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General overview of the post-eruptive seismic activity of the Nyiragongo volcano on May 22, 2021, Eastern DR Congo

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Abstract
The aim of this study was to contribute to the understanding of the processes that generated seismic swarms following the eruptions of the Nyiragongo volcano on May 22, 2021, through statistical analysis, spatial distributions of epicenters and hypocenters, determination of earthquake magnitudes and energies released. The volcano lies on the main axis of the western branch of the East African Rift. The may 22, 2021 followed by intense seismicity, which always results in material and human losses. After several observations and analysis of various parameters, we concluded that this intense seismic activity is generated by rift dynamics after the emptying of magmas in the volcano's magma chamber from depth to the surface, this causing rift instability. This seismicity is distributed throughout the rift, and is most concentrated in the northern part of the rift, at Lake Kivu. Nevertheless, other analyses such as the focal mechanism are essential to increase our understanding of this post-eruptive seismic activity.

Keywords: Seismic activity, Nyiragongo volcano, Eruption, Rift

1. Introduction

The Kivu rift region constitutes the central segment of the western branch of the East African rift system, between the northern termination of the Tanganyika rift and southern extension of the Edward-George rift, (D. Delvaux and B. Smets, 2015; D. Delvaux *et al*., 2019, A. Pouclet *et al*., 2016) [10, 3]. It has been included in the map of more seismic zones. This part is a fault opening at around 2 mm/year, (D. Delvaux *et al*., 2017) [19].

The Kivu rift is one of the dynamically active regions of the East African rift, mainly the volcanic province of Virunga (C. Ebinger & T. Furman, 2003; A. Douglas *et al*. 2015) [7].

The region is highly heterogeneous due to its geological structure, eruption frequencies and seismic activity, (S-B. Fiama *et al*., 2017). In addition to these phonemes, mudflows are also present in the region, the last mudflow is from July 2021 which had washed away much property in the locality of Rugari.

The seismic zones in the Kivu rift have been identified and cited by several authors, namely the Virunga - Rutshuru volcanic zone, the Lake Kivu basin (including the Ngweshe, Masisi and Walikale regions), Rusizi - North Tanganyika and the Lake Edouard zone. These areas are the most seismic in the region, (D. Delvaux *et al*., 2016, M. Bantidi *et al*., 2014) [6].

The Virunga volcanic region lies to the far north of Lake Kivu. It has eight volcanoes, six of which are dormant, and the Nyiragongo and Nyamulagira volcanoes are the most active.Their activity is sometimes linked to the opening of the East African Rift Valley (Kasahara, 1991; Hamaguchi and Zana, 1983), cited by M. Bagalwa *et al*. (2011) [20].

In the Virunga volcanic region, certain earthquakes are due to volcanic or magmatic activity, generated by the accumulation of magma in the magma chamber and the partial melting of lithospheric rocks. These earthquakes are located in the fields of the Nyiragongo and Nyamulagira volcanoes. Other earthquakes are due to tectonic activity in the rift caused by the play of active faults. Active faults have been studied.

According to M. Villeneuve (1980) [19], these faults run in three directions: N-S, SW-NW and NW-SE. The classification of G-B. Ganza *et al*. (2017) [12] determines two general directions: NNE-SSW (which includes the northern part of the Lake Kivu basin) and N-S (which includes the southern parts of the Lake Kivu basin and the Ruzizi river valley to the extreme north of the Lake Tanganyika basin).
The two volcanoes lie 15 km apart along the axis of the Albertine Rift (western branch of the East African Rift) in the north-south fracture system. Nyiragongo is about 20 km north of Lake Kivu, (M. Detay, 2011; M-D. Wafula, 2011; M-C. Kasereka, 2001) [21, 17, 16].
The Nyiragongo volcano, the most deadly of the three, erupted on January 10, 1977, January 17, 2002 and most recently on May 22, 2021.
Nyiragongo's eruptions always cause loss of life due to its proximity to the city of Goma and Nyiragongo territory.
During the 2002 eruption, lava flows followed a north-south fracture network, in the axis of the Albertine Rift. Fractures appeared on the volcano's flank and generated two lava flows, (M. Detay, 2011) [21].
Apart from the lava flows that reach the town of Goma, Nyiragongo's eruptions are always followed by intense seismic activity that lasts for weeks or even months after the eruptions. As P. Allard, *et al*, (2003) [23] and J-C. Komorowski and K. Karume (2015) [15] the towns of Goma and Gisenyi have been shaken by frequent felt earthquakes, some of which have caused damage to buildings and occasional deaths, earthquakes of magnitudes greater than or equal to 4.5 are also recorded.
Seismic activity was characterized by a large number of earthquakes of magnitude 3.5 or greater. For example, three earthquakes of magnitudes 5.2, 5.1 and 5.1 respectively, located at coordinates (1.515S, 28.993E), (1.776, 29.041) and (1.681, 28.981) were felt in the two weeks following the eruption.
This intense post-eruption activity has puzzled scientists, some of whom believe it to be a magmatic intrusion, while others think it is linked to rift activity (S-K. Kavotha, 2003) [25].
As for P. Allard, *et al*, (2003) [23], in their report, they assumed either the probability of an ongoing tectonic crisis in the East African rift or post-eruptive seismicity due to soil compaction following lava drainage. Unfortunately, they argue, the seismic network at the time did not allow for in-depth studies of this seismicity.
However, another worrying situation was the recording of long-period earthquakes and volcanic tremors after eruption, (SADAKA K. K *ET AL* 2003) which prompted other researchers to hypothesize a new magmatic intrusion as the generator of this exceptional seismicity, (D. Tedesco *et al*.,2002 ; A. Polland. Santo *et al*.2003) [2].
Again, the Nyiragongo eruptions of May 22, 2021 were followed by a seismic swarm that began just a few hours after the eruption and continued for several weeks afterwards. Earthquakes of magnitudes greater than 4 were felt, causing the destruction of buildings, roads, etc.
This exceptional, long-lasting activity gave rise to concern, leading to direct speculation about a magmatic intrusion that could lead to a new eruption in the city of Goma. As a result, on May 26, due to fears of a second volcanic eruption and the persistence of earthquakes, the government decided to evacuate people from 10 of Goma's most seismically-affected districts.
The decrease in the number of earthquakes and their magnitudes over the following weeks enabled the government to repatriate the displaced population.
The true significance of the seismic swarms that follow the eruptions of the Nyiragongo volcano is not yet fully understood. The main objective of this study is to understand the processes generating seismic swarms after the eruption of the Nyiragongo volcano on May 22, 2021, through statistical analysis, spatial distributions of epicenters and hypocenters (depths), calculation of the magnitude of recorded earthquakes and their released energy in order to contribute to the understanding of the seismic activity that followed the Nyiragongo eruption of May 22, 2021.

2. Data acquisition and analysis

The data used in this work were provided by automatic recordings from the KivuSnet seismographic network, which currently comprises over 14 stations installed around the Nyiragongo and Nyamulagira volcanoes and in the south-western part of Lake Kivu. These automatic recordings have enabled us to monitor the eruption and seismicity in real time.
Using these automatic recordings, we carried out a statistical analysis based on the daily count of recorded earthquakes and their locations. We also performed a classification based on the analysis of several earthquakes recorded in the area of the Nyiragongo volcano, classifying the earthquakes by depth category and, finally, the energy released through magnitude.
To determine the earthquake types we considered the spectral analysis method using SEISAN (SEISmic Analysis) software. Epicentral distribution maps were produced using either Generic Map Tool (GMT) or QGIS.

3. Results and discussion

- **Observations**

The eruption began on May 22, 2021 at 6:30pm local time.The eruption began on the evening of May 22, 2021 at 6.30pm local time.At the start of the eruption, a fracture opened up to the south of the crater and the lava flowed south-eastwards, cutting the N2 road (Goma-Rutshuru) near Kibati.This was followed by a new lava flow heading south, reaching populated areas in the town of Goma and in Nyiragongo territory. This flow stopped less than 1 km from Goma's international airport on the night of May 22 to May 23, 2021.
In the hours following the eruption, exceptional seismic activity was observed on the same night. Seismic activity continued into June and even July. We were interested in the seismicity of May and June, when activity was high.

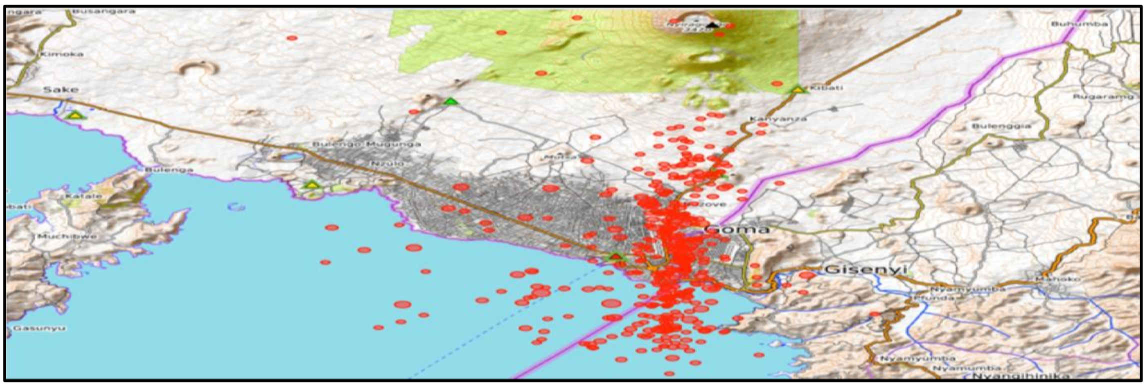

Fig 1: Distribution of earthquakes after the May 22, 2021 eruption, May 26 screenshot

During the night of May 22/23, the activity quickly migrated southwards from the volcano. It reached the town of Goma and continued as far as the northern part of Lake Kivu. As we can see, the migration of activity seems to be drawing a line to the south.

- **Number of seismic events**

Seismic activity developed very rapidly after the eruption, reaching anomalous levels for around six days.

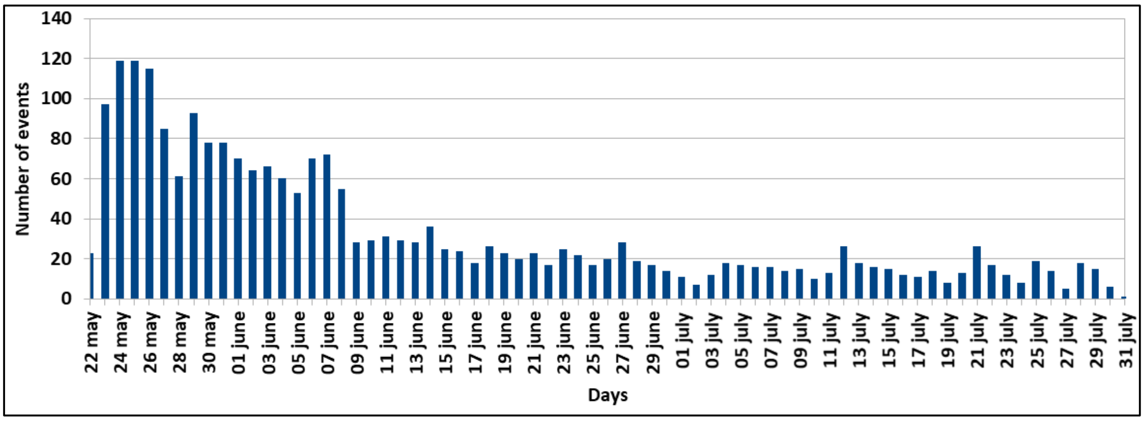

Fig 2: Number of earthquakes recorded daily until July 2021

On the 24th, 25th and 26th, the number of earthquakes reached 120, 120 and 119 respectively. The number of earthquakes decreased to a normal level.

The distribution of epicenters is shown in the following figures.

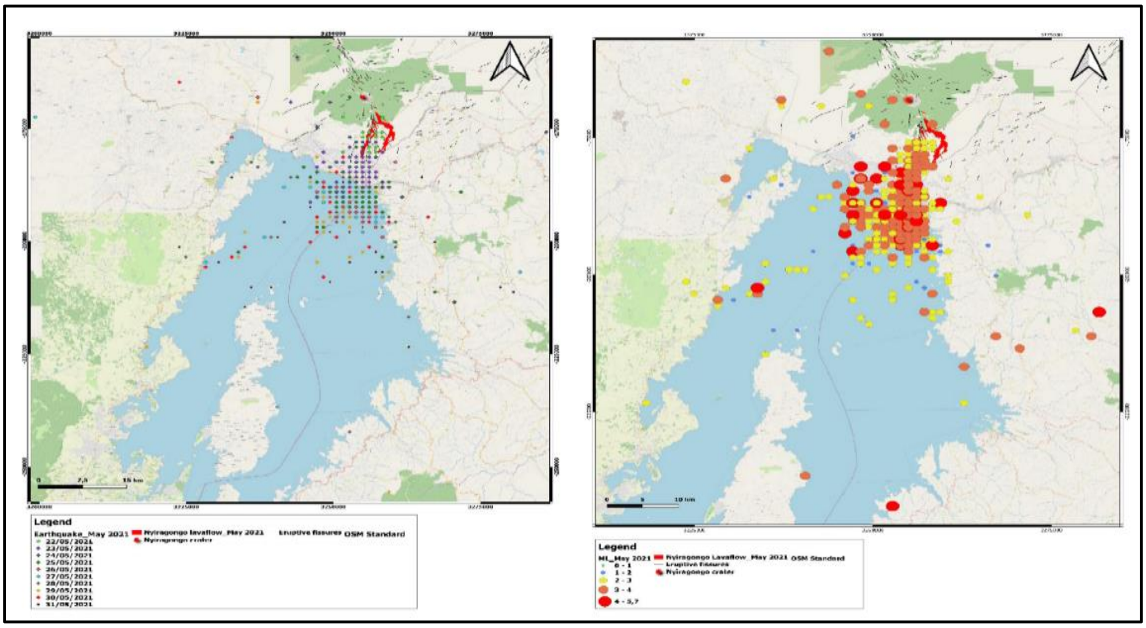

Fig 3: Map of Distribution of epicenters after the May 22, 2021 eruption, May 22 at 7:30 p.m. to May 31, 2021; on the left : daily migration and on the right: classification by magnitude

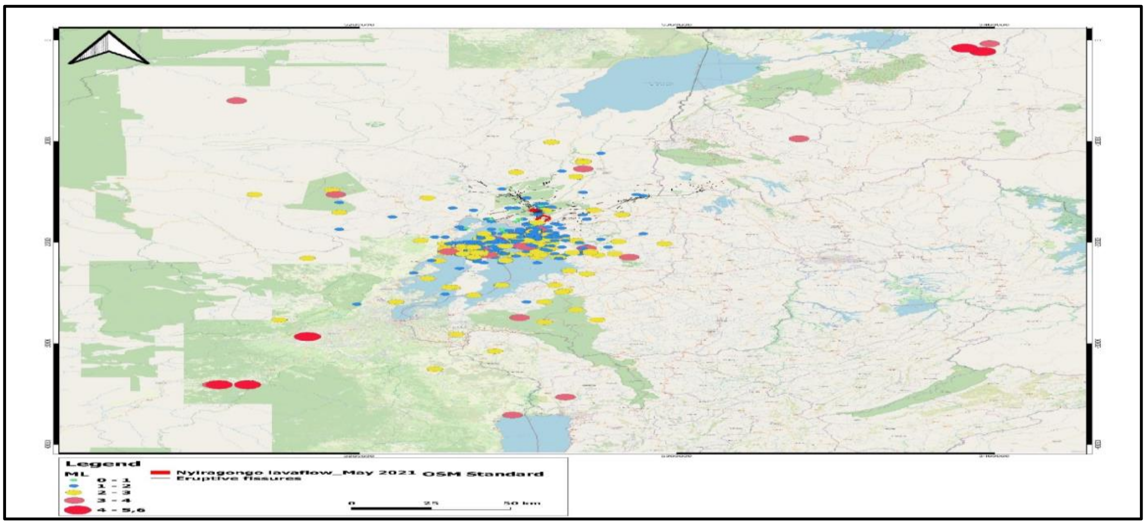

Fig 4: Map of Distribution of epicenters during the month of June 2021, after the eruption of May 22

In terms of the number of earthquakes, activity was intense in May, compared with June, when it decreased slightly. Moreover, in May, activity had migrated as far as the northern part of Lake Kivu, whereas in June, the migration continued as far as the island of Idjwi.

In terms of depth, the majority of earthquakes were less than 20 km deep. In June, there were a large number of earthquakes between 20 and 40 km deep, as shown in the following figure.

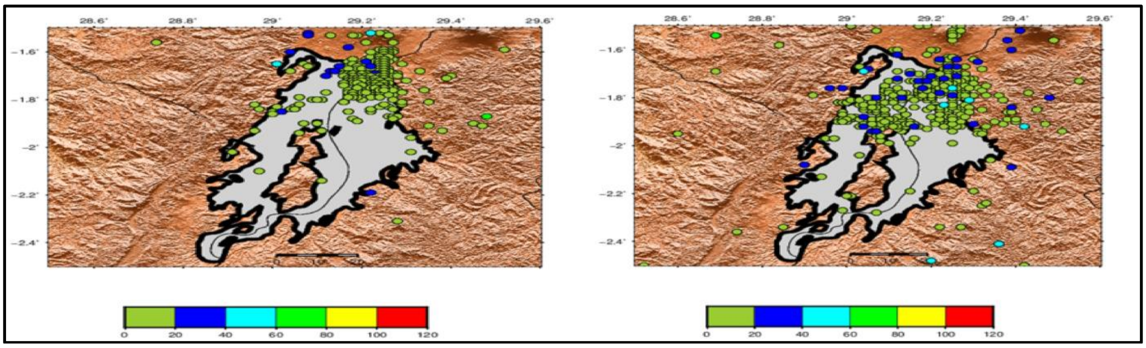

Fig 5: Classification according to depths: on the letf: in May and on the right: in June

Seismicity during the twomonths period was dominated by highfrequency earthquakes, with few of them localized in the Nyiragongo volcano field.

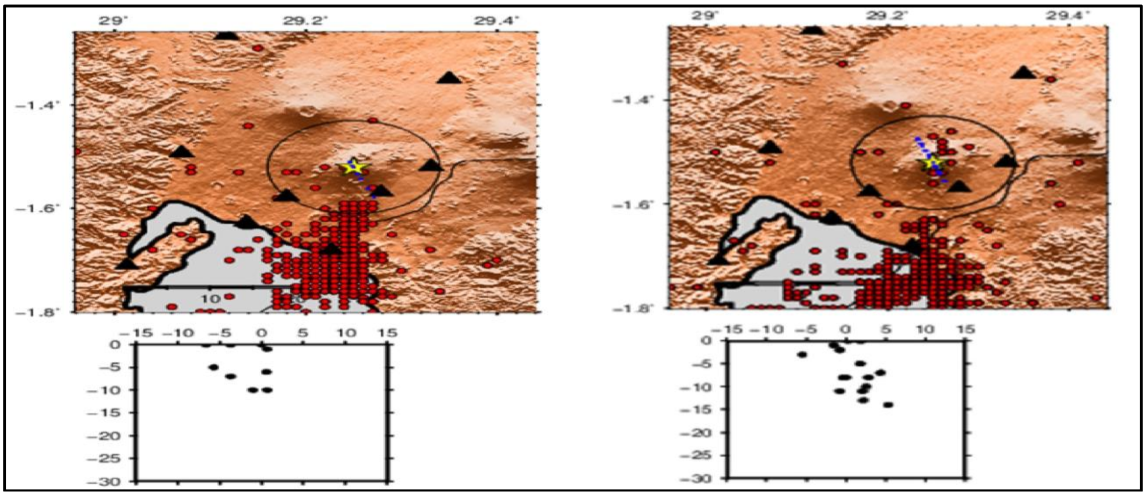

Fig 6: Map of Earthquakes recorded in the Nyiragongo volcano area after the eruption of May 22, 2021; delimited by the circle: may on the left and June on the right

In view of the insignificant number of volcanic earthquakes in the Nyiragongo volcano field, the likelihood of a new eruption cannot be ruled out.

However, the activity we observed in the volcano's field (delimited by the circle on the map) during May and June may have been due to magma movement, magma chamber instability and the several crater collapses observed after the eruption.

- **Assessing magnitude and energy release**

During this period, large earthquakes of magnitudes greater than 3 were recorded. Some earthquakes of magnitude 3 were felt because the activity was shallow. Below is a histogram of the magnitude evolution.

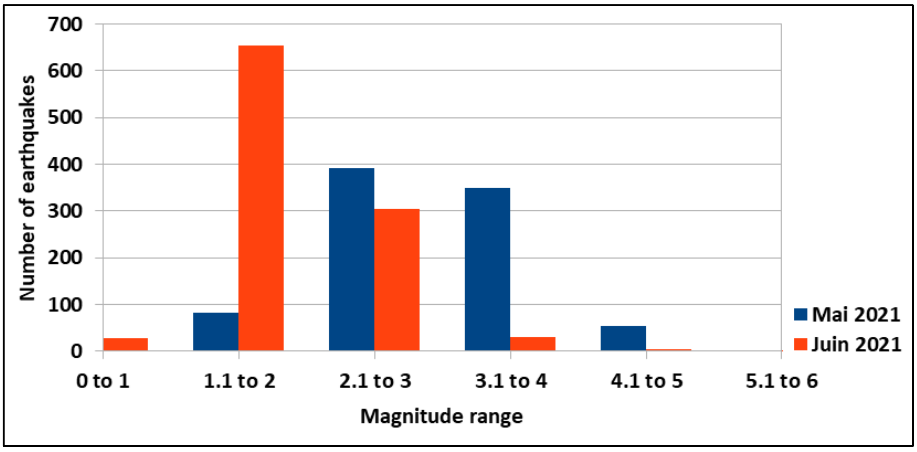

Fig 7: Magnitude versus number of earthquakes

As we can see, seismic activity in May was dominated by earthquakes of magnitude between 2.1 and 4, whereas in June the dominant magnitude was between 1.1 and 2. Two earthquakes of magnitude 5.1 or greater were recorded in May, while in June there was just one. In addition, 54 earthquakes with magnitudes between 4.1 and 5 were recorded in May, whereas only 4 were recorded in June.

The figure above shows the average daily energy. We note that it was on May 25 and 26, 2021 that the energy was highest. The highest peak we see in the figure is due to an earthquake on June 10, 2021 of local magnitude 5.5 recorded around 100 km south of the town of Bukavu in the southern part of the Kivu rift at coordinates 3.08S and 28.43S at a depth of 10km. In the northern part of the rift, in the Volcanic province, two other major events were recorded: an earthquake of local magnitude 5.2 recorded at coordinates 1.71S and 29.23E in Lake Kivu on May 25 at 09h03'01 (UT) and another of magnitude 5.1 recorded at coordinates 2.19S and 29.22E, on May 28 at 19h26'53", on May 26 (M=5) 1.7S and 29.25E.

As these recordings give the local magnitude, to determine the energy we used the relationship of Gutenberg and Richter (1956) which links local magnitude to energy (energy expressed in ergs).

$$log(E) = 11.8 + 1.5 * Ml$$

The energy values released by earthquakes are shown in the graph below:

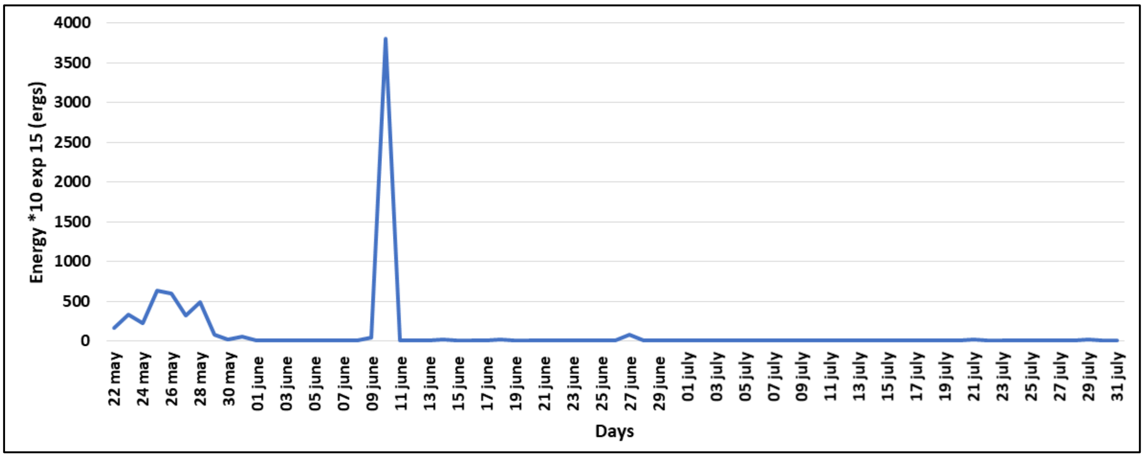

Fig 8: Daily average energy

The figure above shows the average daily energy. We note that it was on May 25 and 26, 2021 that the energy was highest. The highest peak we see in the figure is due to an earthquake on June 10, 2021 of local magnitude 5.5 recorded around 100 km south of the town of Bukavu in the southern part of the Kivu rift at coordinates 3.08S and 28.43S at a depth of 10km. In the northern part of the rift, in the Volcanic province, two other major events were recorded: an earthquake of local magnitude 5.2 recorded at coordinates 1.71S and 29.23E in Lake Kivu on May 25 at 09h03'01 (UT) and another of magnitude 5.1 recorded at coordinates 2.19S and 29.22E, on May 28 at 19h26'53", on May 26 (M=5) 1.7S and 29.25E.

We also note that more energy was released in May than in June.Average energy values ranged from 1.12×10^{14} ergs to 3.80×10^{18} ergs.

- **Analyse du RSAM (Real-time Seismic-Amplitude Measurement)**

RSAM is an important tool for estimating seismic activity during periods of intense activity. This technique enables us to see the evolution of a volcano's seismicity in real time. RSAM determines the average amplitude of ground shaking caused by earthquakes and volcanic tremors over 10-minute intervals.

Thus, we analyzed the RSAM of stations near the Nyiragongo volcano and noted that volcanic activity remained almost constant during the preperuptive period up to May 22, 2021. From that date onwards, activity increased sharply, only to fall a few days after the eruption. See figure below.

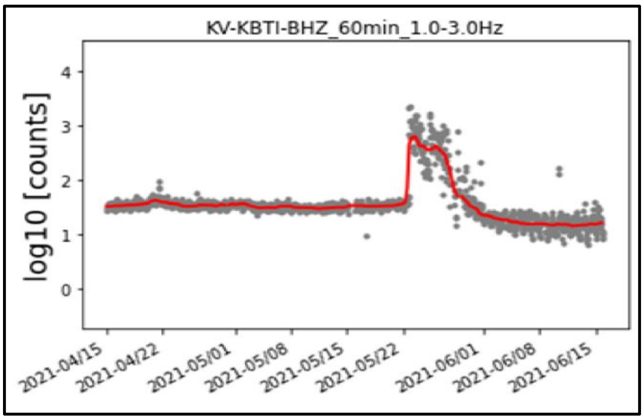

Fig 9: RSAM measurement at KBTI station installed around the Nyiragongo volcano

4. Interpretation

The eruption of May 22, 2021 began at 6.30pm local time. A fracture opened directly to the southeast, allowing the lava flow to flow towards Rwanda. Later, a fracture opened at a lower altitude than the first fracture, and a new flow headed directly south of the volcano, reaching the town of Goma. This flow stopped the same night.

The swarm of earthquakes had begun and rapidly increased to an abnormal level, as shown in figures (1).

In the five days following the eruption, the daily average was estimated at 100 earthquakes. Activity diminished over time, and two weeks later, the daily average was less than 35 earthquakes, as shown in figure (2).

The distribution of epicentres in figures (3) and (4) shows that seismic activity migrated from day to day towards the south of Nyiragongo. By May 23, the activity had spread rapidly to the city of Goma. We can see that the migration of activity followed the main axis of the N-S East African Rift. According to (M. Detay, (2011) [21] and A. Pouclet, K. Bram (2021), the Nyiragongo and Nyamulagira volcanoes are built on this axis. This axis is a fracturing system that always runs in a N-S direction. In June, activity extends southwards, but is more concentrated in the northern part of Lake Kivu, between Idjwi Island and the town of Goma. According to the classifications of active faults made by M. Villeneuve (1980) [19] and G-B. Ganza *et al*. (2017) [12], this activation is well observed in the fault network and more particularly north of Lake Kivu where the rift-bounding faults intersect. According to Chorowicz and Mukonka, (1980) in M.Bagalwa (2011) [20] these rift-bounding faults intersect in Lake Kivu.

This leads us to believe that fault instability occurred after the Nyiragongo eruption. In addition, other earthquakes are distributed throughout the rift in the fault network. This distribution of earthquakes throughout the rift is further proof of the dynamics of the Kivu rift.

As the Nyiragongo volcano is located in the rift, on the main axis, the movement of magma in the crustal faults generates tremors that are at the root of post-eruptive seismic activity.

D'Oreye *et al* (2007) have shown that earthquakes and active faults generate activity in the Nyiragongo and Nyamulagira volcanoes. There is therefore an interaction between faults and magmatism (B. Smets *et al*., 2019; C. Whatier *et al*. 2012). The activity of the volcanoes may still be directly linked to the opening of the West Rift Valley of the East African Rift System in which they are located in the central part, (Hamaguchi and Zana, 1983; M. Bagalwa, 2011) [20].

The distribution of earthquakes clearly shows that these were rift dynamics after the emptying of the Nyiragongo volcano's magma reservoir, especially as the volcano is located on the rift axis. This further confirms the correlation between rift and volcano activation. After the eruption, instability is established in the rift, causing intense fault activity and swarms of earthquakes. The decrease in the number of earthquakes in figure (4) and the decrease in their magnitude in figure (7) show the re-establishment of rift equilibrium.

The same phenomenon was again observed after the eruption of January 10, 1977, with seismic activity localized along the rift axis.As confirmed by H. Hamaguchi *et al* (1982) [13], the spatio-temporal relationship between tectonic seismicity and eruptions suggests a mutual connection between central volcanic activity and the rift phenomenon.

5. Conclusion

The Nyiragongo volcano in the east of the Democratic Republic of Congo is known for its three historic eruptions (January 10, 1977, January 17, 2002 and May 22, 2021). As the volcano is less than 20 km from the town of Goma, these eruptions always reach the town, causing loss of life and property. During the recent eruption on May 22, 2021, two fractures opened up, releasing lava flows in two directions, a swarm of earthquakes was observed in the southern part of the volcano, as far as the town of Goma, and increased rapidly the following day. The distribution of epicenters, the duration of seismic activity after the eruption, the energy released via magnitude were analysed. The results showed little volcanic activity, with few volcanic earthquakes caused either by the movement of magma seeking to stabilize in the magma chamber or by crater collapses. A few hours after emptying the reservoir, the tectonic earthquake swarm had suddenly begun.The distribution of epicenters showed a migration of seismic activity along the axis of the East African rift in a north-south direction, on which the Nyiragongo and Nyamulagira volcanoes are located.Activity remained concentrated in the northern part of Lake Kivu.Post-eruptive seismic activity, dominated by a large number of tectonic earthquakes, is therefore generated by rift dynamics.The emptying of the Nyiragongo volcano's magma reservoir generates an imbalance in the Kivu rift, manifested by intense seismicity distributed along the rift axis and concentrated in the northern part of Lake Kivu, where the various faults that form this part of the rift intersect.Just as fault activity and earthquakes generate volcano activity, so the eruption of the Nyiragongo volcano triggers rift activity. In addition, the absence of long-period earthquakes, and the fall in the RSAM curve, reinforce the idea that rift activity was triggered by the volcanic eruption and the probability of a new eruption was reduced.

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