

Eruption of Nyiragongo Volcano On May 22, 2021 Release Of SO_2 And CO_2 Into The Atmosphere

Faustin S. Habari^{1*}, Olivier M. Munguiko², Marcel B. Rusimbuka¹

¹Geochemistry and Environment Department, Goma Volcano Observatory, Goma, Democratic Republic of Congo

²Seismological Department, Goma Volcano Observatory, Goma, Democratic Republic of Congo.

*Corresponding Author

Faustin S. Habari, Geochemistry and Environment Department, Goma Volcano Observatory, Goma, Democratic Republic of Congo.

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Abstract

Nyiragongo Volcano is located in the western part of the African Rift. Deep fractures allow gas upwelling during passive and active periods. This study presents the variability of sulfur dioxide (SO_2) concentration measured at the Rusayo site and carbon dioxide (CO_2) measured at five separate sites (Bugarura and Munigi) and the seismic activity, most of these measurements were made before and after the eruption. The peak concentrations of SO_2 and CO_2 correlate well with the tremor measured continuously on the volcano. The Nyiragongo volcano erupted on the evening of Saturday, May 22, 2021 at 6:15 pm local time in Goma. Lava flowed in two directions from the flanks of the Nyiragongo volcano, killing 32 people, destroying 17 villages in the Nyiragongo territory, and cracking the ground in the city of Goma and Gisenyi. The Nyiragongo volcano is infamous for its extremely fluid lava that flows like water when the lava lake flows. Nyiragongo is a major contributor of SO_2 and CO_2 to the atmosphere. Note that this eruption of 2021 is similar to the one of 2002, which caused the death of a hundred people and the evacuation of many people, the most deadly date of 1977, had killed more than 600 people. The earthquakes were felt, after the eruption May 22, 2021 the strongest had a magnitude of 5.2

Keywords: Eruption, Carbon Dioxide, Sulfur Dioxide, Tremor, Seismic Activity, Volcano

Introduction

Volatile constituents dissolved in magmas and then emitted to the surface by volcanoes are a crucial source of information for understanding magmatic processes and predicting eruptions. Large increases or decreases in gas emission rates and pronounced changes in the composition of gas emissions are often early warning signs of an eruption [1].

The Nyiragongo volcano erupted on the evening of Saturday, May 22, 2021, at 6:15 p.m. local time in Goma, about 20 kilometers north of the city of Goma and Lake Kivu and west of the border with Rwanda, causing the destruction of houses and cracks in the ground.

A fracture opened up and the first flow went towards the south-east of the crater. A large quantity of lava flowed through several villages in the Nyiragongo Territory. Later, on the same night of May 22-23, the activity quickly migrated southward and another fracture was opened in which lava flowed into the city of Goma

(Figure 1). In total, 17 villages were affected, the main road in the region, linking Goma to the north of the province, and a high-voltage line were cut. The death toll amounted to 32 people burned by lava and asphyxiated by the smoke from the eruption, including ten people asphyxiated by toxic gases, and at least 13 people died as a result of the panic that gripped the city of Goma. A vehicle whose driver lost control ended up in a ravine, killing nine people, and four inmates of the central prison in Munzenze tried to escape, but were hit by bullets from the security forces. Around the city, the material damage is considerable. After the lava flow stopped the next day in the suburbs of Buhene, which marks the northeastern limit of Goma. The city of Goma was barely spared, but the inhabitants and the government were worried about a possible resumption of the eruption. This latest eruption of Nyiragongo is similar to that of January 17, 2002. The Nyiragongo volcano threatens the inhabitants of Nyiragongo territory, the city of Goma and ~ 2 million inhabitants of the cities of Goma (DR Congo) and Gisenyi (Rwanda).

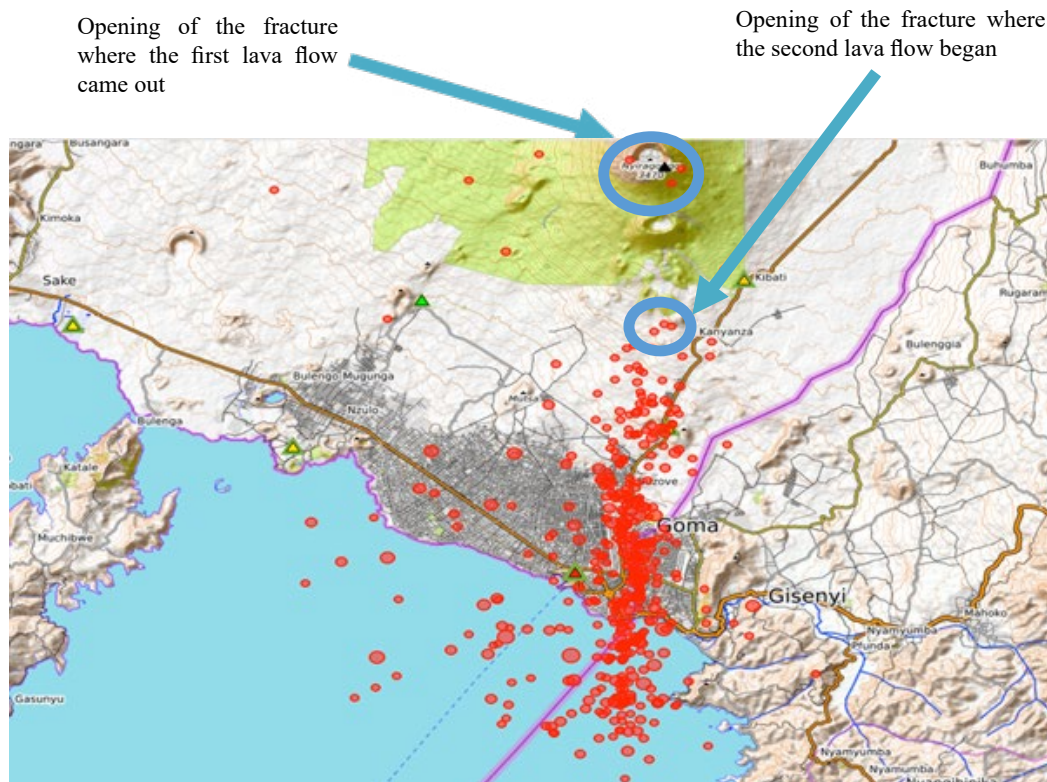


Figure 1: Distribution of earthquakes after the May 22, 2021 eruption, May 26 screenshot.

The volcanic activity of Nyiragongo is closely followed by the inhabitants, and any news related to increased activity agitates the inhabitants of the region, especially the inhabitants of Nyiragongo territory, Gisenyi and those of Goma. Nyiragongo Volcano is a beautiful and active volcano, a large stratovolcano near Lake Kivu on the eastern border of DR Congo with Rwanda in the Virunga National Park, with a slope of about 35° on average, nearly 200 km^3 in volume and about 1.2 km in diameter [2]. Nyiragongo Volcano is infamous for its extremely fluid lava that flows like water when the lava lake flows, it is well known for its lava lake and its Hawaiian-like eruptive dynamics (Sadaka K, 2003).

Indeed, from 1928 to 1977, Nyiragongo crater had a large lava lake that disappeared completely with the eruption of January 10, 1977 [3]. Another lava lake reappeared from 1982 to 1983 [4]. The active volcanoes of the Virunga chain expose the Nyiragongo region to numerous natural hazards such as lava flows, gas plumes, epidemiological diseases and armed conflicts. Of these hazards, volcanic gases are the most permanent threat to the Nyiragongo population because gases are emitted from volcanoes not only during the eruptive period but also during quiet periods [5, 6, 7, 8]. Among the gases emitted are direct emanations from the ground in volcanic regions to the atmosphere. For example, the Virunga Volcanic Province (VVP) has several such areas of gas release, including carbon dioxide (CO_2) and sulfur dioxide (SO_2).

Description of The Study Environment

The Nyiragongo volcano is located in Nyiragongo Territory near

the Rwandan-Congolese border (Figure 2). Its permanent activity and its proximity to the cities of Goma (D.R. Congo) and Gisenyi (Rwanda) explain its dangerous character for the respective populations; the main risks being lava flows, gas emanations (CO_2 , SO_2 , ...), volcanic ashes, etc. Nyiragongo (1.52°S , 29.25°E , 3,469 m, code GVP 0203-03) is a stratovolcano located on the western ascending branch of the East African Rift, in the Democratic Republic of Congo (D.R.C.). Nyiragongo is located about 20 km north of Lake Kivu (surface area $2,060 \text{ km}^2$), and 18 km from the city of Goma (population over 2 million), (Figure 2). The Goma agglomeration continues into Rwanda with the city of Gisenyi (100,000 inhabitants). Nyiragongo has a volume of 500 km^3 and its lava flows cover $1,500 \text{ km}^2$. It is located on the Kivu-Virunga regional dome. The volcanic edifice has a summit crater of 1,300 m in diameter and main adventitious cones located respectively on the southern (Shaheru, 2,800 m) and northeastern (Baruta, 3,200 m) flanks. There are also about 100 small adventitious cones along radiative fissures south of Shaheru, west of the summit in a NE-SW direction to Lake Kivu (4 km from the city of Goma) [9].

Nyiragongo volcano is one of the most active volcanoes in Africa. In addition to Nyiragongo and Nyamulagira remain active, the Virunga chain contains six other volcanoes that are considered dormant; these are Mikeno, Karisimbi, Visoke, Sabinyo, Muhavura and Gahinga

The Territory of Nyiragongo is a deconcentrated administrative entity in the eastern part of the province of North Kivu in the Democratic Republic of Congo (Figure 2). It has only one chiefdom,

headed by the Mwami, and is divided into seven groupings of 58 villages (Figure 2). The chief town is the locality of Kibumba. With an estimated population of some 145,748 inhabitants around 2016 (Bureau Central de la Zone/Territoire Nyiragongo, February 2016) and an area of 163 km²

It is limited:

- In the North: The chiefdom of BWISHA in Rutshuru territory;
- To the South: The commune of Karisimbi in the city of Goma;
- To the East: The Rwandan Republic;
- To the West: The free zone of the Virunga National Park which separates it from the chiefdom of Bahunde in the territory of Masisi.

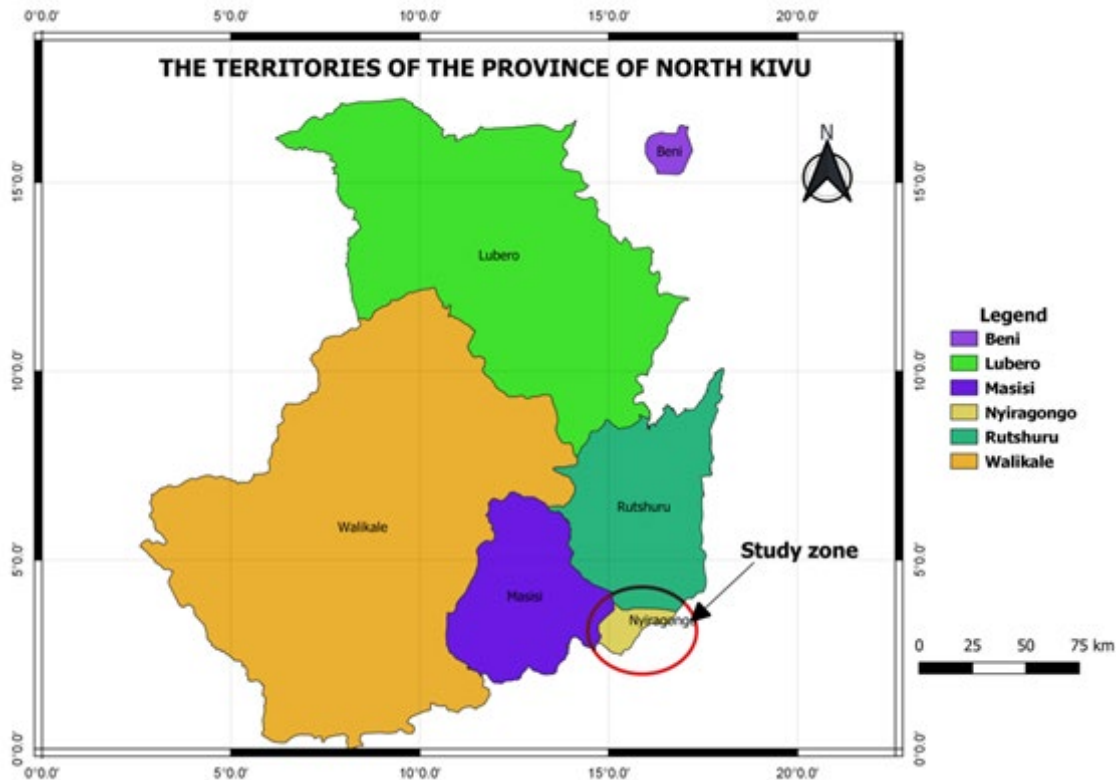


Figure 2: territories of the province of North Kivu

Volatile Compounds Emitted By Nyiragongo Volcano During Passive and Active Periods

The Nyiragongo volcano emits several volatile compounds into the atmosphere, of these compounds, our study focuses only on carbon dioxide (CO₂) and sulfur dioxide (SO₂). Volcanic gases have been described as telegrams from the interior of the earth [10]. Carbon dioxide (CO₂) accumulates by gravity making the air toxic, even lethal. CO₂ is a heavier-than-air gas that is toxic at high concentrations and asphyxiating, irritating to the eyes, nose and throat, and deadly at concentrations as low as 15% [11, 12, 13, 14, 15, 16, 17]. The concentration of CO₂ in the air is mainly due to local outgassing from the ground, while the contribution of crater gas emission is negligible at the human breathing height and always remains well below the lowest threshold for interior CO₂ concentration [18].

In magmatic processes, among the volatile elements, water is the main player, as carbon dioxide and other gases, less soluble in magma, have only a minority action. Carbon dioxide and sulfur dioxide, however, have a significant impact on the climate during major eruptions [19].

Seismicity

The eruption of Nyiragongo, notably in January 2002, the main signals occurred while the edifice was erupting (about one hundred tremors of M>3.5), (Michel Detay, 2011). January 10, 1977, This is the first and most historically known eruption, the seismicity before and after the eruption, at the time the Virunga region did not have a seismographic network to properly monitor the seismic activity. Nevertheless, some earthquakes were felt by the population between September and December 1976. We retained:- An earthquake, considered as a trigger for the magmatic activity of Nyiragongo took place at Ngweshe (South Kivu Province), 150 km southwest of this volcano, on December 5, 1976 (Mb=5), [20].- After this shock, two strong earthquakes were felt in January 1977, a few days before the eruption of January 1, 1977, and on January 6, with a greater magnitude (M = 5.3) [21]. During this period, the seismic activity was marked by the recording of volcanic tremors. After the eruption many earthquakes were felt by the population. As of January 16, 1977, 4 strong earthquakes were felt (Sadaka K. K et al 2003). The activity of the shallow magma chamber of Nyiragongo volcano is well limited by the fact that there is an open system (i.e., the lava lake) that allows for the loss of energy and

gases, and then acts as an overflow pipe that somehow regulates the energy. However, it is still necessary to monitor Nyiragongo's activity very closely in order to better understand the next phases. As is known from previous experiments [22, 23]. Nyiragongo lava

lake activity can change over periods of minutes to hours, and is expressed primarily in lake level changes, but eruptive activities such as those in 1977 and 2002 have shown that there were pre-eruptive signals weeks before [24, 25, 26, 27].



Figure 3: Laves in fractures after the eruption of May 22, 2021



Figure 4: Image showing the formation of the lava lake after the eruption of May 22, 2021

eruption of 2002

The Nyiragongo eruption of January 17, 2002, where 14 to 34 million cubic meters (Mm³) of lava poured out (Michel Detay, 2011).

During the eruption, lava flows flowed along a north-south oriented fracture network, along the axis of the Albertine rift. Fractures appeared on the flank of the volcano and generated two lava flows. The first destroyed the central area of the city up to Lake Kivu, or about 15% of the city of Goma, leaving 120,000 people homeless. There were 470 injuries of varying severity and 170 deaths directly or indirectly related to the eruption. (Michel Detay, 2011). This eruption caused a massive exodus to Rwanda. The second flow was directed towards Lake Kivu. The Nyiragongo volcano had produced lava flows that invaded almost the entire territory of Nyiragongo, the city of Goma and destroyed the economic district of the city, forced a massive exodus of the population and caused the loss of many lives. The latter had caused the death of about 140 people, the destruction of housing of about 120,000 people,

the evacuation of about 300,000 people (Charles M. Balagizi et al 2018).

5.1. before the eruption of Nyiragongo Volcano on January 17, 2002

Seismic activity prior to this eruption was characterized and dominated by type A, B and C earthquakes as well as volcanic tremors [28], which were considered precursors of this eruption. Sometimes the earthquakes appeared as swarms. Two earthquake shock swarms (fractures) were recorded in the Nyiragongo area in October 2001, then on January 4, 2002, 13 days before the start of the eruption and then increasing seismicity between January 4 and 17, which included several felt earthquakes and volcanic tremors. On January 16, a few hours before the start of the eruption, an unusually strong smell of sulfur dioxide was also noticed by the pilot of a small private plane flying north of Nyiragongo [29].

In addition, earthquakes of magnitude greater than or equal to 4

were felt and recorded. Some authors had specified that after these earthquakes, there was a remarkable change in the lava lake of Nyiragongo volcano. These earthquakes are cited by (Wafula M. 2011, and Kasereka.M, 2001): the tremors of March 2 followed those of September 12, 2000 and January 10, 2001. After others were felt: the earthquake of October 7, 2001 of local magnitude 4.6 located in the northern part of Lake Edward to about 140 km, the earthquake of January 4, 2002, 13 days before the eruption, of local magnitude 4.8, generated volcanic tremors of large amplitudes associated with vibrations and rumblings felt by the local population and even the emanation of black smoke at the top of the crater and a significant increase in temperature along the cracks located on the southern flanks of the volcano.

5.2. After the eruption of Nyiragongo Volcano on January 17, 2002

Post-eruption seismic activity was characterized by a large number of earthquakes of magnitude 3.5 or greater. A few earthquakes of magnitudes greater than 3.5 have been recorded by global seismic networks (USGS). The strongest had a magnitude of 5.2. in the two weeks following the eruption, the cities of Goma and Gisenyi were shaken by frequent felt earthquakes, some of which caused damage to buildings and occasional deaths. Many of these tremors were felt as far away as Kigali (120 km) and Bukavu (60 km). Sadaka K. K. AND AL (2003) added that the eruption was followed by intense seismic activity never recorded in the recent history of the Virunga Region.

Materials and Methods

For the measurement of CO₂ concentration in cracks especially in Bugarura and Munigi stations we used a portable gas analyzer GA5000 (Geotechnical Instruments, UK) which gives the concentration in percentage with typical accuracy. CO₂ is measured with a wavelength infrared detector (WIRD) with a reference channel. The GA5000 is equipped with a pump and a

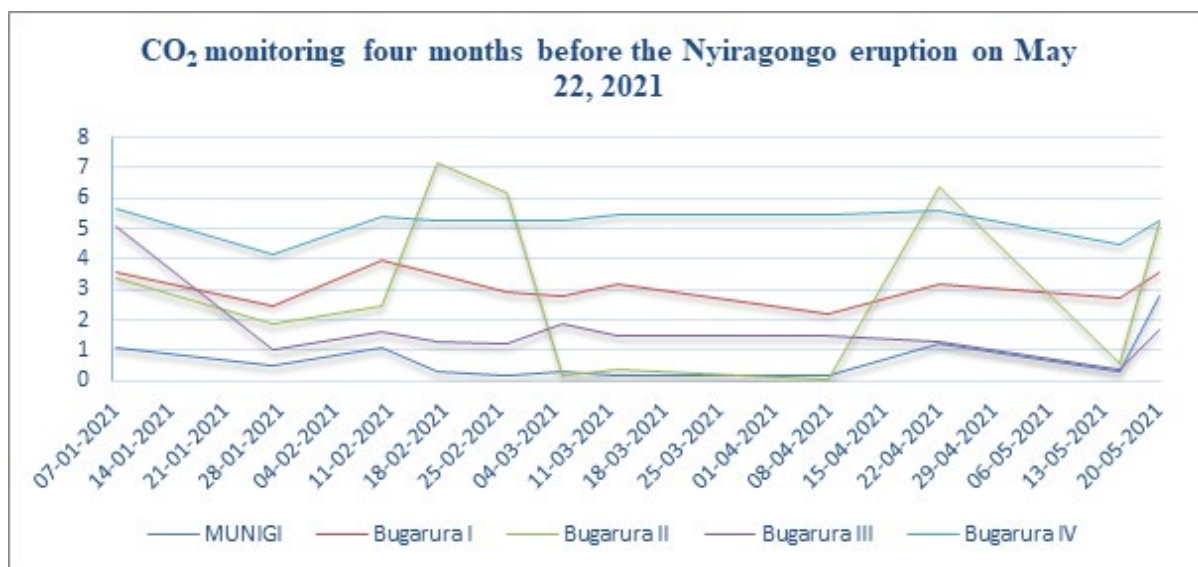
gas inlet connected to a plastic tube. The end of the hose is placed at the precise location where the concentration is to be measured. The pumped gases first pass through a 0.45 µm polysulfone filter and are then conducted to an IR analyzer. The results are displayed on the instrument's screen [30, 31, 32, 33]. Carbon dioxide was measured at ground level at the Bugarura and Munigi stations in a spot manner. For SO₂ data, the technical means to know the composition of the volcanic plumes are improving with time, for the collection of SO₂ data we used the DOAS which is installed at RUSAYO (Figure 6a and 6b).

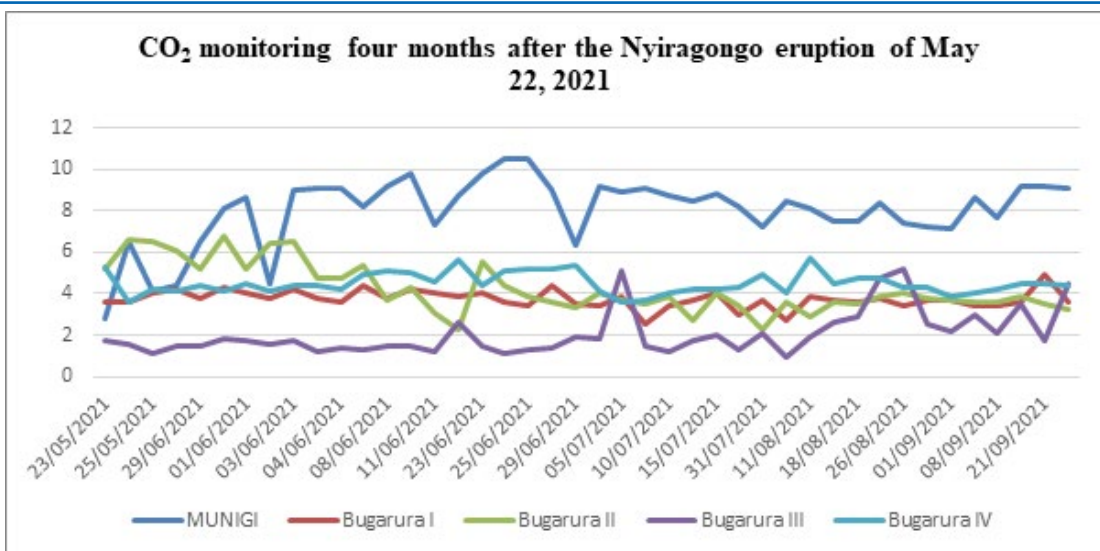
The DOAS is another instrument, using a spectrometer sensitive to ultraviolet wavelengths; it is a relatively new tool, increasingly used to study the degassing and chemistry of a volcanic plume. It is also used in volcanic monitoring and even during phases of eruptive activity, measurements near Nyiragongo volcano allow an estimation of the gaseous composition of volcanic plumes leaving the crater (Figure 6a and 6b). SO₂ is an important source of information on the gases present in volcanic plumes, at larger spatial scales than local measurements. For seismic data, they are acquired from the Kivu Snet seismological network that currently has more than fifteen stations installed around the volcanoes and in the southeastern part of Lake Kivu; it facilitates real-time monitoring of the evolution of magmatic activity. These data were recorded automatically and arrived in real time. We then proceeded to the statistical analysis which consisted in counting the recorded earthquakes on a daily basis. These results are presented in Figure 7.

Results and Discussion

The monitoring du CO₂

Carbon dioxide measurements taken at various sites in Bugarura and Munigi during the passive and active periods of the Nyiragongo volcano show that CO₂ is always present at concentrations well below the lethal dose of 15%.



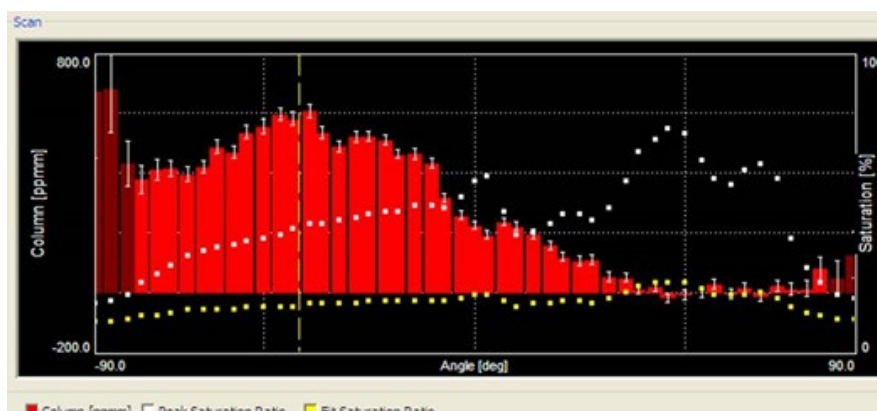


Figures 5: monitoring of CO₂

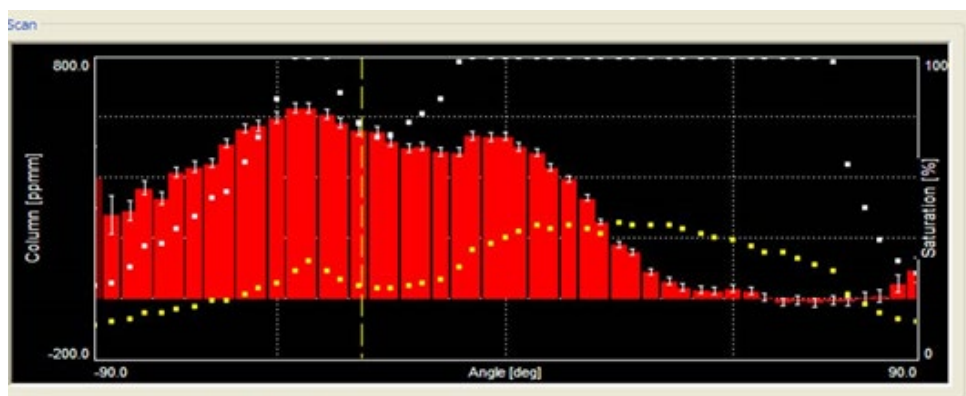
We note that during the entire period of CO₂ monitoring before the eruption of May 22, 2021, in the month of April we observed a large increase in the concentration of CO₂ at the site Bugarura II, the concentration had left from 0.1% to 6.5%. The concentration of CO₂ in the Atmosphere is 0.04% [34], in our sites the concentration

of carbon dioxide has never dropped to 0.04%. Modeling suggests that CO₂ is the primary species to be monitored in the event of a cleanup [35]. As suggested by the modeling in the monitoring of active volcanoes, CO₂ from Nyiragongo Volcano is punctually sampled by the scientific community of the G.V.O

7.2. Sulphur dioxide (SO₂)



SO₂ of April 20, 2021 we have registered 4943Ton/day (Figure 6 a)



SO₂ of April 24, 2021 we have registered 7043 Ton/day (Figure 6 b)

The amount of SO₂ emitted continuously during passive emissions is therefore non-negligible compared to the amounts emitted during eruptive activity [36].

Volcanic eruptions are difficult to study and their behavior remains poorly understood, despite several decades of research [37]. Lascar

Seismicity

volcano emits a significant source of SO₂ during passive degassing with fluxes measured by the DOAS technique ranging from 200 to 2300t/d [38, 39, 40, 41, 42,43] unlike Nyiragongo volcano which emits between 4943 and 7043t/d even more during passive periods (Figure 6a and 6b) we can note that Nyiragongo volcano releases a larger amount of SO₂ into the atmosphere than Lascar volcano.

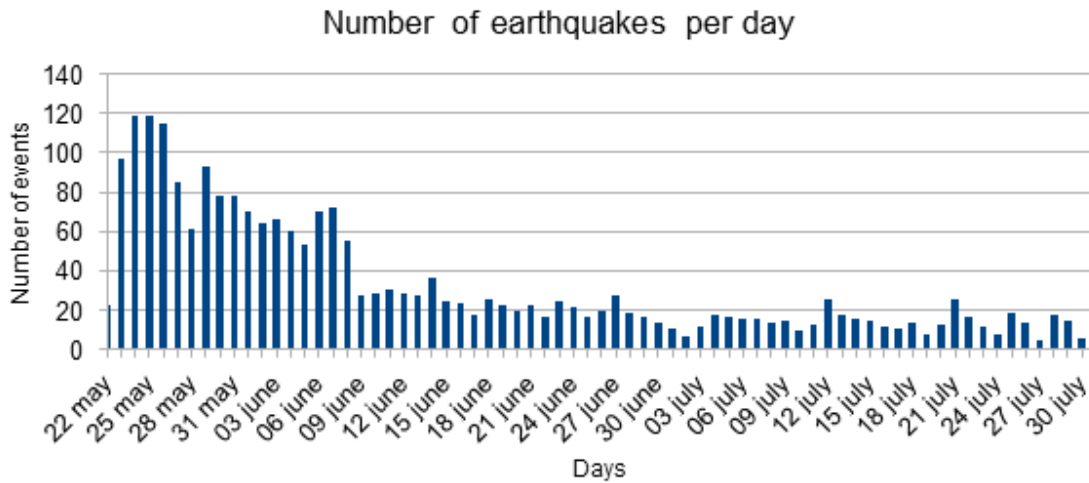


Figure 7: Number of earthquakes recorded daily until July 2021

During the days of 24, 25 and 26 the number of earthquakes reached respectively 120, 120 and 119. Their distributions are presented in the maps below:

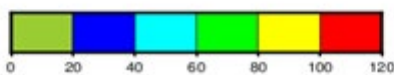
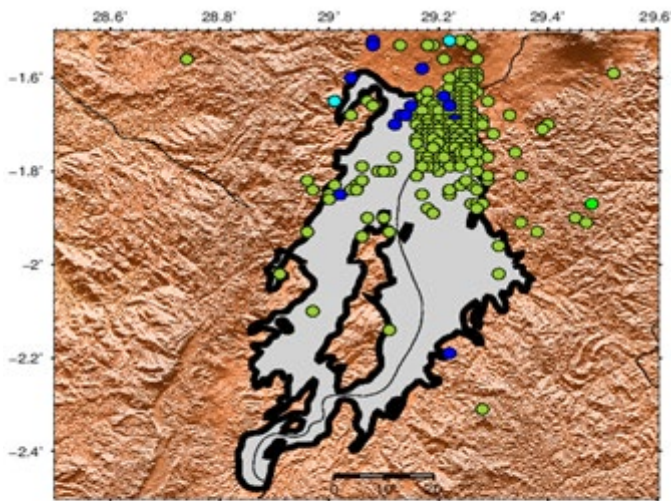


Figure 8: Map of Distribution of epicenters after the May 22, 2021 eruption, May 22 at 7:30 p.m. to May 31, 2021

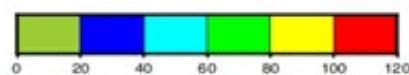
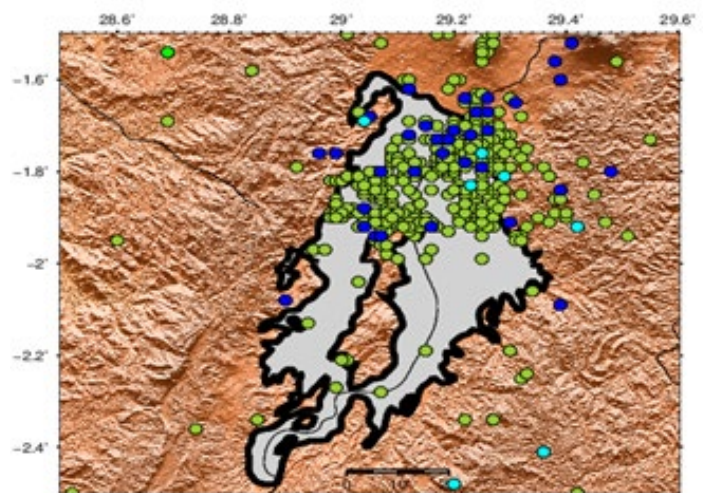


Figure 9: Map of Distribution of epicenters during the month of June 2021, after the eruption of May 22

That the eruption of 2021 is similar to that of 2002

The eruption of Nyiragongo Volcano on May 22, 2021

Compared to other eruptions that Nyiragongo volcano has experienced, the seismic activity before the eruption of May 22, 2021 was not too alarming. Because there were no strong earthquakes (greater than or equal to 3.5) that preceded a few months before the eruption, as had been noticed in previous eruptions. Even the population did not feel anything. However, from the month of April some fracture seisms justifying the magmatic intrusion were recorded and analyzed by the seismology team of the OVG. During the same month, a swarm of long-period earthquakes was recorded between April 20 and 24, 2021, just one month before the eruption. After eruption, an exceptional seismic activity was noticed. Many earthquakes of magnitudes greater than or equal to 3.5 were recorded by the local seismographic network. These earthquakes were felt, the strongest had a magnitude of 5.2. This activity generated a lot of concern, prompting the government to evacuate the population because of a suspected magma intrusion under the city of Goma and the possibility of an eruption. This activity remained at a high level during the month of May, after eruption. The daily average of recordings was 100 earthquakes. Although the peaks for the concentration of CO₂ was high, the concentration of SO₂ as of April 20 and 24 we recorded 4,943 and 7,043 tons per day (Figure 6), during the same Month there were some fracture earthquakes justifying the magmatic intrusion was recorded and analyzed by the seismology team of the OVG but however the scientific community of the O. V.G missed the eruption, we point out that it is not the first community to have missed the eruption, as of September 27, 2014, An unexpected eruption at Mount Ontake, Japan, erupted, killing more than 40 people, even though it is a well monitored volcano. This may seem surprising for a technologically advanced country accustomed to volcanic activity, especially considering that Mount Ontake is one of 47 active volcanoes in Japan that are closely monitored. (<https://cordis.europa.eu/article/id/115892-trending-science-unexpectederuption-at-mount-ontake/fr>).

Conclusion

The Nyiragongo volcano in the east of the Democratic Republic of Congo is known for its three historical eruptions (January 10, 1977, January 17, 2002 and May 22, 2021). This volcano being less than 20 km from the city of Goma, these different eruptions always reach the city and cause loss of life and property. The activity of the Nyiragongo lava lake can change over periods of a few minutes to a few hours, and is expressed mainly in changes in the level of the lake as is the case of the eruption that took place in 2021 which caused the death of 32 people, unlike the eruptive activities such as those of 1977 and 2002 showed that there were pre-eruptive signals weeks before and succession of several earthquakes. Note that the month of April 2022, would serve the scientific community of Goma Volcano Observatory of (G.V.O) to prevent the eruption of May 22, 2022 because for this same month we recorded a swarm of earthquakes long periods but also recorded the increase in concentration of SO₂ and CO₂ during the same month.

The concentration of CO₂ is still present in the territory of Nyiragongo, mainly in the chiefdom of Bukumu. The measurements show that after the devastating eruption of the Nyiragongo volcano in 2021, the concentration of CO₂ in the sites that were already present before this event is still present. The concentration of SO₂ is still permanent in the volcanic plume. We also note that the concentration of CO₂ has not decreased or disappeared in this region, so the variation of CO₂ in this environment makes us believe that an eruption will occur in the next few years. The political and administrative authorities of the Democratic Republic of Congo, in particular those of the Province of North Kivu, should seriously consider the risks posed by the sulfur dioxide (SO₂) and carbon dioxide (CO₂) released during passive and active periods by the Nyiragongo volcano and secure this area. Information and awareness campaigns on the risks related to sulfur dioxide and carbon dioxide are also recommended [44-47].

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