RESEARCH ARTICLE

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# Lava lake activity at Nyiragongo volcano (DRC) between the years 2020 and 2021 documented by seismic activity and sulfur dioxide emissions

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## Abstract

In 2020 and 2021, the Nyiragongo volcano was particularly active, until it erupted on 22 May 2021. Throughout this interval, changes in the style and intensity of volcanic activity were assessed from seismic data and $SO_2$ flux measurements, providing a valuable opportunity to explore their relationships. Our results show that $SO_2$ emission rate, seismic amplitude, and the occurrence of long period seismic events are strongly related. However, the nature of this relationship is highly dependent on the state of the volcano (i.e. whether magma is present in the crater in the form of an active lava lake). Before the eruption, enhanced outgassing of $SO_2$ preceded an increase in the frequency of long period earthquakes. Conversely, after the eruption when the crater was empty, enhanced seismicity was coincident with, or even preceded, elevated degassing of $SO_2$. In addition, our analysis suggests that a threshold $SO_2$ emission rate of 9 kt day$^{-1}$ corresponds to periods where Nyiragongo is exhibiting intense activity that may lead to an eruption if the level of the lava lake is high.

Keywords: Nyiragongo volcano; Seismic activity; Sulfur dioxide; Lava lake; Outgassing.

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## 1 Introduction

### 1.1 The Nyiragongo Volcano

Nyiragongo is the most active volcano in the east of the Democratic Republic of Congo (Figure 1). It is a stratovolcano and one of few volcanoes that host a quasi-permanent lava lake [Durieux 2003; Detay 2011; Pouclet and Bram 2021]. This volcano is located in the western branch of the East African Rift (1.52°S 29.25°E, 3469 m elevation), in its central part of Kivu in the Virunga Volcanic Province (VVP). In addition, it is built on the main north-south axis of this rift [Matondo et al. 2014; Pouclet et al. 2016]. Volcanic activity is sometimes linked to dynamics of the rifting process [Hamaguchi and Ndontoni 1990; Bagalwa et al. 2011; d'Oreye et al. 2011; Wauthier et al. 2012; Smets et al. 2017]. Nyiragongo volcano has exhibited three major fissure eruptions in recent decades, which produced lava flows outside of the crater from the flanks of the volcano: 10 January 1977, 17 January 2002, and most recently on 22 May 2021. With the exception of these flank fissure events, most of Nyiragongo's eruptions take place inside the crater where molten lava in the form of an actively overturning lava lake is frequently visible. For example, the eruption of 23 June 1994 was characterized by the reactivation of the lava lake after a period of relative quiescence [Wafula et al. 1999; Wafula 2011]. Another eruption that occurred inside the crater is that of 28 February 2016 during which a new eruptive vent formed and the lava lake was again observed to be active within the crater; this sequence of activity generated a swarm of volcanic earthquakes [Matamba et al. 2018]. From 2016 to 2021, Nyiragongo's lava lake was permanent and active. Most recently, the lava lake at Nyiragongo drained again during the fissure eruption of 22 May 2021. Lava effusion occurred from a lateral vent on the flanks and flowed down slope until reaching about tens of kilometers south-east of the volcano. Four months after this eruption, the lava lake experienced an episode of reactivation on 28 September 2021 that persisted until December 2021.

Volcano monitoring and eruption forecasting require multi-parameter analyses to understand the mechanisms that lead to eruptions. Variations in sulfur dioxide ($SO_2$) emission rate or gas chemistry, for example, can provide valuable insights into changes in the state of the magmatic system, especially when combined with geophysical monitoring of seismicity or ground deformation [Sparks 2003; Varley 2019]. The ascent of potentially eruptible magma is often accompanied by long-period seismic activity and enhanced degassing of $SO_2$ [Barrière et al. 2017]. To assess volcanic activity using gas emissions, a mini-DOAS (differential optical absorption spectroscopy) station has been installed near Nyiragongo volcano [Arellano et al. 2017; Brenot et al. 2018]. The rate of $SO_2$ release during magma ascent is then derived and remains an important tool that can inform on the intense activity of a volcano.

The recent eruption of Nyiragongo volcano, which occurred abruptly and with apparently few precursory signals, has prompted a multi-parameter review of both seismicity and $SO_2$ emission rates. In a recent study comparing long-period seismicity and satellite-based observations of $SO_2$ emissions over a period of three years (2014 to 2017), Barrière et al. [2017] noted that Nyiragongo had an almost constant background volcanic tremor and low $SO_2$ outgassing. Our aim in this study is to explore how variations in these two parameters correspond to changes in the style of activity within the lava lake and consequently to identify signals that may be considered as potential eruption precursors in the future. The main objective of this study is to establish a relationship between seismic activity and $SO_2$ emissions at Nyiragongo.

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Further, to improve the ability to forecast transitions in eruptive behavior effectively, we focus on combining seismic time series (event locations and real-time seismic amplitude measurement; RSAM) with measurements of $SO_2$ emission rates; this relationship is not well constrained for the volcanoes of the VVP and yet has been shown to yield valuable insights into magmatic processes at volcanoes elsewhere (e.g. Etna, Italy [Salerno et al. 2018]; Villarrica, Chile [Palma et al. 2008]; and Fuego, Guatemala [Nadeau et al. 2011]).

### 1.2 Seismicity in the Virunga Volcanic Province

The Virunga volcanic region is located in the extreme north of Lake Kivu. The region contains eight volcanoes, six of which are dormant and two that are more active: Nyiragongo and Nyamulagira. In the volcanic province of Virunga, some earthquakes are due to volcanic activity such as the migration as well as the accumulation of magma, including long period (LP), very long period (VLP), hybrid, and volcano tectonic (VT); whilst others derive from the tectonic activity of the rift due to active faulting. In general, the appearance of hybrid earthquakes and the repetition of seismic events dominated by LP and VLP earthquakes, followed by volcanic tremor, are often considered as indicative of a potential eruption [Wafula and Bagalwa 1999; Allard et al. 2002; Kavotha et al. 2003; Mavonga et al. 2006; 2010; Wafula 2011; Birimwiragi Namogo et al. 2016; Kosongo et al. 2017]. Volcanic tremor can be generated by the ascent of magma prior to and during an eruption, by the displacement of magma through narrow fissures, and by the pulsation of pressurized fluids inside the volcano [Droznin et al. 2015]. The tremor intensity may depend on the velocity of magma movement and the magma properties such as viscosity and gas content [Bhugwant et al. 2002].

## 2 Data acquisition and analysis

### 2.1 Seismic data

The data used in this work were provided by the KivuSnet seismographic network built around the Nyiragongo and Nyamulagira volcanoes (Figure 1). To monitor volcanic activity, the KivuSnet network has about 15 broadband seismographic stations telemetered in real-time [Oth et al. 2017].

For locating earthquakes and detecting their type (by spectral analysis) we used the SEIsmic ANalysis (`SEISAN`) software. From raw seismic data, we also calculate RSAM, which is a measure of seismic energy, and provides a metric to summarize the intensity of seismic activity by a single parameter [Sassa 1936; Schick et al. 1982; Schick 1988; Endo and Murray 1991; Budi-Santoso et al. 2013]. RSAM is calculated from the seismic amplitude and is based on the average amplitude of earthquakes over 10-minute intervals. Increases in tremor amplitude or the rate of occurrence and size of earthquakes results in increasing values of the RSAM*. In other words, RSAM includes contributions from all seismic event types (VT, LP, and VLP) and can be used as a proxy for the intensity of volcanic seismicity, including tremor. To calculate the RSAM, we use either the NYI station or the KBTI station closest to the Nyiragongo volcano.

*https://avo.alaska.edu/rsam/index

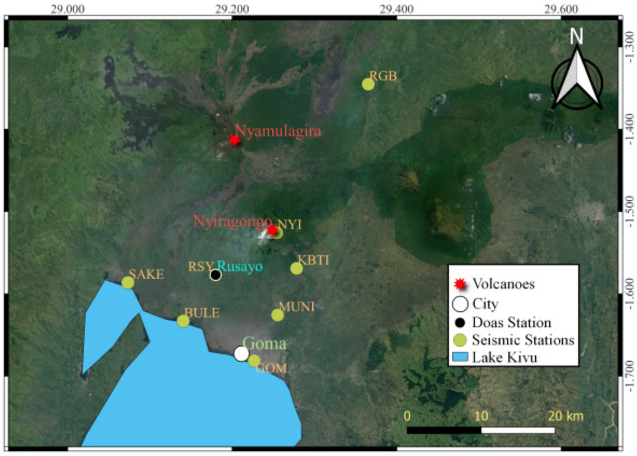


Figure 1: KivuSnet stations used in this study, also showing locations of Nyamulagira and Nyiragongo. The map also shows the position of the Rusayo mini-DOAS station in relation to the Nyiragongo volcano. This station was set up to the south-west of Nyiragongo (−1.577°S 29.17988°E, elev. 1688 m); the preference for this location was due to the usual direction of the gas plume.

### 2.2 Sulfur dioxide data acquisition and processing

In addition to these seismographic stations, the Observatoire Volcanologique de Goma (GVO) assesses the activity of Nyiragongo volcano from the mini-DOAS station at Rusayo (Figure 1). The mini-DOAS quantifies the amount of $SO_2$ contained in a path (column) through the gas plume based on characteristic absorption features in the ultraviolet region of scattered sunlight, and is a tool used to study the degassing flux and chemistry of a volcanic plume [e.g. Galle et al. 2003; Bani 2006; Heard 2006; Platt and Stutz 2008]. $SO_2$ emission rates can be derived from DOAS measurements of the amount of $SO_2$ within a plume cross-section when combined with independent measurements of plume speed [e.g. Galle et al. 2010]. As the technique relies on incoming solar radiation, these measurements are only possible during daylight hours.

Prior to 2020, mini-DOAS measurements were not carried out regularly and there are periods when data are missing. Therefore, in this work we used two years of data collection (2020 and 2021) during which the data recording is almost complete. Data acquisition software developed through the NOVAC program [Network for Observation of Volcanic and Atmospheric Change; Galle et al. 2010] was used to calibrate the instrument, evaluate uncertainties, and import the data in `Excel` format for analysis. A wind speed of $10\,\mathrm{m\,s^{-1}}$ was estimated from the average of different wind speeds recorded by weather stations in the region, and used as a constant in this analysis.

## 3 Results

### 3.1 General observations of volcanic activity

From the year 2016 until its eruption on 22 May 2021, the lava lake of Nyiragongo volcano has experienced periods of instability (increase in the level of the lava lake, fall of the lava lake, eruption, and reappearance of the lava lake). As of 28 February 2016, there was an opening of an eruptive vent inside the crater [Matamba et al. 2018] and long-period earthquake swarms were located in the Nyiragongo volcano field. Between 17–19 April 2020, a drop in the level of the lava lake was observed [Barrière et al. 2022]. On 22 May 2021 at 6:30 pm local time, some cracks on the southern flank opened and a fissure eruption began, emptying the lava lake. The lava flow lasted approximately three hours, stopping less than 1 km from Goma international airport. On 28 September 2021, a new lava lake was observed to have formed in the crater of Nyiragongo volcano.

During and after the eruption on 22 May 2021, seismic activity in the Virunga region was intense, dominated by tectonic earthquakes (Figure 2). Seismicity began a few hours after the eruption and quickly migrated towards the volcano's southern flank, following the main axis of the N-S rift. Seismicity remained concentrated in the northern part of Lake Kivu. Very few long-period volcanic earthquakes were recorded during the eruption, due to magma movement as the reservoir emptied. The few earthquakes observed in and around the volcano's crater were due to the crater collapsing in the first week of June.

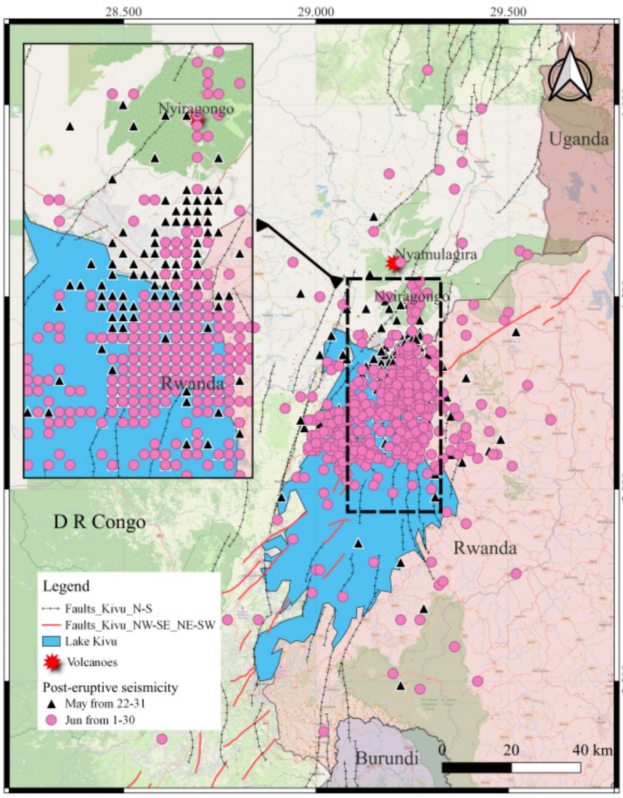


Figure 2: Spatial distribution of post-eruptive seismicity from the Nyiragongo eruption of 22 May 2021 for the months of May and June 2021.

The local seismographic network detected renewed seismic unrest marked by volcanic earthquakes recorded in the Nyiragongo volcano field in August 2021. Swarms of LP earthquakes were recorded and localized in Nyiragongo between 24–30 August 2021. Two short duration swarms of LP events were observed on 7 and 13 September, after which the lava lake gradually reappeared in small quantities on the night of 28 September 2021; this was first reported at 9:45 pm local time. A glow was observed emanating from the crater. From that date of reactivation for several weeks, the seismic activity was characterized by volcanic tremor. To assess the potential risk from a magmatic injection at depth to the surface, a team of researchers was dispatched to the crater of Nyiragongo volcano to assess this renewed activity. They confirmed the presence of vigorous magmatic activity with lava present and active inside the crater. They also observed lava fountaining activity in especially active regions of the lava lake, degassing fumaroles, and small gas plumes. The photos in Figure 3, taken by the team in the field, illustrate these observations.

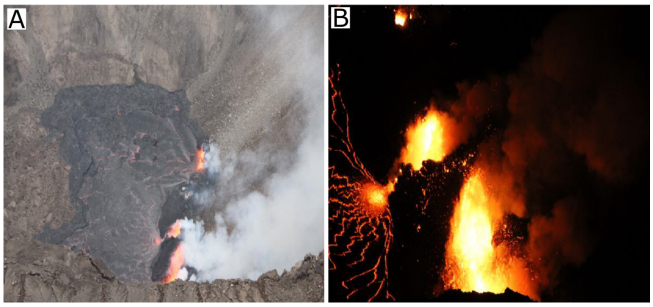


Figure 3: Photos showing the inside of the Nyiragongo volcano crater, taken respectively on 30 September 2021 at [A] 5:12 pm and [B] 6:18 pm (local time), two days after lava lake reappearance.

A few weeks later, around 17 October 2021, the lava once again disappeared from the crater of Nyiragongo. Simultaneously, the amplitude of the tremor also diminished and was only observed at the NYI station, installed at the top of the volcano. Long period earthquakes had not been recorded since the tremor began to be observed. On 4 November 2021, a small swarm of long period earthquakes was recorded and located close to Nyiragongo. On 17 December 2021, intense seismic activity recommenced, with high amplitude tremor observed at almost all stations around the volcano. During the following week, a strong glow was observed from the crater by the local population, suggesting lava was present at the surface. The amplitude of seismic tremor increased and was detected especially by the stations on the southern flank of the volcano, remaining elevated until the end of March 2022.

### 3.2 $SO_2$ emission rates

A time series of the daily average $SO_2$ emission rate from Nyiragongo volcano between January 2020 and February 2022 is presented in Figure 4. During the period of observation, the highest $SO_2$ emission rate occurred on 17 November 2020 when an emission of 13.21 kt day$^{-1}$ of $SO_2$ was recorded. In this study, we will focus on examining the eruptive processes taking place during the following periods of elevated degassing:

- 11–16 April 2020: high $SO_2$ emissions of 12.97, 11.98, 11.24, and 12.48 kt day$^{-1}$, respectively, on 11, 12, 13, and 16 April 2020.

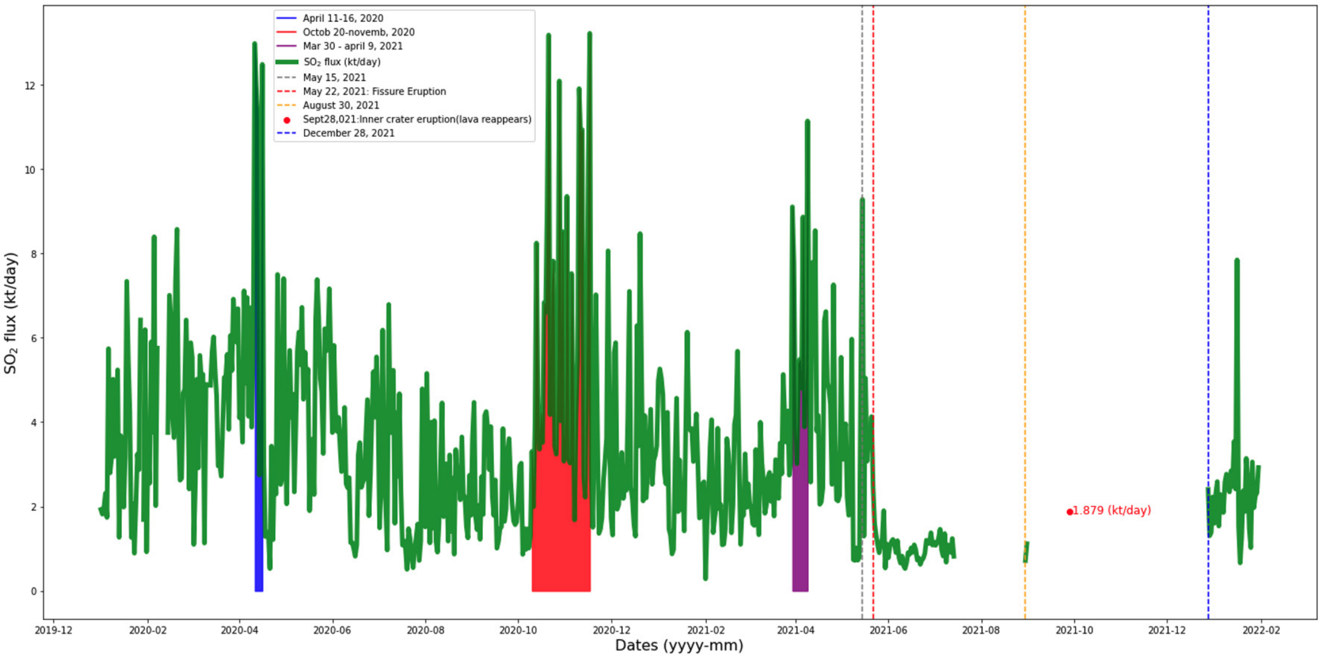


Figure 4: Evolution of $SO_2$ emission rate in the Nyiragongo gas plume from January 2020 to February 2022. The red dashed line indicates the eruption date.

- 20 October to 17 November 2020: high $SO_2$ emissions were observed on some dates: 13.17 and 12.09 kt day$^{-1}$ on 21 and 28 October and 9.35, 11.90, 10.78, 10.93, 10.13, and 13.21 kt day$^{-1}$ on 2, 10, 11, 12, 16, and 17 November 2020, respectively.
- 30 March 2021: 9.11 kt day$^{-1}$ of $SO_2$ was emitted.
- 9 April 2021: 11.14 kt day$^{-1}$ of $SO_2$ was emitted (one month before the eruption on 22 May 2021).
- 15 May 2021: 9.28 kt day$^{-1}$ of $SO_2$ was emitted (one week before the eruption).

Figure 4 also shows that, after the eruption, the rate of $SO_2$ emissions decreased abruptly. From July 15 onwards, $SO_2$ emissions were no longer detectable until 30 and 31 August 2021, the dates on which small $SO_2$ emission rates were measured. This is consistent with the return of LP volcanic earthquakes recorded inside the Nyiragongo crater from 24 August 2021. After 31 August 2021, small $SO_2$ emissions (0.92 kt day$^{-1}$) were again observed on 31 September 2021, just after a swarm of LP earthquakes on 7 and 13 September 2021. According to the same figure, $SO_2$ emissions were again observed on 25 September (3 days before the return of lava) and on 28 September during the eruption inside the crater. This again coincides with the recording of large-amplitude volcanic tremors on the seismograms. As we can notice, there were no $SO_2$ emissions from 28 September to 28 December 2021. This may be due to the insufficient quantity of lava present and the low level of activity observed a few weeks after the appearance of the lava lake. On 17 October the lava disappeared and a decrease in the amplitude of volcanic tremors was also reported. On 17 December 2021 lava returned to the crater with volcanic tremors of great amplitude, and on 28 December 2021 $SO_2$ emissions were regularly observed. To understand the events that took place on these dates in more detail, we also examine the seismicity occurring during the same intervals; specifically, the number and type of volcanic earthquakes, RSAM, and the spatial distribution of earthquake epicenters.

### 3.3 Seismic activity in the Virunga Volcanic Province before the 22 May 2021 eruption

During 2020 and 2021, the Nyiragongo lava lake experienced moments of instability, characterized by the fall and rise of the lava lake level. Figure 5 shows the instability of the lava lake over time, identified as periods of enhanced variability in RSAM. In this work, we consider only the periods of greatest $SO_2$ emission rates: the first episode appeared between 11–16 April 2020 and the second occurred between 21 October and 17 November 2020, as shown in Figure 4. The RSAM time-series (Figure 5) also showed changes during these periods; on 15 April 2020 the RSAM decreased, and on 17 April 2020 a swarm of earthquakes commenced that produced a peak in RSAM (Figure 6B). From 20 October to the end of December 2020, we observe large fluctuations in RSAM (increases and decreases; Figure 5). This corresponds well with high $SO_2$ emission rates (Figure 4) over the same period, and intermittent intense seismicity dominated by LP and VLP events shown in Figure 7. The April 2020 seismic activity was dominated by LP earthquakes, whereas the October 2020 activity included both LP and VLP earthquakes.

A third episode of interest runs from 30 March 2021 to the eruption date as shown in Figure 4, with high emission rates of 9.10, 11.14, and 9.28 kt day$^{-1}$ on 30 March, 9 April, and 15 May 2021, respectively. Following these emissions on 30 March and 9 April 2021, a swarm of LP earthquakes appeared between 20–24 April 2021, one month before the eruption (locations shown in Figure 8). The seismicity analysis carried

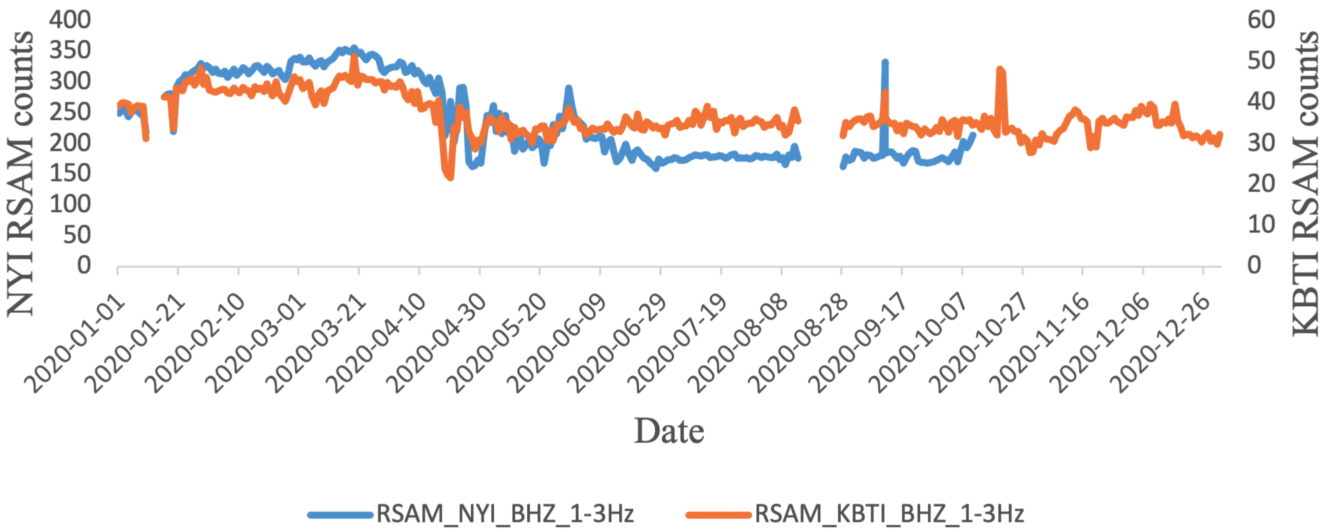


Figure 5: RSAM timeseries during 2020 at NYI and KBTI stations in the LP frequency range (1–3 Hz).

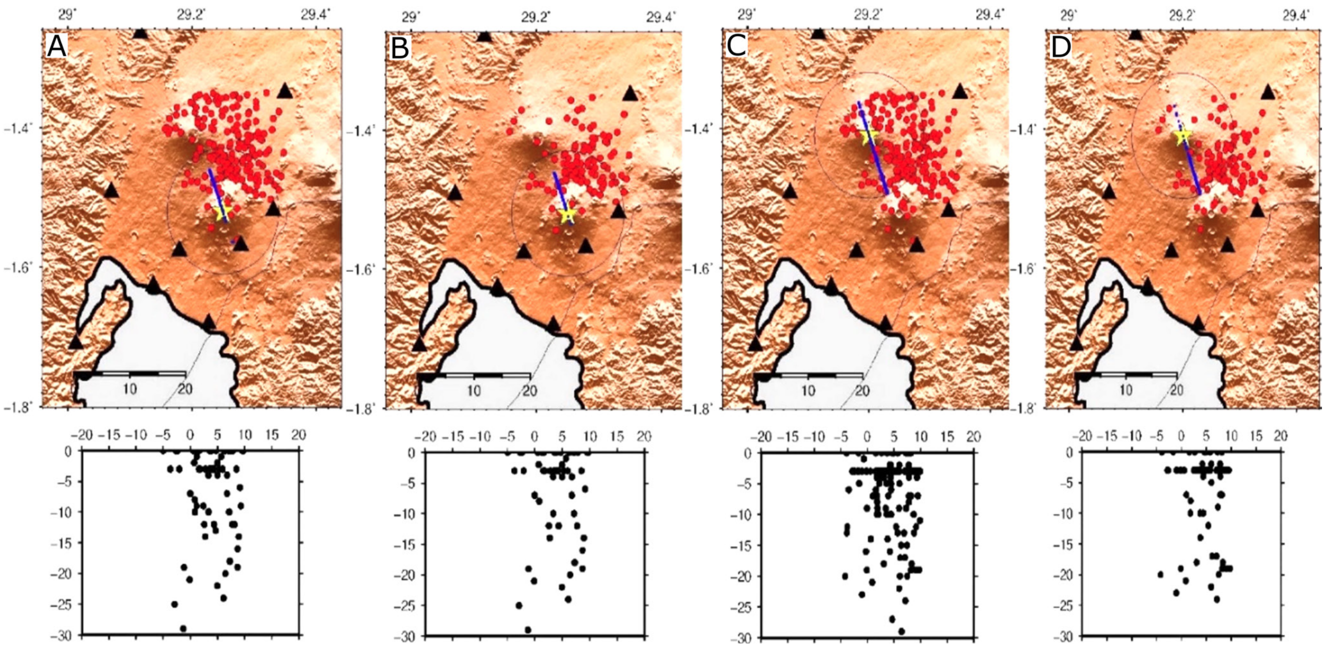


Figure 6: Distribution of epicenters and hypocenters of LP earthquakes in the area of [A] Nyiragongo and [B] Nyamulagira volcanoes during during April 2020. [B] and [D] represent only the swarm of LP earthquakes on 17–19 April 2020 in the area of the same volcanoes. The yellow stars show the positions of the two volcanic craters connected by the blue lines following the direction of the rift axis that joins the Nyiragongo and Nyamulagira volcanoes. The black dots in the graphs below each map show the depth distribution (hypocenters) of the earthquakes inside the circle in the maps: these hypocenters are counted from the surface to depth and the units on the two axes are given in km.

out by Sadiki et al. [2023] also revealed the recording of other types of volcanic earthquakes: hybrid events were recorded prior to this swarm of long-period earthquakes, notably between 9–10 April 2021. This high level of seismicity induced a very slight increase in RSAM and lava lake level (Figure 9; note the difference in y-axis scale from Figure 5).

The seismic activity in April 2020 was elevated relative to background, especially on 17 and 19 April 2020. The distribution of epicenters and hypocenters in the Nyiragongo and Nyamulagira volcano fields are presented in Figure 6. Seismic activity during April 2020 was most concentrated in the field of Nyamulagira volcano, north-east of Nyiragongo volcano. Earthquake hypocenters were distributed over a range of depths and along a NNW-SSW trending axis between the two volcanoes. At the same time, between 17–19 April 2020, a drop in the level of the lava lake was observed [Barrière et al. 2022] and a sudden decrease in the RSAM on the same date was observed (Figure 5). Together, these observations suggest that a lateral intrusion to the north-east of Nyiragongo, along the rift, may have drained the shallow magmatic system beneath Nyiragongo and caused the lava lake level to fall. A similar event was observed prior to the flank eruption of Pu'u

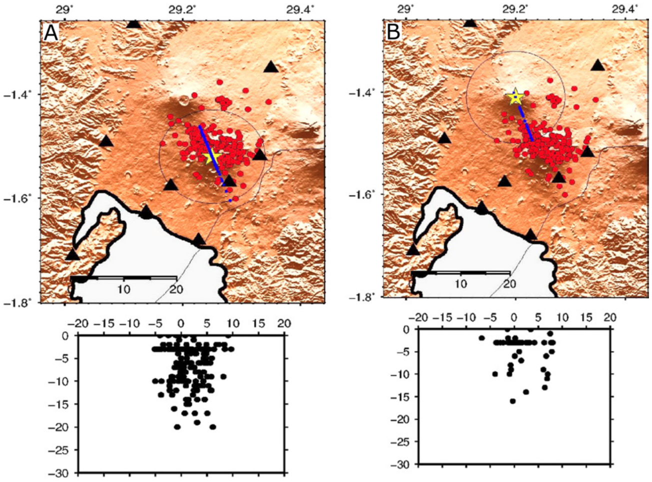


Figure 7: Distribution of epicenters and hypocenters of LP and VLP seismic events in the area of [A] Nyiragongo and [B] Nyamulagira volcanoes in October and November 2020. Further description as in Figure 6.

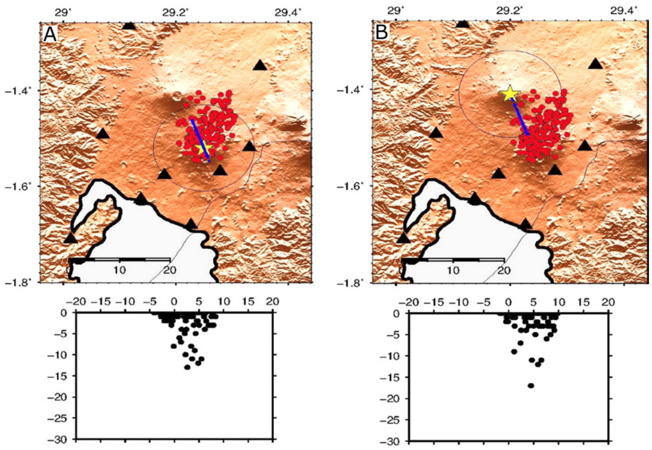


Figure 8: Distribution of epicenters and hypocenters of an LP earthquake swarm in the area of [A] Nyiragongo and [B] Nyamulagira volcanoes on 20 and 21 April 2021. Further description as in Figure 6.

ʻŌʻō at Kīlauea volcano, Hawaiʻi, in 2018 [Neal et al. 2019; Patrick et al. 2020], where an intrusion into the Lower East Rift Zone caused magma to drain and propagate down-rift following collapse of the lava lakes from both Puʻu ʻŌʻō and Kīlauea's summit.

The RSAM increased again on 1 and 26 May 2020 and it remained almost constant for several months until October 2020. Another period of instability of the lava lake occurred between 20 October and 20 November 2020, again evidenced by fluctuations in RSAM (Figure 5). During this period, long period seismicity was concentrated in the crater of Nyiragongo, at a depth of 1–15 km, in contrast to the previous swarm in April where seismicity was more widely distributed along the rift. Some earthquakes were also observed to the south-east of Nyiragongo. In addition, the activity was characterised by both LP and VLP earthquakes.

According to previously published work, this activity reflects the renewal of the lava lake and/or lake overflows; where lava flows from the cone and inundates the bottom platform [Barrière et al. 2022]. These previous explanations can be reinforced by the presence of high levels of $SO_2$ emissions between 20 October and 17 November, indicating that new volatile-rich magma had reached shallow levels and begun to degas. The distribution of epicenters and hypocenters of LP and VLP earthquakes in the fields of the two volcanoes is presented in Figure 7.

Intense seismic activity was recorded in the Nyiragongo volcano field between 20 and 24 Apri 2021. This activity was strongest on 20 and 21 April 2021 when around 120 volcanic earthquakes (mostly LP) occurred each day on average. Compared to the previous periods of elevated seismic activity (April and October 2020), this swarm was concentrated in the Nyiragongo volcano field, similar to the October–November 2020 activity but shallower; this time between 0 and 5 km deep (Figure 8). Only a month before the fissure eruption, the lava lake was at a high level with magma close to the crater floor. We noticed a slight increase in RSAM at this time. The hybrid earthquakes that were recorded and localized to the south-east flank in the Nyiragongo volcano field [Sadiki et al. 2023], followed by a swarm of long-period earthquakes, are a sign of strong activity at the volcano. These events are interpreted as a shallow magmatic intrusion towards the south-eastern part of the crater.

### 3.4 Seismic activity in the Virunga Volcanic Province after the eruption of 22 May 2021

We highlight three episodes of notable RSAM fluctuations during and following the fissure eruption of 20 May 2021. We correlate these episodes to observed changes within the Nyiragongo lava lake. In Figures 10 and 11, we present the RSAM time series and corresponding helicorder plots, respectively, at the NYI and KBTI stations.

A peak in RSAM on 22 May 2021 corresponds to the eruption of the volcano on the southern flanks. On this date, there was a substantial magma movement associated with the drainage of the magma reservoir and the emplacement of lava flows. We observed that the increase in seismic activity started a few hours before the eruption and had slightly decreased by the end of the day. Tectonic seismicity then increased abruptly from 23 May 2021 until six days after the eruption, during which time the average number of earthquakes was about 100 per day. After this date, we observed a sharp drop in RSAM followed by an extended period of about four months during which the seismic activity of the volcano is subdued relative to previous RSAM background and remained relatively constant (Figure 9). Post-eruption seismic activity was characterised mostly by tectonic earthquakes. However, despite a swarm of tectonic earthquakes after the eruption of 22 May 2021, the RSAM did not remain elevated.

On 28 September 2021 the RSAM increases abruptly, back to a level almost equal to that seen during the previous eruptive episode. This event correlates with the reappearance of lava within the crater of Nyiragongo and the reactivation of the lava lake. Figure 10 shows the abrupt transition from background seismicity to strong tremor when lava appears. The images shown in Figure 11 testify to the presence of lava in

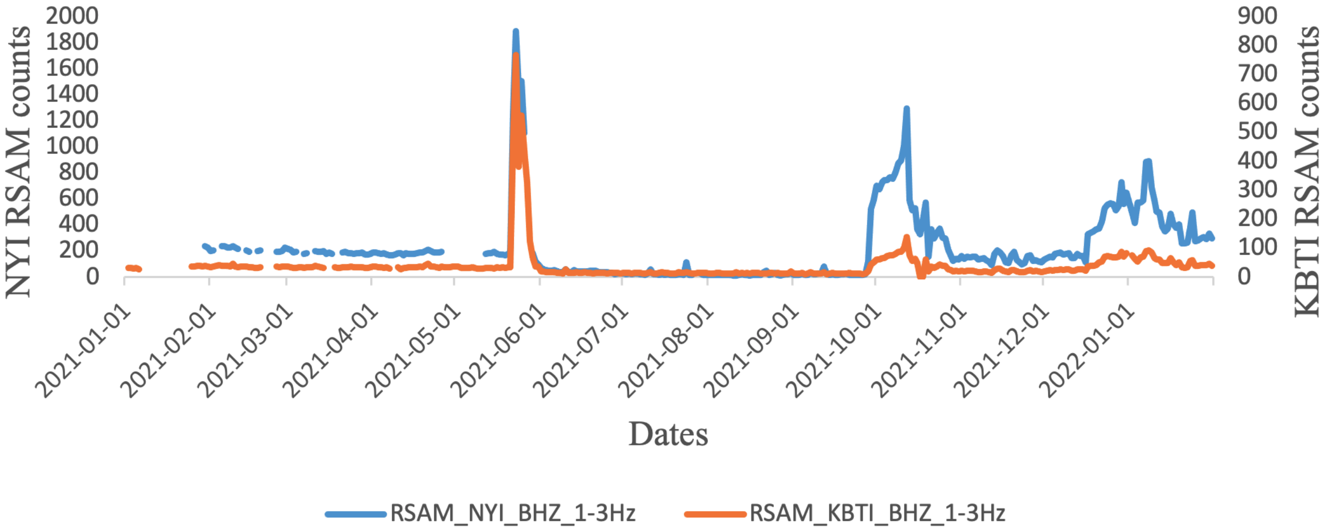


Figure 9: RSAM measurement for 2021 year from NYI and KBTI stations (1–3 Hz).

the Nyiragongo crater and therefore to the high activity of the lava lake. One month prior to the reactivation, two swarms of LP earthquakes located in the field of Nyiragongo volcano occurred from 24–28 August 2021 (Figure 12) and from 7–8 September 2021 with a daily average of 100 LP earthquakes; we infer that these LP earthquakes swarms may have heralded a period of magma intrusion and migration to shallow depths ahead of the reappearance of lava within the crater. After initial vigorous activity, the lava lake became progressively more quiescent, accompanied by a gradual reduction in RSAM. However, RSAM remained highly variable during this period (after 28 September), reflecting lake level fluctuations (Figure 9).

The third distinct change in RSAM occurred from 17 December 2021, where RSAM began to increase again, but this time more slowly than during either of the previous events described. This change corresponds to the onset of more vigorous activity of the lava lake (including small fountains and lava flows inside the crater) and a substantial increase in lake level. Seismicity is characterised by continuous tremor. A small glow could be seen from the town of Goma and field observations on the following day confirmed a small quantity of lava in the crater (Figure 11). Compared to the activity of 28 September 2021, the elevated seismicity was detected even by stations located on the southern flanks of Nyiragongo volcano. The tremor continued at the NYI station (summit station) until February 2022, which means that lava lake activity was concentrated in the central crater; however, the tremor amplitude decreased over time.

### 3.5 Temporal relationship between variations in volcanic seismic activity and $SO_2$ emission rate

We compare time series of RSAM and $SO_2$ emission rate in 2020 and 2021 in Figures 13 and 14, respectively. $SO_2$ emissions exceeded 9 kt day$^{-1}$ in April, October, and November 2020; these elevated emissions are broadly coincident with intervals of more variable RSAM, which we relate in Section 3.3 to intervals of instability in the lava lake level. $SO_2$ emission rates peak at 13 and 12.5 kt day$^{-1}$ on 11 and 16 April 2020, respectively. On 15 April 2020, we also reported a decrease in RSAM and on 17, 18, and 19 April we observed a drop in the level of the lava lake and a swarm of LP earthquakes located to the north-east of the crater of Nyiragongo volcano. Strong $SO_2$ emissions were also observed between 20 October and 17 November. Again, RSAM showed corresponding changes during this period; a decrease in RSAM occurred on 25 October 2020 shortly after the onset of enhanced outgassing, and was maintained until 15 November 2020. RSAM subsequently began to increase on 17 November 2020 and 13.2 kt of $SO_2$ was emitted (i.e. the largest emission recorded during our study period). Short duration swarms of LP earthquakes accompanied these emissions and were located in the crater of the Nyiragongo volcano.

The $SO_2$ emission rate increased during 30 March and early 15 May 2021; peaking at 9.1, 11.1, and 9.3 kt day$^{-1}$, respectively, on 30 March, 9 April, and 15 May 2021 (i.e. one month before the flank fissure eruption; Figure 14). These events took place before a slight increase in seismic energy release and seismic events were localised beneath the central crater of Nyiragongo volcano between 19–24 April 2021. On 22 May 2021 (the day of the flank fissure eruption), we recorded a large and abrupt increase in the RSAM, which quickly dropped in the hours following the eruption. Following the eruption initiation, $SO_2$ emissions reduced rapidly over several days to <1 kt day$^{-1}$, and then from 15 July to 28 August 2021 no $SO_2$ emissions were detected. It was only after a swarm of LP earthquakes in the Nyiragongo crater between 24–28 August 2021 that we measured again a small and transient $SO_2$ release (i.e. on 30 and 31 August 2021). Short-lived $SO_2$ emissions were again observed on 13 September 2021, following another seismic swarm between 7–8 September 2021, two weeks prior to the reactivation of the lava lake. Further gas emissions were observed on 25 September 2021, three days before the lava appeared.

Interestingly, after the initial reappearance of the lava lake, no further $SO_2$ emissions were detected for several months (from September until 27 December 2021). However, this is not unexpected as this reduction in emissions coincides with

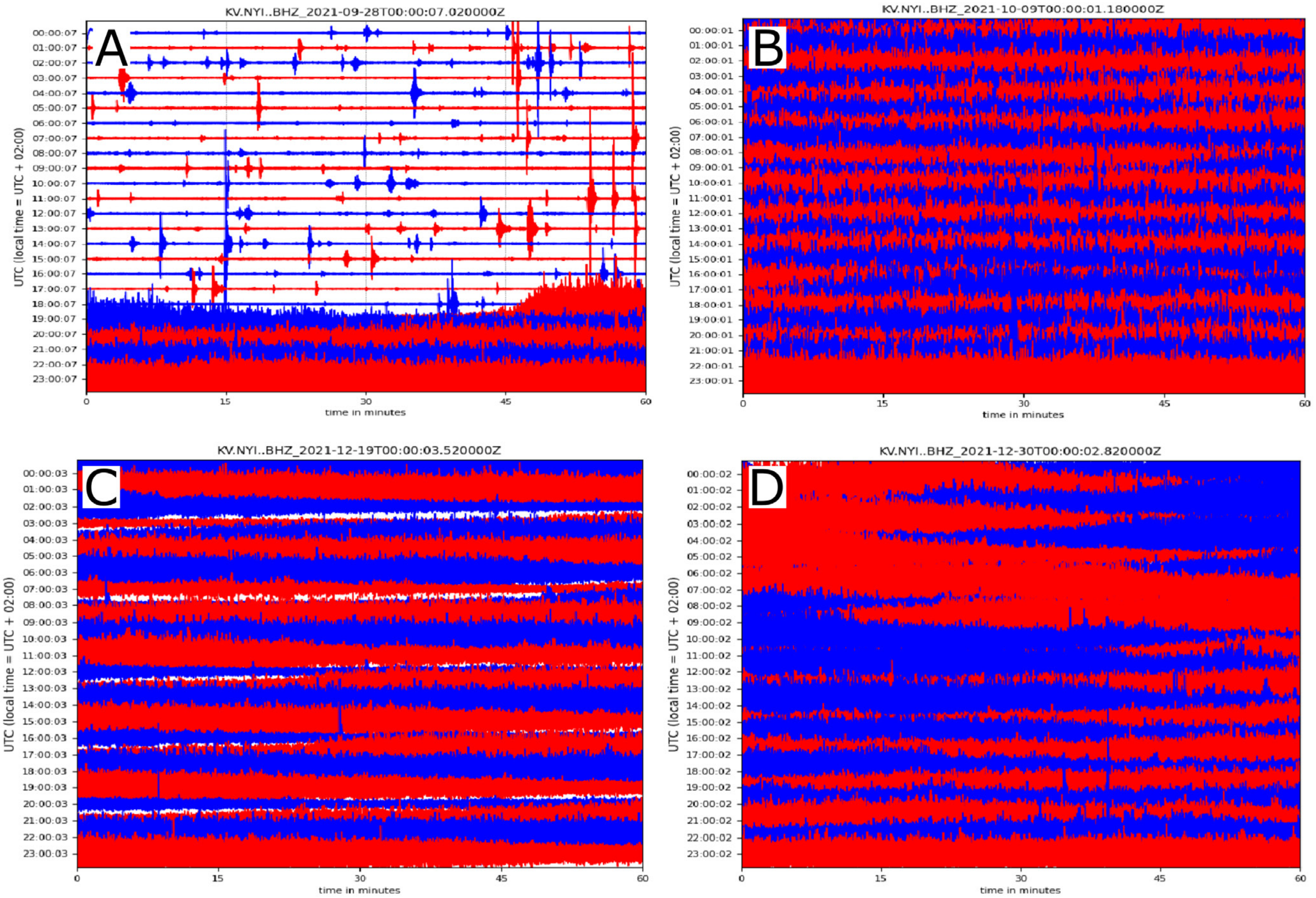


Figure 10: Helicorder plots from NYI station on [A] 28 September 2021, [B] 9 October 2021, [C] 19 December 2021, and [D] 25 December 2021.

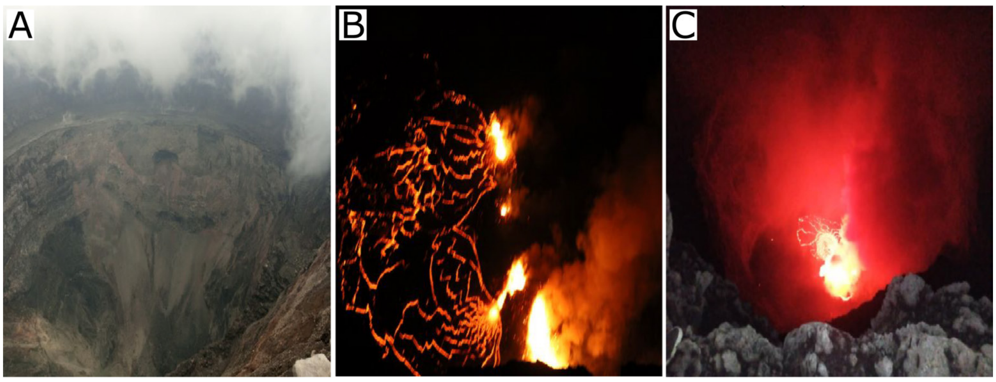


Figure 11: Photos of the Nyiragongo crater: [A] 3 September 2021 at 1:52 pm (local time) after the 24–30 August 2021 swarm, [B] 18 October 2021, and [C] 26 December 2021 at 3:00 am (local time).

the disappearance of lava in the crater and the decrease in tremor amplitudes observed, as explained above. This could be explained either by an insufficient quantity of lava in the crater, or by weak magmatic activity at depth. We could also add that, as the lava lake was not yet stable, the lava could have flowed back into the deeper parts of the crater.

By 17 December 2021 seismic swarms of LP earthquakes were again observed and correspondingly the RSAM had begun to increase; large amplitude tremors were observed and $SO_2$ emission had resumed until 28 December 2021 when a flux of 2.4 kt day$^{-1}$ of $SO_2$ was recorded. Strong glows were observed on several days from the town of Goma and persistent $SO_2$ emissions until February 2022 evidenced the continued presence of the Nyiragongo lava lake.

## 4 Discussion and conclusion

Identifying and understanding the relationships between geochemical and geophysical parameters is crucial for effective volcano monitoring and the detection of eruptive precursors. A correlation between $SO_2$ flux and seismicity was identified at Villarrica volcano in Chile [Palma et al. 2008], where it was noted that the seismic tremor is mainly caused by

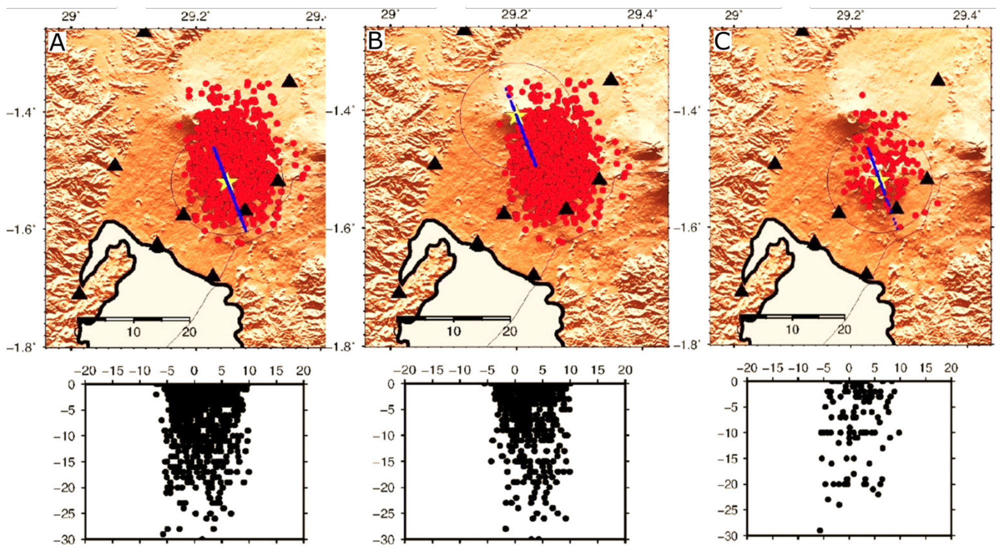


Figure 12: Distribution of epicenters and hypocenters of volcanic earthquakes (LP and VLP) in the area of [A] Nyiragongo and [B] Nyamulagira volcanoes from August to December 2021, and [C] August 2021 seismic activity isolated at Nyiragongo. Further description as in Figure 6.

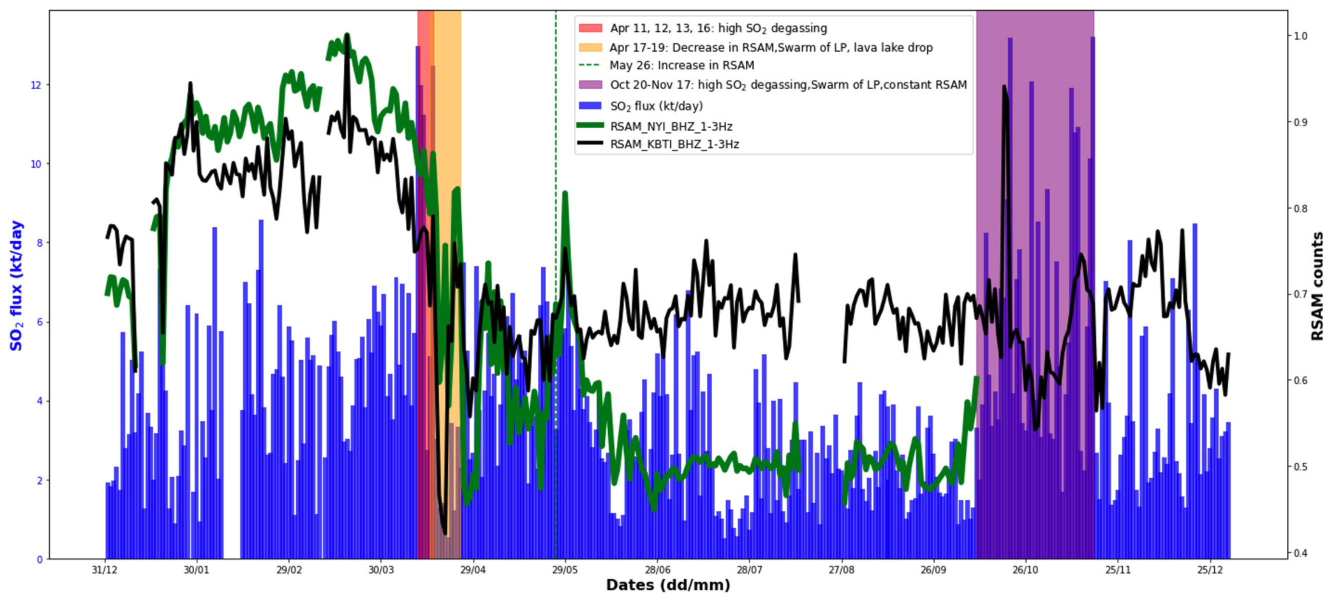


Figure 13: Comparison between timeseries of $SO_2$ flux and seismic RSAM evaluated at NYI and KBTI stations during 2020, in the Nyiragongo volcano field.

explosive degassing activity. In addition, higher $SO_2$ emissions appeared to be linked to higher lava lake levels, greater bubble bursting activity, and changes in the morphology and texture of the crater floor. During the ongoing eruption of Soufrière Hills volcano, Montserrat, hybrid and long-period seismic events were associated with changes in the rate of $SO_2$ emission at the surface at different times during the eruption [Edmonds et al. 2003]. At Mount Etna, a correlation was found between long-period earthquakes, volcanic tremor, and degassing [Zuccarello et al. 2013], and consequently it was noted that tremor amplitude can be used as a first-order approximation of the volcano's background degassing activity. Similarly, at Fuego volcano a link has been shown between volcanic tremor, degassing, and the observed eruption dynamics; higher bubble concentrations or faster flow of bubble-rich fluids generated stronger tremor and larger bubble volumes produced higher amplitude tremor signals and would ultimately lead to higher $SO_2$ emission rates [Nadeau et al. 2011]. At Kīlauea volcano, it was noticed that the changes in $SO_2$ emission rate at the summit often corresponded to a change in RSAM, meaning that an increase in RSAM can be linked to magma or gas movement [Elias and Sutton 2012]. However, only when the temporal resolution of $SO_2$ monitoring is improved, towards the sampling rate of geophysical techniques, will it be possible to correlate and assess short-term changes effectively, on timescales of hours to days.

In this study, we present time series monitoring data for the parameters of $SO_2$ emission rate and seismicity (event rate, location, event type, and RSAM) at Nyiragongo volcano during the period 2020 to 2021. We have focused on describing

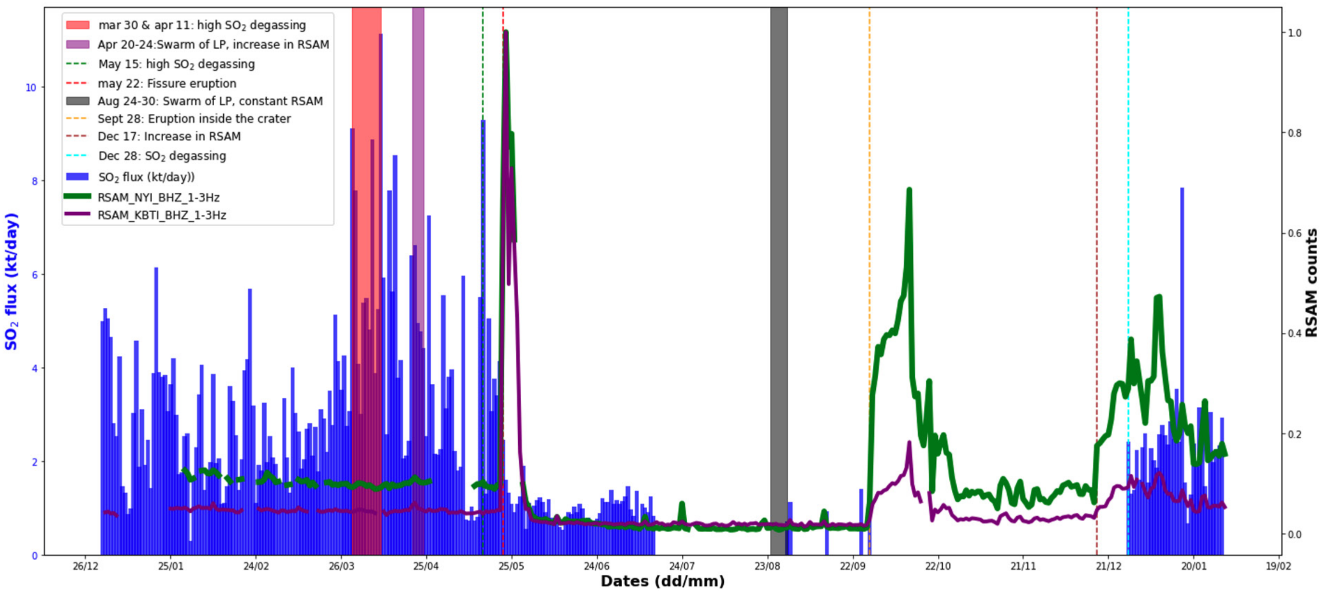


Figure 14: Comparison between timeseries of $SO_2$ flux and seismic RSAM evaluated at NYI and KBTI stations during 2021, in the Nyiragongo volcano field.

several episodes of rapid or substantial change in detail to explore the relationship between seismicity and degassing, and we have related these episodes to synchronous observations of lava lake activity to interpret the volcanological mechanisms that underpin this relationship. The lava lake was active for about one year before the 22 May 2021 flank eruption. After erupting, the Nyiragongo crater remained empty for more than four months, representing a period of recharge prior to the reactivation of a new lava lake. Prior to this eruption, when lava was observable in the crater at appreciable levels and quantities, $SO_2$ emissions ranged from 0.3 to 13.2 kt day$^{-1}$. Our analysis demonstrated two contrasting relationships between seismic energy released and gas emission rates, which depends on the state of the lava lake at the time (i.e. whether lava is present within the crater or not).

1. Lava present in crater and lake active: a decrease in seismic energy release (expressed as RSAM) following periods of strong outgassing. We attribute this reduction in seismic energy to a decrease in the lava lake level, which in turn is inferred to reflect gas loss (volume reduction) and depressurisation in the shallow magmatic system, potentially accompanied by endogenous lateral intrusions at depth [Barrière et al. 2022; Walwer et al. 2023].

2. Lava drained from crater and lake not active: an increase in seismic energy release accompanies increasing outgassing. Together, we explain co-variation in these two parameters as reflecting the migration of new volatile-rich magma to shallow depths (above the sulfur exsolution level) beneath the crater of Nyiragongo. Accordingly, re-pressurisation of the reservoir and shallow conduit as a result of magma movement and degassing during these periods may explain coincident observations of increasing lava level within the crater. Seismic swarms dominated by long-period earthquakes are also often observed a few days after degassing, further supporting the migration of either magma or exsolved gases.

Notably, one month before the fissure eruption of 22 May 2021, a protracted period of strong outgassing was accompanied by a small and transient increase in RSAM and a swarm of long-period earthquakes located beneath the crater of Nyiragongo volcano. We interpret this relationship as the expression of the migration of volatile-rich magma from depth to a region of shallow magma storage. Localized hybrid earthquakes on the south-east flank suggest lateral shallow magma transfer accompanied by brittle rock failure as new pathways for magmatic fluids opened, potentially in response to changes in the shallow stress distribution resulting from new magma intrusion.

After the eruption of 22 May 2021, when the crater was empty of lava, $SO_2$ emissions were largely absent, reflecting a lack of undegassed magma remaining stored at shallow depths. However, transient emissions were detected following seismic swarms of long-period events. We infer that the seismicity reflects fluid movement (gas and/or magma) as new magma migrates to recharge the shallow magmatic system and degasses, which is subsequently expressed as short-lived episodes of gas release at the surface.

The recent eruption of the Nyiragongo volcano, which began somewhat unexpectedly and apparently without precursory signals, prompted us to review and compare time series of seismicity and $SO_2$ emission rate to further develop our understanding of how co-variations in these two parameters relate to ongoing or future volcanic activity. These insights can be considered as precursors of the 22 May 2021 eruption and will contribute to improving our ability to forecast transitions in eruptive behavior in the future. We found that RSAM provided an informative metric for quantifying variations in seismic intensity that correlate temporally with changes in lava lake level during the period 2020 to 2021. Further, by analysing pre-, syn-, and post-eruptive periods, we found that events of marked change in the activity of the Nyiragongo lava lake are generally associated with $SO_2$ emission rates in excess of 9 kt day$^{-1}$. This threshold in gas emission rate may provide a useful precursory indicator of impending eruptive transitions, including potential flank eruptions. Lastly, we found a contrasting relationship between seismicity and degassing depending on whether lava was present within the crater as an active lava lake.

Our results show that regular assessment of seismic activity and $SO_2$ emission rate are indispensable tools for robust monitoring of Nyiragongo volcano. In particular, during periods where lava is absent from the crater, correlated increases in these two parameters may provide early indication of the ascent of volatile-rich magma to shallow depths ahead of lava lake reactivation or flank eruption. The Nyiragongo volcano is still active; it is therefore essential to prioritise developing effective monitoring strategies to forecast eruptive transitions and potential eruptions in the future.

## Author Contributions

Olivier Munguiko proposed the study and the data analysis protocol, compiled and analysed the data, and drafted the manuscript. The co-authors were involved in processing the data, as well as commenting on and amending the manuscripts before submission.

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## Data Availability

The data used in this study is not yet available to third parties as it is subject to agreement. However, we declare that they are not subject to any conflict of interest.

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