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## Eruption of Nyiragongo Volcano in May 2021 degassing of CO<sub>2</sub> before and after eruption in the atmosphere

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### ABSTRACT

The Nyiragongo volcano is located in the western part of the African Rift. The deep fractures allow the upwelling of gases before and after the eruption, especially carbon dioxide (CO<sub>2</sub>). We want to understand the behaviour of carbon dioxide before and after the eruption of the Nyiragongo volcano on 22 May 2021.

The Nyiragongo volcano erupted on the evening of Saturday 22 May 2021 at 18:15 local time in Goma, about 20 km north of the city of Goma. The lava flowed in two directions from the flanks of the volcano, one flow coming to a halt in the northeastern suburbs of Goma, The other flow cut off one kilometre of the national road 4 linking Goma to Butembo, a major regional road vital for the supply of the city of Goma, causing 32 victims, the production of several volatile gases in the atmosphere, the destruction of 17 villages in the territory of Nyiragongo and the cracking of 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, which is monitored by the scientific community of the Goma Volcanological Observatory (O.V.G), the lava lake is the seat of an intense gas production.

CO<sub>2</sub> is a gas that is heavier than air, asphyxiating, and deadly at a concentration of 15%. The variation of CO<sub>2</sub> in the different sites allows us to study the behaviour of the Nyiragongo Volcano, one Month before the eruption, the CO<sub>2</sub> showed an increasing trend in some sites and a few Months after the eruption we observed a slight decrease in all the CO<sub>2</sub> monitoring sites.

Nyiragongo is an important contributor of CO<sub>2</sub> and SO<sub>2</sub> to the troposphere.

This 2021 eruption is similar to the one of 17 January 2002, which caused the death of about 100 people and the evacuation of several people. The most deadly eruption of Nyiragongo was in 1977, when more than 600 people died.

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Post-eruption seismic activity was characterised by a large number of earthquakes of magnitude 3.5 or more. A few earthquakes of magnitudes greater than 3.5 have been recorded by global seismic networks (USGS), the strongest of which had a magnitude of 5.2 in 2002. Compared to other eruptions that Nyiragongo volcano has experienced, the seismic activity before the eruption of 22 May 2021 was not too alarming. This is because there were no strong earthquakes (greater than or equal to 3.5) that preceded the eruption a few months before, as had been noted in previous eruptions.

After eruption, 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 having a magnitude of 5.2

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Keywords: eruption, degassing, carbon dioxide, seismic, magnitude

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## 1. INTRODUCTION

The Nyiragongo volcano erupted on the evening of Saturday 22 May 2021 at 18:15 local time in Goma, some 20 km north of the city of Goma and Lake Kivu and west of the border with Rwanda, causing the destruction of houses and cracking of the ground.

A total of 17 villages were affected, and 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 town of Goma.

A vehicle whose driver lost control ended up in a ravine causing the death of 9 people, while 4 inmates of the central prison of Munzenze tried their luck and escaped; unfortunately they were hit by bullets from the security forces. Around the town, the material damage is considerable.

After a break in the lava flow the next day in the suburbs of Buhene, which marks the north-eastern edge of Goma. The city of Goma was barely spared, and the inhabitants and the government were worried about a possible resumption.

On 26 May 2021, due to the fear of a second volcanic eruption and the persistence of earthquakes, the military governor of North Kivu province asked the populations of 10 districts of the city of Goma in the red zone to move.

This latest eruption of Nyiragongo is similar to that of 17 January 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).

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<sup>3</sup> in volume and about 1.2 km in diameter (Sarah, J, 2005)

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 type eruptive dynamism (Sadaka K, 2003). Indeed, from 1928 to 1977, the Nyiragongo crater had a large lava lake that disappeared completely with the eruption of 10 January 1977 (Hamaguchi. H, 1992). Another lava lake reappeared from 1982 to 1983 (Tazieff, H, 1984).

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 risks, volcanic gases are the most permanent threat to the Nyiragongo population because gases are emitted by volcanoes not only during the eruptive period but also during quiet periods (Blong, 1984; Williams-Jones and Rymer, 2000; Hansel and Oppenheimer, 2004; Viveiros et al, 2009, Faustin Safari Habari et al 2021). 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 gas emitting areas, including carbon dioxide (CO<sub>2</sub>) and sulphur dioxide (SO<sub>2</sub>).

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## **2.DESCRPTION OF THE STUDY ENVIRONMENT**

The Nyiragongo volcano is located in Nyiragongo territory near the Rwandan-Congolese border. 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<sub>2</sub>, SO<sub>2</sub>, ...), 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 (DRC). Nyiragongo is located about 20 km north of Lake Kivu (surface area 2,060 km<sup>2</sup>), and 18 km from the city of Goma (population over 2 million). The Goma agglomeration continues into Rwanda with the town of Gisenyi (100,000 inhabitants). Nyiragongo has a volume of 500 km<sup>3</sup> and its lava flows cover 1,500 km<sup>2</sup>. 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 radiating fissures south of Shaheru, west of the summit in a NE-SW

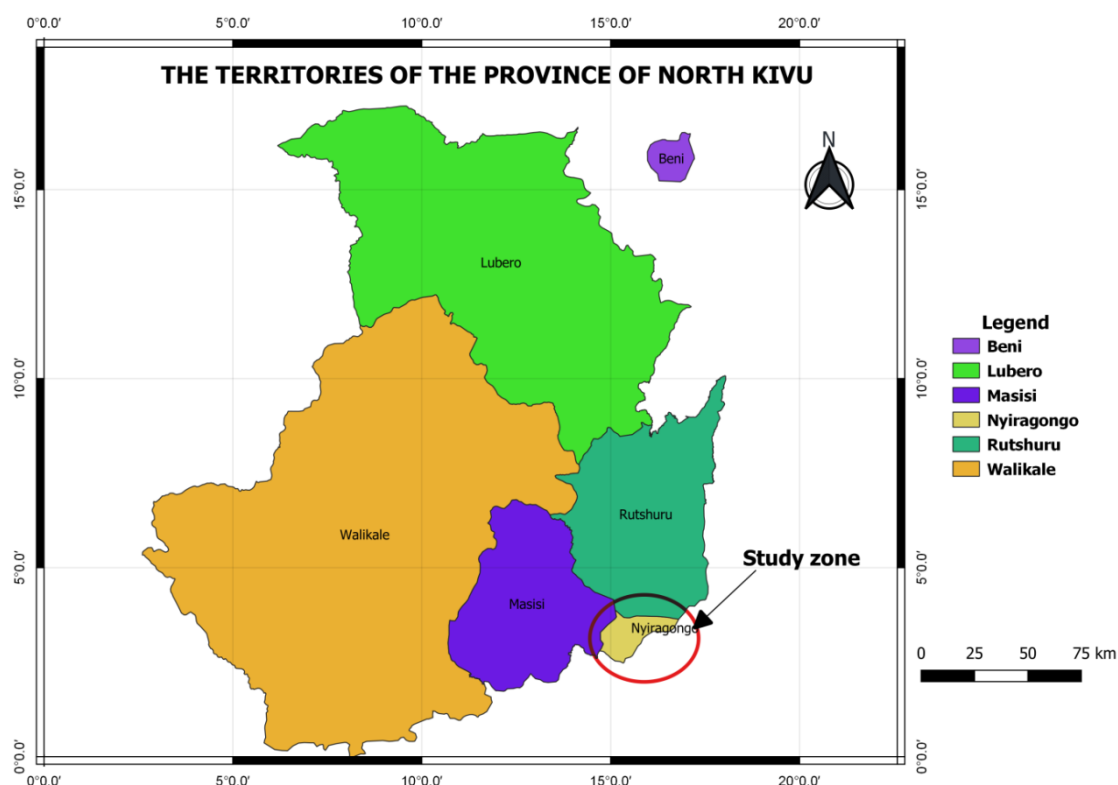
direction as far as Lake Kivu (4 km from the town of Goma), (Michel Detay, 2011).

Nyiragongo 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. It has only one chiefdom, headed by the Mwami, and is divided into 7 groups of 58 villages. Its capital 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 km<sup>2</sup>

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 Republic of Rwanda;
- To the West: The free zone of the Virunga National Park which separates it from the chiefdom of Bahunde in the territory of Masisi.



### 1. Volatile compounds emitted by the Nyiragongo volcano during the May 2021 eruption

The Nyiragongo volcano emits several volatile compounds into the atmosphere, of these compounds,

our study focuses only on carbon dioxide (CO<sub>2</sub>).

Carbon dioxide (CO<sub>2</sub>) accumulates by gravity making the air toxic, even lethal. CO<sub>2</sub> is a heavier-than-air gas, toxic in high concentrations and asphyxiating, irritating to the eyes, nose and throat and lethal at concentrations as low as 15% (Hathaway et al. 1991; Langford, 2005; Beaubien et al., 2003; Cantrell and Young, 2009; Lockwood and Hazlett, 2010; Amaral and Rodrigues, 2011; Baxter, 2011, Faustin Safari Habari et al., 2021). The concentration of CO<sub>2</sub> in the air is mainly due to local outgassing from the ground, while the contribution of gas emission from the crater is negligible at the breathing height for humans and always remains well below the lowest indoor CO<sub>2</sub> concentration threshold (Granieri, D. et al 2014).

## 2. Seismicity

The eruption of Nyiragongo, notably in January 2002, the main signals occurred while the edifice was erupting (a hundred tremors of  $M > 3.5$ ), (Michel Detay, 2011).

On 10 January 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 monitor seismic activity. Nevertheless, some earthquakes were felt by the population between September and December 1976 and according to the scientists, the trigger of a volcanic activity that had preceded this eruption. We had retained:

- An earthquake, considered as a trigger for the magmatic activity of Nyiragongo, took place at Ngweshe (South Kivu Province), 150 km southwest of the volcano, on 5 December 1976 ( $M_b = 5$ ), (Kasereka. M, 2001).
- After this shock, two strong earthquakes were felt in January 1977, a few days before the eruption of 1 January 1977, and on 6 January, with a greater magnitude ( $M = 5.3$ ), (Durieux, J., 2003).

During this period, seismic activity was marked by the recording of volcanic tremors. After the eruption many earthquakes were felt by the population.

As of 16 January 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) which allows for the loss of energy and gases, and then acts as an overflow pipe which regulates the energy to some extent. 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 (e.g. Burgi et al. 2014; Bobrowski et al. 2015).

Nyiragongo's lava lake activity can change over periods of minutes to hours, and is mainly expressed in lake level changes, but eruptive activities such as those in 1977 and 2002 have shown that there were pre-eruptive signals weeks before (e.g. Tazieff 1977; Hamaguchi et al. 1992; Durieux

2004b; Komorowski et al. 2004; Kavotha et al. 2004, Charles M. Balagizi et al 2017).

### 3. deformation

The Nyiragongo volcano poses risks to the population of Nyiragongo territory, the city of Goma and Gisenyi; the eruption of 22 May 2021 resulted in a total of 17 villages being destroyed by the lava flow. In addition to the lava flow which destroyed all the property in its path, houses, cars, water networks and electrical wires. We have identified the destruction of houses and the cracking of road infrastructure in the city of Goma and Gisenyi as a result of the multiple earthquakes.

*Image of the eruption of the Nyiragongo volcano on 22 May 2021*



*Image of the eruption of Nyiragongo volcano on 17 January 2002*

### 4. Eruption of 2002

The eruption of Nyiragongo on 17 January 2002, where 14 to 34 million cubic metres (Mm<sup>3</sup>) of lava flowed (Michel Detay, 2011).

During the eruption, the lava flows followed 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 one destroyed the central area of the city up to Lake Kivu, i.e. 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 provoked a massive exodus to Rwanda. The second flow was directed towards Lake Kivu.

In 2002, the volcano produced lava flows that invaded almost the entire territory of Nyiragongo, the city of Goma and destroyed the economic district of the city, forcing a massive exodus of the population and causing the loss of many lives. The latter caused the death of about 140 people, the destruction of the homes of about 120,000 people and the evacuation of about 300,000 people

(Charles M. Balagizi et al 2018).

## 5. MATERIALS AND METHODS

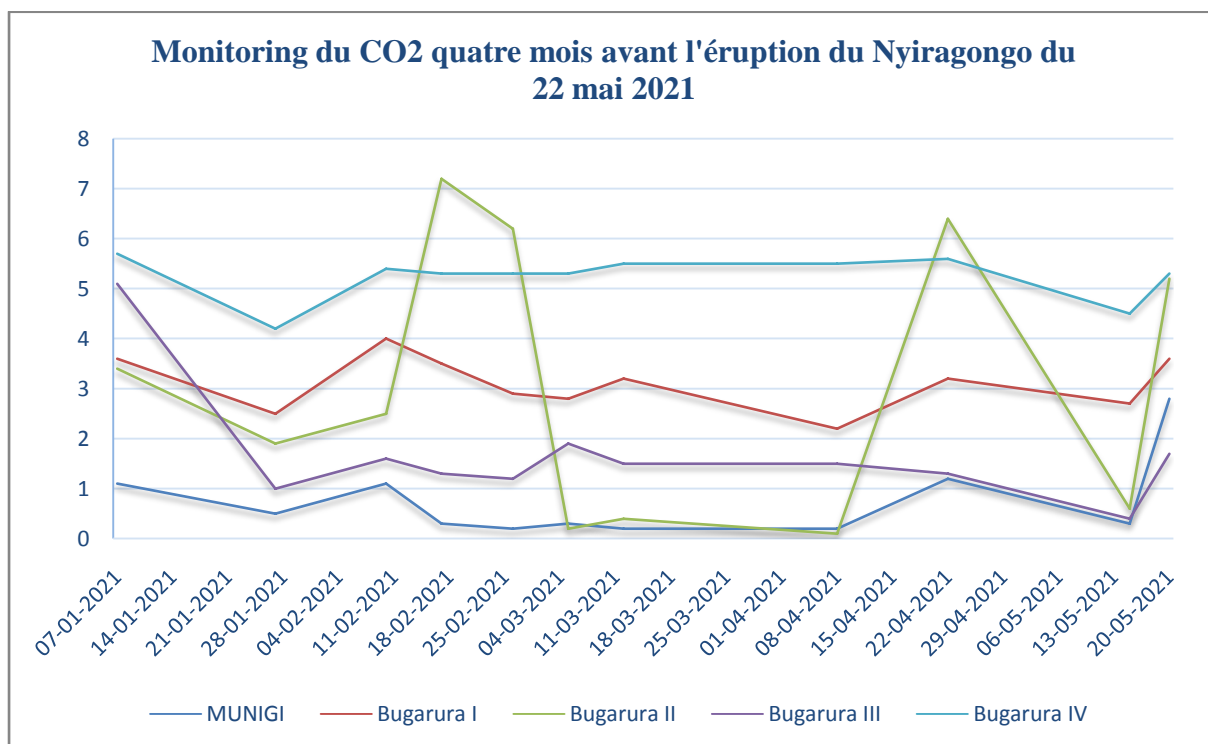
For the measurement of the CO<sub>2</sub> concentration in the cracks especially in the Bugarura and Munigi stations we used a portable gas analyser GA5000 (Geotechnical Instruments, UK) which gives the concentration in percent with typical accuracy.

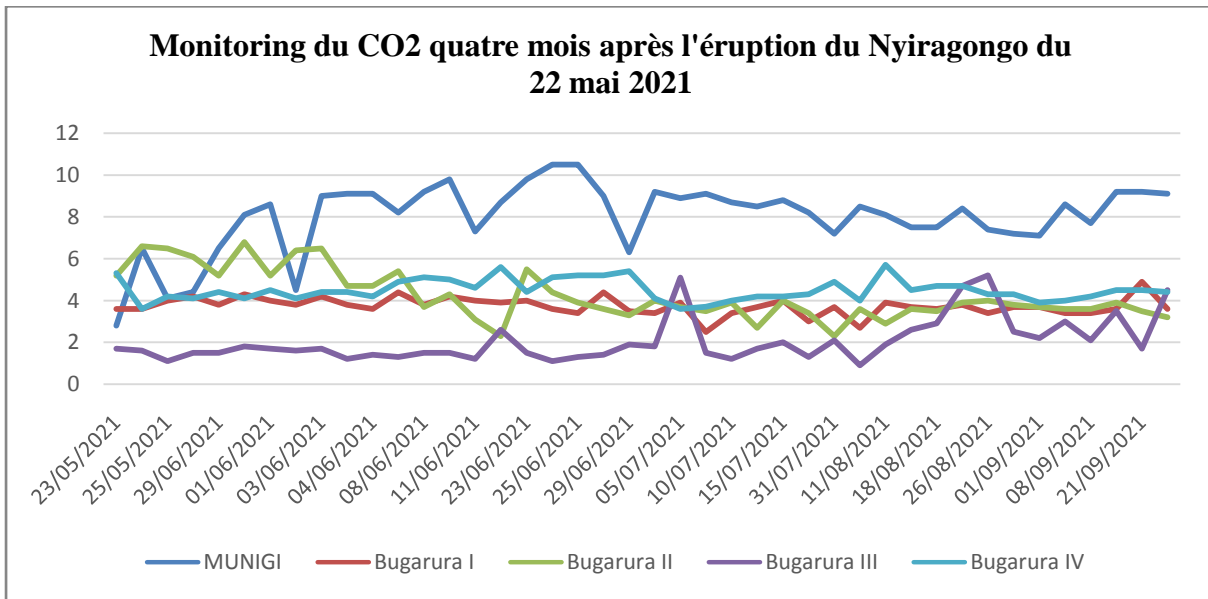
CO<sub>2</sub> is measured with a wavelength infrared detector (WIRD) with a reference channel. The GA5000 has a pump and a gas inlet connected to a plastic tube. The end of the hose is placed at the precise location where the concentration is to be measured. The pumped gases first pass through a 0.45 µm polysulfone filter and are then conducted to an IR analyser. The results are displayed on the instrument's screen (Yalire et al, 2007; Balagizi et al, 2016; Kasereka et al 2017, Faustin Safari Habari et al 2021). Carbon dioxide was measured at ground level in Bugarura and Munigi stations in a spot manner.

## 3. RESULTS AND DISCUSSION

### 3.1. CO<sub>2</sub> monitoring

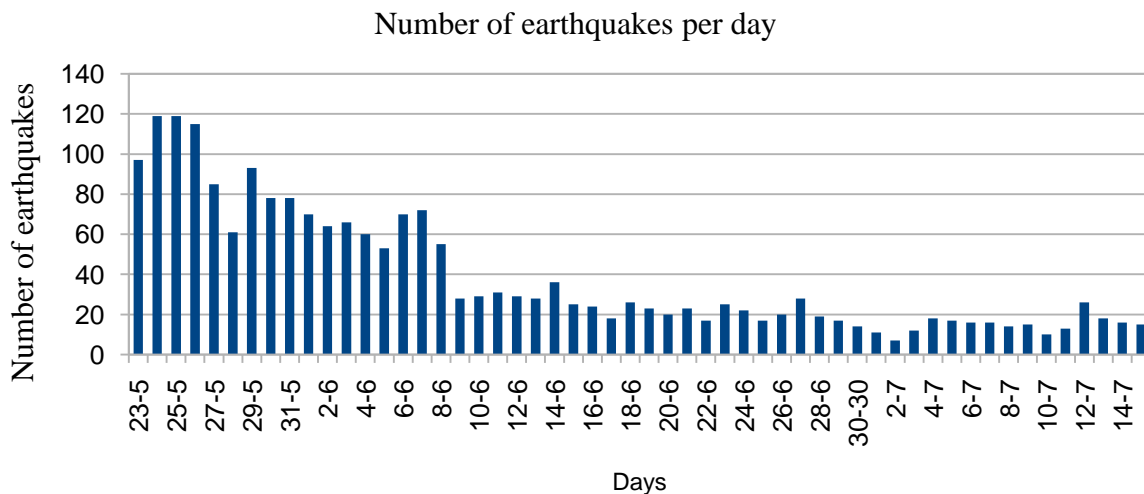
Carbon dioxide measurements at the Bugarura and Munigi sites 4 months before and 4 months after the eruption of 22 May 2021 show that CO<sub>2</sub> is still permanent at concentrations well below the lethal dose of 15%.





We note that during the entire period of CO<sub>2</sub> monitoring prior to the eruption of 22 May 2021, in the month of April we observed a large increase in the concentration of CO<sub>2</sub> at the Bugarura II site, the concentration had left from 0.1% to 6.5%. The concentration of CO<sub>2</sub> in the Atmosphere is 0.04% (Mayengo et al 2007), at our sites the concentration of carbon dioxide has never dropped to 0.04%. Modelling suggests that CO<sub>2</sub> is the main species to be monitored in case of scrubbing (R.B.Symondsa et al 2001). As modelling suggests in the monitoring of active volcanoes, CO<sub>2</sub> from Nyiragongo Volcano is punctually sampled by the scientific community of the G.V.O.

### 3.2. Seismicity



After analysing the earthquakes we found that the 2021 eruption is similar to the 2002 eruption. The eruption of Nyiragongo Volcano on 17 January 2002

#### 1) Before the eruption



The seismic activity before this eruption was characterized and dominated by A, B and C type earthquakes as well as volcanic tremors, (Wafula M. 2011), which were considered as 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 4 January 2002, 13 days before the start of the eruption, and then increasing seismicity between 4 and 17 January, which included several felt earthquakes and volcanic tremors. On 16 January, a few hours before the start of the eruption, an unusually strong smell of sulphur dioxide was also noticed by the pilot of a small private plane flying north of Nyiragongo, (Allard. P., et al, 2003).

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 earthquakes of 2 March followed those of 12 September 2000 and 10 January 2001. The earthquake of 7 October 2001, of local magnitude 4.6, located in the northern part of Lake Edouard, about 140 km away, and the earthquake of 4 January 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 noticeable increase in temperature along the cracks located on the southern flanks of the volcano

## 2) After the eruption

Post-eruption seismic activity was characterised by a large number of earthquakes of magnitude 3.5 or greater. A few earthquakes of magnitudes greater than 3.5 were recorded by global seismic networks (USGS). The strongest had a magnitude of 5.2.

Allard. P., et al, (2003), 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 et al (2003) added that the eruption was followed by intense seismic activity never recorded in the recent history of the Virunga Region.

## The eruption of Nyiragongo Volcano on 22 May 2021

Compared to other eruptions that Nyiragongo volcano has experienced, the seismic activity prior to the eruption of 22 May 2021 was not too alarming. Because there were no strong earthquakes (greater than or equal to 3.5) that preceded the eruption a few months before it, as was the case for previous eruptions. Even the population did not feel anything.

However, from April onwards, some fractured earthquakes justifying the magmatic intrusion were recorded and analysed by the OVG seismology team. During the same month, a swarm of long-period earthquakes was recorded between 20 and 24 April 2021, just one month before the eruption.

After eruption, 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 having a magnitude of 5.2. This activity generated a lot of concern which led the government to evacuate the population as it was thought that there would be a magmatic intrusion under the city of Goma and that a possible eruption was possible. This activity remained at a high level during the month of May, after eruption. The daily average of recordings was 100 earthquakes. Although the CO<sub>2</sub> concentration was high in April and in the same month there were some fracture earthquakes supporting magmatic intrusion recorded and analysed by the OVG seismology team 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 unplanned 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>).

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#### 4.CONCLUSION

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 in 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 which showed that there were pre-eruptive signals weeks before and a succession of several earthquakes

As a densely urbanised region, Goma and its surroundings are one of the areas most threatened by various natural hazards.

CO<sub>2</sub> concentration is still present in Nyiragongo territory, mainly in the Bukumu chiefdom. Measurements show that after the devastating eruption of the Nyiragongo volcano in 2021, the CO<sub>2</sub> concentration in the sites that was already present before this event is still present. As the CO<sub>2</sub> concentration has not decreased or disappeared in this region, the variation of CO<sub>2</sub> in this environment makes us believe that an eruption will take place in the coming 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 carbon dioxide released by the Nyiragongo volcano and make this area safe.

Information and awareness campaigns on the risks of carbon dioxide are also recommended.

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