lava composition appears to have shown little variation during historic eruptions, at least since 1953 (e.g., Tazieff 1977, Krafft and Krafft 1983), and the 2002 lavas were similar to those erupted in 1977 (P. Allard, unpublished data in GVN 2002b).

THE 17 JANUARY 2002 ERUPTION

In the months preceding the 17 January 2002 eruption of Nyiragongo several episodes of increased fumarolic activity were reported following seismic events (TABLE 1), and on 16 January 2002 an abnormal odour of SO_2 was reported by a pilot north of the volcano (GVN 2002b). The eruption began when a system of fractures opened on the south flank of Nyiragongo, triggering drainage of the lava stored within its shallow plumbing system (e.g., GVN 2002a). Although the exact timing of the eruption is uncertain, the Goma Volcano Observatory (GVO) reported that it began at 08:25 local time (GVN, 2002b; it is not clear what event signaled the beginning of the eruption), and that the uppermost portion of the fracture system began erupting at 08:35 local time (GVN, 2002a). All subsequent times given in this paper are local unless otherwise noted.

Characteristics of the eruption plume

The first EP TOMS overpass following the start of the eruption occurred at 11:08, and a small SO_2 plume was detected extending approximately west from the volcano (FIGURE 1). MODIS data from the EOS Terra spacecraft were collected at 1050, although the Nyiragongo eruption plume appeared unremarkable in visible satellite imagery (FIGURE 1) due to its high water vapour content, which resulted in high plume opacity that obscured any ash present at lower altitudes. The time at which the eruption plume first appeared over the volcano has been constrained using geostationary Meteosat-7 data collected every 30 minutes over Africa; these data indicate that the plume was absent at 09:00 but had appeared by 09:30 (Watkin *et al.* 2003), suggesting that substantial eruptive degassing began ~35-65 minutes after the initial opening of the eruptive fractures (GVN 2002a, 2002b). A reasonable inference is that the eruption was not initiated by gas overpressure within the shallow magma storage system beneath Nyiragongo, which is consistent with the currently favoured 'tectonic' hypothesis that a regional rifting event triggered the eruption (Tedesco *et al.* 2002, Allard *et al.* 2003).

The Terra MODIS data at 10:50 (FIGURE 1) give minimum channel 31 (11 µm) brightness temperatures of ~196-210 K (-77 to -63°C) over the area of the volcanic plume. Radiosonde data are rarely available for this region of Africa, hence atmospheric profiles for Nyiragongo were derived from NCEP/NCAR Reanalysis (NNR) meteorological analysis data (Kalnay *et al.* 1996; FIGURE 2) interpolated to the location of the volcano. The model temperature profile indicates a thermal tropopause height of ~17-18 km, corresponding to temperatures of ~192 K (-81°C) on 17 January 2002 (FIGURE 2). Cloud-top temperatures from MODIS therefore suggest that the Nyiragongo plume rose to altitudes of ~14-17 km (FIGURE 2), very close to the tropopause. Similar results are obtained if a standard tropical atmospheric profile is used rather than the NNR model profile.

These inferred altitudes are also consistent with the observed plume transport direction and model wind profiles (FIGURE 2). At altitudes of 14-17 km, model

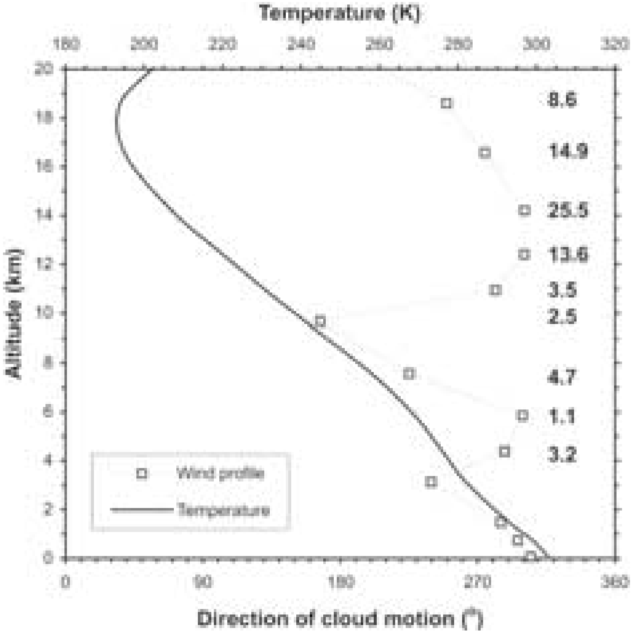

FIG. 2. Model wind profile, atmospheric temperature profile and cloud motion (North = 0°) for Nyiragongo on 17 January 2002 at 08:50 UT, derived from NCEP/NCAR Reanalysis data. Model-derived wind speeds (m s^{-1}) at selected altitudes are plotted to the right of the profiles.

wind profiles indicate wind speeds of 15-26 m s^{-1} (Figure 2), and combining this information with the observed extent of the plume in the MODIS image at 10:50 (~156-195 km from Nyiragongo, depending on where the distal end of the plume is judged to be; Figure 1) gives an onset of plume emission at ~07:15-09:10. Plume emission commencing at 09:00-09:10 is in agreement with the Meteosat-7 data (Watkin *et al.* 2003) and hence it seems likely that plume development occurred ~25-45 minutes after the eruption started, with the bulk of the emissions traveling at ~26 m s^{-1} at an altitude of ~14 km. These calculations assume that the plume rose rapidly from the vent at ~3.5 km altitude to altitudes of 14-17 km, which would have been promoted by the low predicted wind speeds at intermediate levels (Figure 2; e.g., Bursik, 2001).

Sulphur dioxide production

The only SO_2 emission data presently available for the 17 January 2002 eruption are from EP TOMS. No SO_2 signal was apparent in the Terra MODIS 7.3 µm channel at 1050, probably due to significant water vapour content in the plume and/or atmosphere, and no clear volcanic cloud was evident when the next MODIS overpass occurred at 23:10 on 17 January. The SO_2 cloud observed by EP TOMS at 11:08 (Figure 1) contained 9.3 ± 2.8 kt of SO_2, assuming an upper tropospheric cloud height as suggested by the temperature data, although the total eruption production remains uncertain due to probable continuation of degassing after the TOMS overpass. An EP TOMS data gap covered the Virunga region on 18 January 2002 but no drifting SO_2 cloud was apparent west of the region over central Africa, and no emissions were detected near Nyiragongo on 19 January.

Given the 9.3±2.8 kt of SO_2 measured by EP TOMS at 11:08 and the estimated onset of plume emission at 09:00-09:10, implied SO_2 emission rates during the initial phase of the Nyiragongo eruption were ~850-1700 kg s^{-1} (equivalent to ~73-148 kt day^{-1}), assuming no substantial SO_2 loss in this period. These rates are significantly higher than eruptive SO_2 fluxes measured at Mt. Etna (peak SO_2 fluxes of ~30 kt day^{-1} during paroxysms; e.g., Allard 1997) and Kilauea (minimum paroxysmal SO_2 fluxes of ~30 kt day^{-1} measured during the Pu'u 'O'o-Kupaianaha eruption since 1983; Sutton *et al.* 2001), though considerably lower than SO_2 fluxes approaching 1 Megaton (Mt) day^{-1} measured during recent eruptions of Nyamuragira (Carn and Bluth 2003). Extrapolation of these fluxes to obtain an estimate of total SO_2 production for the eruption is hindered by inadequate knowledge of the duration of degassing activity. The final eruptive fractures opened in the vicinity of Goma at about 1620 on 17 January (GVN, 2002a, 2002b) and although the time at which lava effusion ceased is unknown, a rough estimate of ~7.75 hours for the fracturing phase of the eruption can be derived. Continued SO_2 emissions at the rates derived above for this length of time would have resulted in a total emission of ~24-48 kt SO_2, which is probably an upper limit for the eruptive discharge given that no residual SO_2 was observed on the following day. Inspection of browse imagery from geostationary satellites positioned over Africa and the Indian Ocean indicates the absence of a substantial plume from Nyiragongo at 1400 on 17 January, therefore the vigorous phase of degassing may have lasted =5 hours, giving a maximum SO_2 production of ~15-31 kt. Analysis of full resolution Meteosat data would place better constraints on the eruption chronology and hence the total mass of SO_2 emitted.

Source of the eruption plume

Knowledge of the physical source of the observed gas plume from Nyiragongo (and the precise duration of the emission) would greatly assist elucidation of the eruption mechanism and the source of the emitted SO_2. However, available satellite data are of minimal use in this endeavour owing to their relatively low spatial resolution and also to obscuration of the volcano by meteorological cloud and the plume itself (e.g., Figure 1). MODIS data show that the plume clearly originated from the environs of the summit crater of Nyiragongo, and whilst discriminating between gases emitted from erupting lava flows or fire fountains and emissions from within the summit crater (where no lava was erupted) is impossible, the timing of plume development discussed above tends to favour the latter.

A key observation concerned the solidified surface of the lava lake in Nyiragongo's summit crater, which had remained intact since at least 1996 (GVN, 2002b). The lake surface was still present on 21 January 2002 but it «was cut by a N-S steaming graben» of uncertain dimensions, and it finally collapsed completely during the night of 22-23 January (GVN, 2002b). The 22-23 January crater collapse produced no emissions detectable in either EP TOMS or MODIS data. A possible scenario for the 17 January eruption, compatible with these observations, is that initial draining of lava through the eruptive fissures weakened the crusted lake surface within the crater to some degree, such that a small collapse occurred, forming the graben observed on 21 January. Collapse of a portion of the lava lake surface could have triggered phreatomagmatic or phreatic explosions as groundwater trapped in the lava lake crust came into contact with high temperature material beneath the crust, which produced the observed plume, mixed with gases emitted from lava beneath the surface and from erupting lava flows. Similar phreatomagmatic activity was implicated in the 'mushroom cloud' event witnessed during the 10 January 1977 eruption (SEAN 1977b). If such explosions occurred they were clearly not powerful enough to fragment the lava lake surface, but may have involved release of high pressure gases through cracks and fissures in the crater floor. Another potential source of the observed SO_2 is degassing of new magma rising within Nyiragongo, but this is considered unlikely since the volume of the crater exposed following the collapse on 22-23 January was approximately commensurate with the volume of the emitted lava flows, suggesting that magma stored within shallow plumbing system supplied the eruption (GVN 2002b).

Although there is considerable uncertainty as to the total SO$_2$ emitted during the 17 January 2002 eruption of Nyiragongo, the range of predicted values (~15-48 kt) is an order of magnitude lower than the typical daily discharge observed during an eruption of Nyamuragira (e.g., Carn and Bluth, 2003). The lower SO$_2$ emissions from Nyiragongo can be partly attributed to a smaller erupted volume of lava; the volume of the 17 January 2002 lava flows has been estimated at $30 \pm 10\times10^6$ m^3 (GVN 2002b, Allard *et al.* 2003), which is less than half the volume disgorged by most of Nyamuragira's post-1980 eruptions (e.g., Burt *et al.* 1994). Eruptive SO$_2$ emissions are also influenced by lava effusion rates (e.g., Sutton *et al.* 2003), but at Nyiragongo these were clearly very high (averaging ~232-463 m^3 s^{-1}, assuming that lava effusion continued for $\leq$ 24 hours), and by the sulphur content of the magma. Sulphur contents of primary Virunga magmas are currently unknown, although high S solubility would be consistent with their highly alkaline compositions (e.g., Ducea *et al.* 1994). A possible explanation for reduced SO$_2$ release is that the batch of erupted lava had been significantly degassed during a long residence time in the upper conduit and crater of the volcano, probably since at least 1994. However, there is also petrological evidence that the 2002 Nyiragongo lavas did not completely degas during the eruption. Initial analyses of bulk volatile contents in the lavas erupted on 17 January 2002 (and one sample from the 1977 eruption) have revealed rather high sulphur contents for ostensibly degassed lavas (~0.2 wt% total S; P. Allard, unpublished data, in GVN 2002b). Given an erupted volume of $30\pm10\times10^6$ m^3 and an SO$_2$ emission of 15-48 kt, and assuming a magma density of 2.65, the emitted SO$_2$ would constitute only ~0.01-0.05 wt% S in the magma. It is therefore possible that eruptive degassing of the lavas was inhibited in some way, perhaps related to the rapid effusion rate of the lavas.

In summary, limitations of the available data preclude a full appraisal of the source of SO$_2$ emitted during the 17 January 2002 eruption. There is currently no clear evidence that degassing during the 2002 eruption differed substantially from the 1977 eruption, and both events probably involved partial collapse of solidified lava lake material within the crater, resulting in generation of a large gas plume as groundwater flashed to steam. Whether this process could have generated some of the measured SO$_2$ (e.g., by vaporization of groundwater containing accumulated dissolved volcanic gases) remains unclear, but degassing of erupted lavas, whilst apparently restricted, likely contributed some proportion of the total discharge. The gas emissions provide more support for the 'tectonic' eruption scenario (*i.e.* a regional rifting event fractured the cone and released stored magma) than for the 'magmatic' hypothesis (*i.e.* that an influx of magma from below caused fracturing).

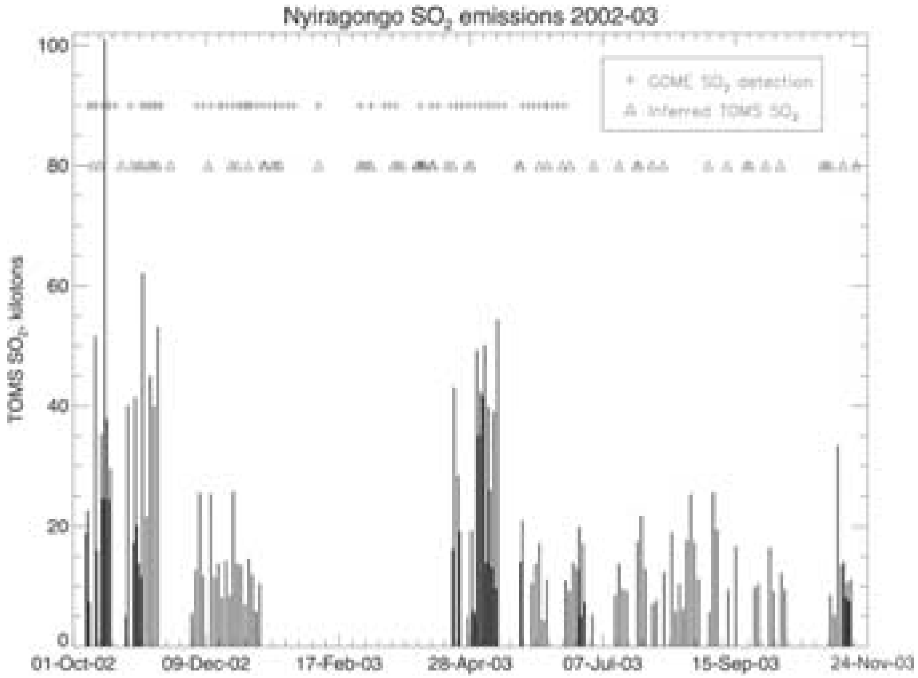

FIG. 3. SO$_2$ emissions (in kt) from Nyiragongo measured by EP TOMS, 7 October 2002-17 November 2003. Each division on the horizontal axis corresponds to 1 week. Also shown are non-quantitative indications of SO$_2$ emission derived from the Global Ozone Monitoring Experiment (GOME; this sensor ceased operations in June 2003) and EP TOMS (*Inferred TOMS SO$_2$* – denotes the presence of a weak SO$_2$ signal in EP TOMS data, precluding a quantitative SO$_2$ retrieval).

TABLE 2. Degassing of SO_2 from Nyiragongo magmas, 7 October 2002 - 17 November 2003.

Sulphur degassed (wt %)	SO_2 emission per km^3 degassed magma (Mt)*	Volume of degassed magma (km^3)
0.01	0.53	9.1 – 16.8
0.05	2.65	1.81 – 3.37
0.21	11.13	0.43 – 0.80
0.25	13.25	0.36 – 0.67

* Assumes a density of 2.65 for Nyiragongo nephelinite.

SO_2 DEGASSING ASSOCIATED WITH RENEWED LAVA LAKE ACTIVITY (OCTOBER 2002 - PRESENT)

Following the 17 January 2002 eruption, fresh lava was not observed within the summit crater until mid-May 2002 (TABLE 1), with no reports of substantive degassing in the intervening months. Reports of an emission plume and the odour of SO_2 were then communicated in mid-July 2002, evolving to high pressure degassing in late September (TABLE 1). MODIS IR thermal alerts also indicate an absence of thermal anomalies at the summit of Nyiragongo from 24 February - 12 June 2002 (GVN 2003a). More frequent alerts began to be observed in early September 2002 (GVN 2003a), indicating that persistent magmatic activity in the summit crater began around this time, although cloud cover may have obscured some activity. Since September 2002 near-continuous lava lake activity has continued in the crater of Nyiragongo, producing a persistent, strong plume above the volcano (e.g., GVN 2003a). This activity represents a return to the vigorous lava lake behaviour observed at Nyiragongo in the 1970s.

Renewed SO_2 emissions from Nyiragongo were not detected by EP TOMS until 7 October 2002, although the onset of SO_2 discharge likely coincided with the appearance of new lava in the summit crater. Other sensor data for this period of unrest (e.g., MODIS) has not been extensively studied to date, but the generally poor performance of IR instruments under the atmospheric conditions prevailing in central Africa may prevent further refinement of the existing chronology. Since 7 October 2002 persistent SO_2 plumes from Nyiragongo have been detected by EP TOMS (Figure 3), typically extending west from the volcano across D. R. Congo and often tracked several hundred kilometers downwind, and this activity is ongoing at the time of writing. EP TOMS cannot distinguish between SO_2 emitted by Nyiragongo and any gas originating from Nyamuragira, but in the absence of eruptive activity at the latter all the observed SO_2 is attributed to Nyiragongo. Although the EP TOMS record is not continuous owing to data gaps and meteorological factors (e.g., rainy season cloud cover), intermittent plume and crater observations by GVO, low-level SO_2 signals in EP TOMS data and SO_2 detection by the GOME instrument strongly support continuous degassing (FIGURE 3). These emissions have elevated Nyiragongo to its current status as one of the strongest sources of volcanic SO_2 on the planet in 2002-2003.

The EP TOMS data provide the only estimates of SO_2 emissions from Nyiragongo available at present, since ground-based instrumentation is yet to be deployed. Although TOMS measures the total SO_2 mass within a scene rather than the SO_2 flux from a volcanic source, SO_2 fluxes can be estimated if some assumptions are made concerning SO_2 lifetime and hence plume dispersion. A common assumption for volcanoes in tropical environments is that rapid SO_2 removal (e.g., Oppenheimer *et al.* 1998) results in no SO_2 persisting for more than 24 hours, and in this case the daily TOMS totals would represent a minimum daily SO_2 flux. This is a significant assumption, and is dependent on plume height and environmental factors, which are often poorly constrained. Applying this reasoning to the recent TOMS data for Nyiragongo produces SO_2 fluxes in excess of 50 kt day^{-1} (~580 kg s^{-1}) on several occasions (FIGURE 3).

The altitude of the persistent plume from Nyiragongo has been estimated by GVO to reach 4-6 km, though it is often lower (GVO, personal communication, 2002). Altitudes of ~5 km or more are above the freezing level in a standard tropical atmosphere (e.g., FIGURE 2) and suggest that ice formation probably occurs within higher plumes as emitted and entrained water vapour freezes. Scavenging of SO_2 in explosive eruption clouds has been linked to formation of ice (e.g., Rose *et al.* 1995), with subsequent SO_2 release on ablation of the ice, and at Nyiragongo this process may act to reduce the SO_2 mass detected by TOMS close to the vent. At times the detected SO_2 is a distinct mass situated some distance from the volcano (as opposed to a plume 'attached' to the volcano), suggesting that downwind release of SO_2 due to ablation of ice may be occurring. More detailed investigations of this effect are planned for the future.

The cumulative SO_2 emissions from Nyiragongo observed by EP TOMS to date (7 October 2002 – 17 November 2003) amount to ~2 Mt. However, due to data gaps, meteorological factors and variations in plume height this does not represent the total mass of SO_2 emitted by the volcano; quantifiable SO_2 plumes from Nyiragongo were observed on only 117 days during this 406-day period. Extrapolation of this figure to an estimate of the actual SO_2 production is difficult, particularly for the longer measurement gaps such as January-April 2003 (FIGURE 3). In the absence of a more robust technique the data gaps have been filled using an average SO_2 emission computed from the sequence of measurements closest to each gap. Using this method, the estimated total SO_2 mass released in the ~13 months amounts to 6.9 ± 2.1 Mt (30% error on TOMS SO_2 retrievals assumed), with an average SO_2 emission of ~16 kt day^{-1} (~185 kg s^{-1}). This daily average is comparable to Le Guern's (1987) assessment of SO_2 fluxes from the lava lake in 1972 (23 kt day^{-1} or 266 kg s^{-1}).

During this period of vigorous degassing no lava has been erupted outside the crater of Nyiragongo, but clearly a substantial volume of magma has been degassed to generate the very high SO_2 fluxes, symptomatic of an efficient conduit convection system (e.g., Kazahaya *et al.* 1994). Quantification of the degassed volume requires knowledge of the sulphur content of primary Nyiragongo magma, which is currently unknown. However, it can be constrained using the 17 January 2002 SO_2 emission data and available petrological data (P. Allard, unpublished data, in GVN 2002b). As discussed above, the estimated 15-48 kt SO_2 released during the 17 January 2002 eruption would constitute only ~0.01-0.05 wt% S in the erupted lava volume of $30 \pm 10 \times 10^6$ m^3. Petrological data indicate that these erupted lavas retained ~0.2 wt% S (P. Allard, unpublished data, in GVN 2002b), giving a predicted original S content of ~0.21-0.25 wt% if the emitted SO_2 was derived solely from the erupted magma (which remains uncertain as discussed previously). The fraction of magmatic S released during the current degassing activity is also unknown, but using the range of values above an SO_2 emission per unit volume of magma may be calculated for variable amounts of degassed S, and this can then be used to estimate the volume of magma potentially responsible for the SO_2 emissions observed by TOMS. The results of these calculations are summarized in Table 2, and the wide range of calculated magma volumes (0.36-16.8 km^3) reflects the uncertainty on the amount of S degassed from the magma, with limited degassing (as suggested by the 17 January 2002 data) requiring a larger volume. An alternative approach would be to use the more complete and extensive TOMS database of SO_2 emissions from Nyamuragira to derive a relationship between degassed magma volume and emitted SO_2; however, the values used for Nyiragongo (Table 2) effectively bracket those determined for Nyamuragira and hence similar results are obtained.

Discussion

Various estimates of magma volumes implicated in activity at Nyiragongo have been made over the years, and these are summarized in Table 3, which also presents data from other active lava lakes and convecting basaltic systems. It should be noted that the volumes given in earlier studies of Nyiragongo are largely based on crater morphology and are probably underestimates of the actual volume of magma cycled through the system, hence estimates based on heat fluxes (e.g., Harris *et al.* 1999; Table 3) are deemed more realistic. The data in Table 3 give a maximum volume of 0.7-1.9 km^3 magma involved in activity at Nyiragongo from 1959-January 2002 (43 years). Results derived here for 2002-2003 from SO_2 emission data (Table 2) are comparable, with the exception of the higher values (9.1-16.8 km^3) which are considered extreme, and suggest a radical change in degassing activity and magma supply at Nyiragongo following the 17 January 2002 eruption. Harris *et al.* (1999) give a volume of $185\text{-}235 \times 10^6$ m^3 for the shallow reservoir at Nyiragongo and the volumes estimated here (Table 2) exceed this figure, implying that magma supply from a deeper source may be required to explain the current activity.

Although active lava lakes have been documented at ~30 volcanoes (Simkin and Siebert, 1994), most have

Table 3. Magma budgets of active lava lakes and convecting basaltic systems.

Volcano	Date(s)	Volume (km^3)	Flux (kg s^{-1})	Reference(s)
Nyiragongo	1959		2757-3497	Harris *et al.* (1999)
	1959-1972	0.5-1.7	2757-10350	Harris *et al.* (1999)
	1969-1971	~0.027		CSLP (1971)
	1969-1972	~0.054		Demant *et al.* (1994)
	1972		8162-10350	Harris *et al.* (1999)
	10 Jan 1977 eruption	0.02-0.022		Tazieff (1977)
	10 Jan 1977 eruption	0.007-0.019		Harris et al. (1999)
	21 Jun-15 Sep 1982	0.065-0.07		Krafft and Krafft (1983); Tazieff (1984)
	21 Jun-early Oct 1982		19900*	Tazieff (1984)
	Aug 1987		1-2	Harris *et al.* (1999)
	23 Jun-16 Dec 1994	~0.025		GVN (1995)
	End Apr-mid Aug 1995	~0.056		GVN (1996)
	17 Jan 2002 eruption	~0.02-0.04		GVN (2002b); Allard *et al.* (2003)
	7 Oct 2002-17 Nov 2003	~0.4-3.4	30220-256850*	This study
Erta 'Ale	Jan 1973		14902-18204	Harris *et al.* (1999)
	Jan 1986		44-104	Harris *et al.* (1999)
	Feb 2001		~10000	Oppenheimer & Yirgu (2002)
Erebus	Jan 1985		38-76	Harris *et al.* (1999)
	Jan 1989		30-69	Harris *et al.* (1999)
	1963-1983	1.7	7280	Rose *et al.* (1985)
Pu'u'O'o	Jul 1991		1553-2079	Harris *et al.* (1999)
Izu-Oshima	Jan 1988-Mar 1990	0.26	≤10000	Kazahaya *et al.* (1994)
Miyakejima	Aug-Nov 2000	0.3	115740	Geological Survey of Japan website†

* Assumes a density of 2.65 for Nyiragongo nephelinite.

† Miyakejima data available at: http://staff.aist.go.jp/kazahaya-k/miyakegas/COSPEC.html

been ephemeral and hence datasets comparable to that presented here for Nyiragongo are scarce. Lava lakes at Erta 'Ale (Ethiopia) and Erebus (Antarctica) have been studied for many years but estimated magma fluxes for the past few decades at these systems, and also at Pu'u'O'o (Kilauea, Hawaii) in 1991, are significantly lower than those calculated for Nyiragongo in 2002-03 (Table 3). The phonolitic lava lake at Erebus, discovered in 1972, is perhaps the best analogue for the alkaline lake at Nyiragongo although the highly evolved composition and low oxygen fugacity of the Erebus magma promote low sulphur concentrations in surface lava (Kyle *et al.* 1994). Emissions of SO_2 have been measured annually at Erebus since 1983 using correlation spectrometry (cospec), but published emission rates are 2-3 orders of magnitude lower than estimated SO_2 fluxes at Nyiragongo and total SO_2 production for 1983-1991 was only ~0.2 Mt (Kyle *et al.* 1994). Discharge of SO_2 from the Erta 'Ale lava lake, estimated at 0.58 kg s^{-1} (~50 tons day^{-1}) in 1973 (Le Guern *et al.* 1979), is similar to that at Erebus. The Erebus data do, however, indicate significant (10-fold or more) diurnal variations in SO_2 flux from the lava lake that may reflect variable convection rates or plume 'puffing' (Kyle *et al.* 1994). This may also be a feature of degassing at Nyiragongo but is impossible to detect in the daily toms SO_2 data. Continuous long-term measurements of SO_2 emissions from Erebus are precluded as field campaigns are limited to the austral summer (Kyle *et al.* 1994).

Whilst active lava lakes are relatively rare, ultimately they are no more than the exposed caps of magma columns that are present at shallow depths in the conduits of many open-vent basaltic volcanoes. Large and/or persistent heat and volatile emissions delivered by convecting magma are a common feature of these volcanoes (e.g., Francis *et al.*, 1993, Kazahaya *et al.* 1994; Allard, 1997). Degassed volumes and magma fluxes at two archetypal conduit convection systems, Izu-Oshima and Miyakejima (Japan), are also given in Table 3 and they are of the same order as the recent Nyiragongo data. Since erupting in 2000, Miyakejima has been one of the largest contemporary volcanic SO_2 emitters, with observed fluxes averaging 42 kt day^{-1} between September and December 2000 (Shinohara *et al.* 2003; ep toms detected SO_2 plumes from Miyakejima in late August and September 2000). Fluxes have diminished progressively since then to current values of ~4-9 kt day^{-1} (gvn 2003b) and we may expect a similar waning trend in the Nyiragongo data provided the system is not recharged with fresh magma. Plume altitudes at Miyakejima are typically under 2 km (gvn 2003b) and hence ep toms has detected its SO_2 emissions much less frequently than at Nyiragongo.

From a volcanic hazards perspective it is important to understand the fate of the large volume of magma degassed at Nyiragongo since 2002. Assuming that the magma supplying the observed gas flux rises close to the surface by convection, after degassing the magma must descend and be accommodated within the system (Kazahaya *et al.* 1994; see Harris *et al.* [1999] for a discussion of several models). Tazieff (1977) surmised that 140×10^6 m^3 of magma could have been accommodated by endogenous intrusion into the 20-km long fracture system that developed during the 1977 eruption. The estimates in Table 2 indicate that a minimum of 0.22 km^3 additional magma may have been degassed at Nyiragongo since 2002, but the 2002 fracture system is of considerably greater extent than that developed in 1977 (gvn 2002b). However, there is currently no additional evidence signifying the mode of accommodation of the degassed magma. Further insight into the location and depth of magma storage beneath Nyiragongo may be gained by measuring ground deformation in the region (e.g., using synthetic aperture radar interferometry [InSAR]).

The exceptional SO_2 emissions from Nyiragongo also have implications for fluxes of other volcanic gases. Compositions of eruptive gases in 1959 and 1972 are notably rich in CO_2 and relatively SO_2-poor (Le Guern *et al.* 1977, Gerlach 1980), and if the current eruptive gases are of similar composition CO_2 fluxes could be up to 7 times greater than the SO_2 flux, although some proportion of magmatic CO_2 is degassed diffusively through the volcanic edifice as evidenced by the CO_2-rich zones or 'mazukus' common in the Virunga area. Sampling of current eruptive gases emitted from fumaroles in the crater of Nyiragongo also point to very high halogen concentrations in the gases (e.g., HF/SO_2 ratios of 10-62; D. Tedesco, personal communication, 2003). Accurate determination of SO_2 emissions is therefore essential to an assessment of the complete volcanic gas budget at Nyiragongo, which will permit a more rigorous appraisal of the environmental and health hazards associated with the current degassing activity.

Finally, it is perhaps worthwhile to consider the possibility of explosive activity at Nyiragongo. The edifice has the morphology of a stratovolcano rather than a shield volcano, and Tazieff (1977) notes the existence of 180 m-thick, fine-grained melilite-rich pyroclasts exposed in the crater wall. These deposits may be of phreatomagmatic origin, since such activity clearly played a role in the 1977 eruption and possibly also in the 17 January 2002 eruption, although Tazieff (1977) attributes the deposits to explosive activity. Given the current elevated gas fluxes, if the system should revert to closed-system degassing then more explosive activity may be a hazard. Continued surveillance of SO_2 emissions at Nyiragongo is certainly warranted.

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