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# Precursory seismic signal of the May 19, 2023 eruption of Nyamulagira Volcano in the Virunga Volcanic Province, Democratic Republic of Congo

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**ABSTRACT:** The 2023 eruption of Nyamulagira volcano (DR Congo) began on May 19 with lava overflowing from the summit crater. We analyze seismic data from two nearby stations (RGB2 and RSY2) to investigate the precursory signals leading up to the eruption. Our results show a clear and gradual increase in RSAM (Real-time Seismic Amplitude Measurement) starting around 10 days before, followed by a seismic swarm from May 18 to early May 19. Correlation analyses reveal a weak relationship between RSAM and the number of daily volcanic events, suggesting distinct physical processes: RSAM is sensitive to continuous tremors linked to magma ascent, whereas event counts reflect brittle fracturing. Despite moderate correlation between RSAM values at both stations, local effects may influence amplitude differently. We conclude that RSAM trends, especially progressive increases followed by swarms, may serve as reliable early indicators of eruptive activity, even in the absence of detectable surface deformation.

**KEYWORDS:** volcano activity, seismic activity, seismic amplitude.

## 1 INTRODUCTION

### 1.1 THE NYAMULAGIRA VOLCANO

Nyamulagira is a volcano located in North Kivu, eastern Democratic Republic of Congo, about 15 km northwest of Nyiragongo volcano, in the East African Rift system. It is an active shield volcano located in the Virunga region, has an ancient existence and requires in-depth studies. It reaches an altitude of 3,058 meters and is located on the rim of a caldera 2,150 meters in diameter, formed 300 to 500 years ago. The lava emitted is mainly of leucitic basanite and other similar compositions. A N- NW/S-SE fault zone influences its morphology and eruptive behavior, playing a key role in the dynamics of its eruptions, including lava drainage during explosive events (Smets et al. 2015; Pouclet A., Bellon H., and Bram K. 2016).

The plumbing system of Nyamulagira volcano comprises three distinct reservoirs, essential for its magmatic activity. The first, located between 2 and 3 km deep, feeds historical eruptions and is linked to superficial dykes and reservoirs, particularly on the upper and middle flanks of the volcano. The second reservoir, at 6-8 km deep, is a shallow stratified magma chamber that supports successive eruptive phases. Finally, the third reservoir, located 10-14 km below the surface, corresponds to a deeper crustal magma chamber. (Pouclet and Bram 2021).

The volcano has experienced several eruptive phases, each with unique characteristics, including explosive phases that influenced its morphology. The first phase of eruptions at Nyamulagira volcano began in 1865 with a historic eruption on the Mushumangabo cone, followed by further eruptions between 1882 and 1884 (Pouclet 2021). These events marked the beginning of recorded eruptions, which occurred mainly on the flanks of the volcano, at a frequency of approximately one eruption every 1–3 years (Smets et al. 2015). Between 1901 and 1905, a second phase of volcanic activity occurred, characterized by Strombolian eruptions and summit activity, alternating with caldera filling and emptying. This period was marked by distinct lava flows and a change in the patterns of volcanic activity. (Pouclet and Bram 2021). A third phase began with the collapse of the caldera in the 1900s, leading to progressive filling and overflow of the caldera with various lava compositions, including leucite-rich basanites. The remarkable eruptions of 1904 and 1912–1913 occurred without co-eruptive activity in the central caldera, suggesting the involvement of deeper magmatic reservoirs (Smets et al. 2015; Pouclet and Bram 2021). Between 1938–1940 an atypical eruption drained the upper magmatic system, triggering a caldera collapse. Five eruptions occurred in 1951, 1956, 1957, 1967, and 1971, with three major events in 1948, 1954, and 1958. The fourth phase of volcanic activity, extending from 1971 to 1982, was marked by an intensification of eruptions, particularly between 1971 and 1972, with notable effusive and explosive events. A prolonged eruption occurred from 1976 to 1977, creating three cinder cones, although the volume of lava was relatively small. In 1980, volcanic activity increased again, culminating in a large but brief eruption in 1981, followed by three more classic eruptions between 1984 and 1988. After a period of inactivity from 1982 to 2001, the Nyamulagira volcano experienced a fifth phase of activity between 2002 and 2014, marked by recurrent eruptions every two years. These eruptions, closer to the caldera, were concentrated along a network of NNW-SSE fissures (Smets et al. 2015; Pouclet and Bram 2021). A renewed effusive activity was observed in 2002, followed by further eruptions in 2004, 2006, 2008, 2010 and between 2011 and 2012 (Mavonga et al. 2006; Mavonga et al. 2010 a; Mavonga et al. 2010 b; Birimwiragi Namogo et al. 2016; RUSANGIZA et al. 2017).

Since June 2014, a new phase, called the sixth phase, has begun for the Nyamulagira volcano, marked by the formation of a lava lake in its central crater. This lava lake activity has remained permanent and active until now.

In June 2014, a lava lake formed in the central crater of Nyamulagira volcano, rising and expanding rapidly. According to Coppola et al. (2016), this shift in activity from the flanks to the center is not due to an increase in magma, but to a disruption of the magma plumbing system caused by a previous eruption in 2011–2012. To maintain an active lava lake, three conditions must be met: a stable magma supply, the ability of the plumbing system to handle the magma mass, and a favorable tectonic setting. The study by Coppola et al. also highlights that the plumbing system has been regularly fed by short- lived eruptions. Field observations show that during 2023-year, significant events, such as crater overflows and flank lava flows, occurred.

Since late 2022, Nyamulagira volcano has experienced a transition in activity from flank to central activity, marked by eruptions different from those observed between 2002 and 2012. Intracrater effusive activity has been noted, with lava fountaining on 10 March 2023 and an overflow of the central crater on 19-20 May 2023, resulting in a lava flow extending up to 3 km to the northwest (see OVG weekly bulletin of 26 May 2023). Although lava flows on the upper northwest flank began to solidify on 28 May 2023, effusive activity in the central crater continued until June 2024, with periods of intermittent activity.

Recording seismic events is essential for monitoring active volcanoes, and seismo-volcanology researchers are interested in analyzing them to understand the underlying mechanisms. Measuring seismic amplitudes via RSAM (Real Seismic Amplitude Measurement) has proven effective in predicting increased volcanic activity and eruptions at several volcanoes (Endo and Murray 1991; Endo, Murray, and Power 1996).

This study focuses on the events that took place at the Nyamulagira volcano between late 2022 and late 2023 based on analyses of seismic data, including RSAM measurements and daily counting of LP earthquakes as well as their location at the surface and at depth to better understand the dynamics of its lava lake but also improve the understanding and interpretation of the variations observed on the RSAM curve.

### 1.2 Overview On The Pre-Eruptive Seismicity Of The Nyamulagira Volcano

The post-eruptive seismic activity of Nyamulagira volcano has been mainly characterized by volcanic Long Period (LP) earthquakes, according to different studies. Other events, such as hybrid earthquakes, have also been observed and analyzed as precursors of past eruptions. The long-period seismicity observed before eruptions often manifests itself in the form of swarms, with events documented from 2002 onwards. The study by Mavonga et al. (2006) analyzed the seismicity preceding the eruption of Nyamulagira on 8 May 2024. The authors observed swarm seismicity, mainly of long-period earthquakes, signaling the eruption 2–4 months before it, with a notable increase in seismic activity 10 months before. Seismic events included both shallow and deep earthquakes, with the former becoming more significant as the eruption approached.

Rusangiza et al. (2017) analyzed the frequency distribution and m-value variation before the Nyamulagira volcanic eruptions. The results showed several earthquake swarms, mainly LP events, with m-values generally between 0.9 and 1.6, but increasing to between 1.7 and 3.23 two to four months before the eruptions. This highlights the importance of long-term earthquake monitoring to improve eruption prediction at Nyamulagira. A study by Birimwiragi Namogo et al. (2016) between 2002 and 2011 revealed 73 swarms dominated by LP events and five eruptions of Nyamulagira, without an eruption of Nyiragongo. Analysis of the epicenters highlighted zones of weakness between the two volcanoes, essential for understanding magmatic intrusions.

Prior to the appearance of a new lava lake at Nyamulagira volcano in June 2014, significant seismic activity was observed, marked by a long-period earthquake swarm in April 2014. This swarm, which lasted four days, was located in the northeast of the crater (Birimwiragi Namogo et al. 2016). In June, seismic activity increased, leading to reactivation of the dyke intrusion and rapid magma ascent, accompanied by volcanic tremors and hybrid tremors leading to the formation of the lava lake. After the formation of the lava lake, seismic activity related to LP events decreased, but volcano-tectonic events remained constant, indicating underlying volcanic activity (Birimwiragi Namogo et al. 2016; Mateso Kasongo et al. 2017). Hybrid earthquakes, observed before the formation of the lava lake, occur at a depth of 0 to 5 km and in a frequency range of 3 to 10 Hz. They are related to rock rupture and intrusions in the superficial part of the crater (Mateso Kasongo et al. 2017).

## 2 Data Analysis

### 2.1 GVO Seismic Network

All the data in this work were collected by the GVO Snet broadband seismic. The seismic stations are located around the two active volcanoes Nyiragongo and Nyamulagira and in the Lake Livu bassin. These stations are: Rumangabo (RGB2), Rusayo (RSY2), Munigi (MUN2), Goma (GOM2), Bulengo (BUL2), Kalehe (KAL2), Idjwi (IDJ2), Lwiro (LWI2) and Nyabibwe (NYA2) (Mavonga et al. 2023). The location of the earthquakes (epicentres and hypocentres), waveforms analyses and spectral content were examined using the SEISAN software. The maps were produced either by GMT or QGIS. On the other hand the RSAM analysis were done using scripts developed in python and has been used to analyse the seismic activity preceded the May 2021 Nyiragongo volcano eruption (Sadiki et al. 2023; Munguiko et al. 2024). The continuous RSAM seismic measurements from October 2022 to December 2023, we used data recorded at two seismic stations: RGB2 (or RGB) and RSY2 (or RSY), located near the volcano at 19.64 km and 18.89 km from the Nyamulagira volcano, respectively. Real-time Seismic Amplitude Measurement (RSAM) was calculated in the 0.3–5 Hz frequency band to track variations in seismic energy over time.

RSAM values were averaged daily to identify long-term trends. Tectonic earthquakes with magnitude ≥ 4.0 were included using regional seismic catalogs. All RSAM data were normalized to facilitate interstation comparison. Statistical correlations were computed between RSAM values, seismicity, and between stations.

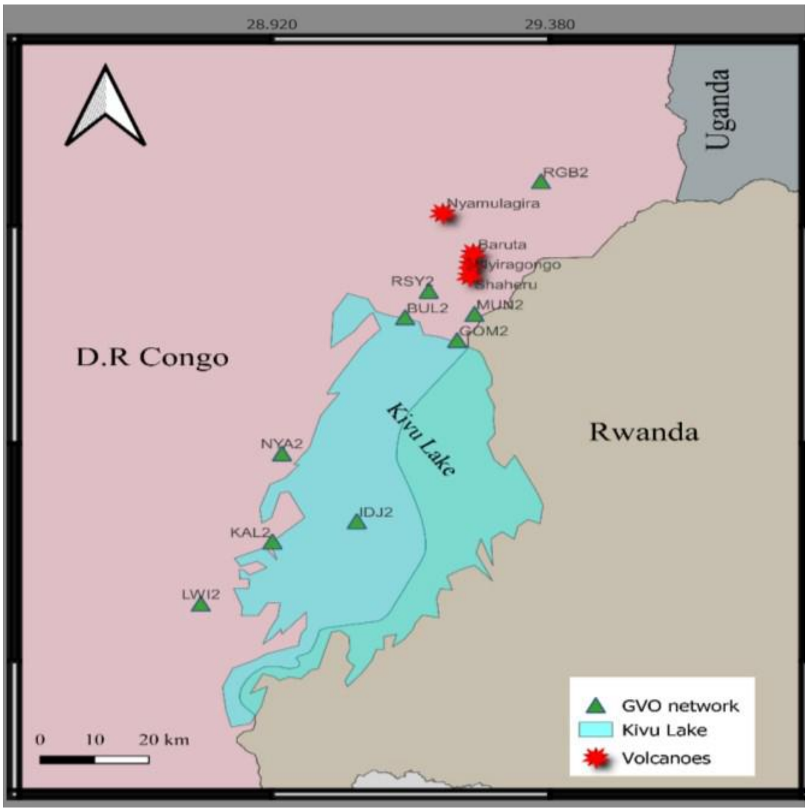


*Fig. 1. GVO network: The seismographic network of the Goma Volcanological Observatory (source: QGIS)*

### 2.2 LONG PERIOD LP SEISMICITY SIGNIFICANT

Long-period earthquakes are often associated with magmatic activity and may indicate an increase in this activity, potentially leading to volcanic eruptions. Examples include the eruptions of Nyamulagira volcanoes in 2004 and 2011 (Mavonga et al. 2006, 2010; Birimwiragi Namogo et al. 2016), Nyiragongo in May 2021 (Sadiki et al. 2023; Mavonga et al. 2023), Mt. Etna in 2004–2005 (Lokmer et al. 2008), and Tongariro in August 2012 (Hurst et al. 2014). Studies have shown that magmatic degassing is a key driver of volcanic events such as LPs, VLPs, and tremors. In particular, LPs and tremors are related to magma fragmentation, degassing, explosions, and oscillations in magma flow channels. They can also result from repeated injections of ash-laden gases or from variations in the voids of a magmatic conduit (B. Chouet, Dawson, et Arciniega-Ceballos 2005; Arciniega-Ceballos, Dawson, et Chouet 2012; Lokmer et al. 2008; B. A. Chouet et Matoza 2013; Lyons et al. 2016). Long-period earthquakes are often attributed to impulsive excitation and resonance of fluid-filled fissures resulting from magmatic–hydrothermal interactions, which can lead to volumetric oscillations in subhorizontal fissures (Matoza et al. 2015). At Popocatépetl volcano (Chouet et al. 2005), LPs are related to the opening of an escape route for volcanic gases and ash, resulting from a slow pressurization of the sill caused by magma crystallization. They are characterized by a cycle of compression, expansion and recompression, illustrating phases of pressurization, depressurization and repressurization. Depressurization occurs during gas evacuation, while pressurization is due to the diffusion of gases from the magma to the bubbles. The study by Bean et al. (2014) examines long-period seismicity in shallow volcanoes. The results show that long-period (LP) earthquakes are not only related to the resonance of fluid-filled conduits, but rather to the slow rupture of unconsolidated volcanic materials. Thus, LP events would be indicators of deformation of the upper edifice, without fluids directly intervening in the seismic process. Deep long-period (DLP) seismicity has been detected at various volcanoes and in different tectonic settings, at depths of 10 to 60 km. It is generally related to the transport of magma between the upper mantle and the lower crust, often preceding shallow seismic events, tremors and steam emissions a few hours later (Chouet and Matoza 2013).

Volcanic tremors are a series of seismic events and RSAM (Real-time Seismic Amplitude Measurement) is used to monitor these events by measuring the amplitude of seismic signals in real time. It allows to assess the magnitude of seismic activity, including various types of volcanic events (VT, LP, VLP and tremors). At Nyiragongo volcano, a study showed that RSAM increased significantly on the day of the May 2021 eruption and during the return of the lava lake (Munguiko et al. 2024). Although intense tectonic seismicity followed this eruption, RSAM rapidly decreased after the cessation of the eruption, indicating that it was directly related to magmatic activity and not influenced by the ongoing tectonic earthquake swarm that was indicative of tectonic activity.

## 3 RESULTS

### 3.1 EVOLUTION OF LONG PERIOD (LP) SEISMIC ACTIVITY

Following the eruption of Nyiragongo volcano on 22 May 2021, Nyamulagira volcano showed intense magmatic activity in its crater. Since August 2022, magma movement has been observed inside the central crater. In 2023, lava lake activity was marked by several events, with long-period seismicity dominated by earthquakes with a frequency in the 0.3 Hz to 5 Hz frequency range.

The distribution of long-period events in the Nyamulagira and Nyiragongo volcano fields are shown in the figure below:

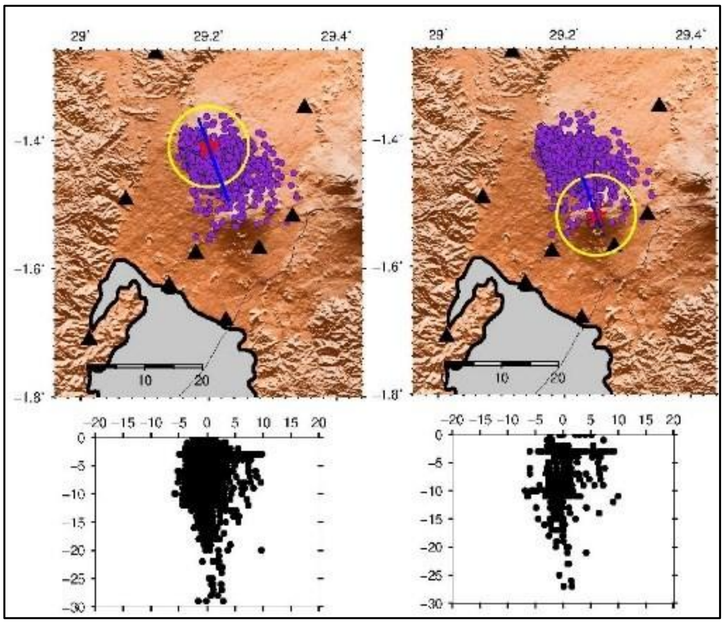

*Fig. 2. The distribution of LP earthquake epicenters and hypocenters in the Virunga Volcanic Province between October 2022 and December 2023: on the left the Nyamulagira volcano and on the right the Nyiragongo volcano, with yellow circles delimiting their respective areas. An active seismic region, oriented along the fracture connecting the two volcanoes, is indicated by a blue line on the graph. The black triangles represent the seismic stations*

This figure shows that both volcanoes were active, but the activity of Nyamulagira volcano involves a large number of LP earthquakes. LP seismic activity is most observed between the two volcanoes, along the fracture that connects them.

The time evolution of the hypocenters was analyzed separately and is shown in Figure (3) below:

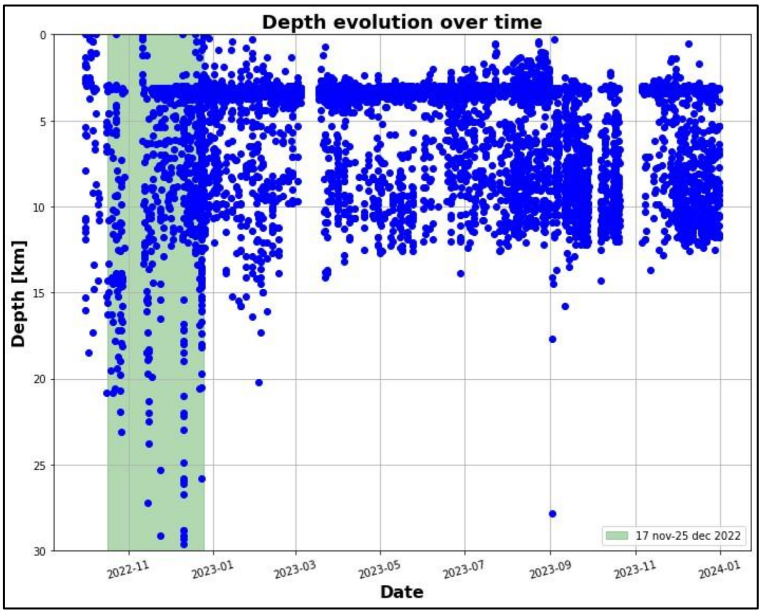


*Fig. 3. Evolution of hypocenters over time*

An evolution of seismic depths was observed, with deep earthquakes reaching 30 km between October and December 2022, indicating deep magmatic activity. In addition, long-period superficial earthquakes are observed, see figure (3). This long-period seismic activity at depth as in the superficial part may indicate a magmatic displacement from depth to the upper reservoirs. Subsequently, seismicity was concentrated at less than 15 km, especially between 2-4 km and 8-14 km, suggesting a continuous and sustained supply of the first reservoir. According to (Pouclet and Bram 2021). Examining figure (3) we notice that from January 2023, long-period seismicity was more concentrated at less than 14 km depth until the event of May 19-20, 2023, marked by the overflow of lava in the crater of the Nyamulagira volcano.

### 3.2 RSAM Evolution From October 2022 To December 2023

Daily RSAM values at stations RGB2 (or RGB) and RSY2 (or RSY) exhibited temporal variations throughout the study period. A clear and sustained increase in RSAM was observed at both stations beginning on May 10, 2023. This trend continued over the following days and culminated on May 19, coinciding with the onset of the lava overflow eruption (Fig. 4a–b). Other transient RSAM peaks occurred in response to regional tectonic earthquakes, such as the March 27, 2023 events, but did not result in sustained RSAM elevation. The average RSAM (11.4 for RGB and 27.9 for RSY) level remained relatively stable outside these episodes.

Daily volcanic earthquake counts revealed episodic swarms. Notable increases in event numbers occurred from December 23–25, 2022, April 1, 2023, and October 17, 2023 (Fig. 2c). The 1rst April swarm followed two tectonic events that occurred on 27 March that caused RSAM fluctuations. The average number of daily volcanic events remained below 20 for most of the year, with spikes exceeding 100 during swarm periods.

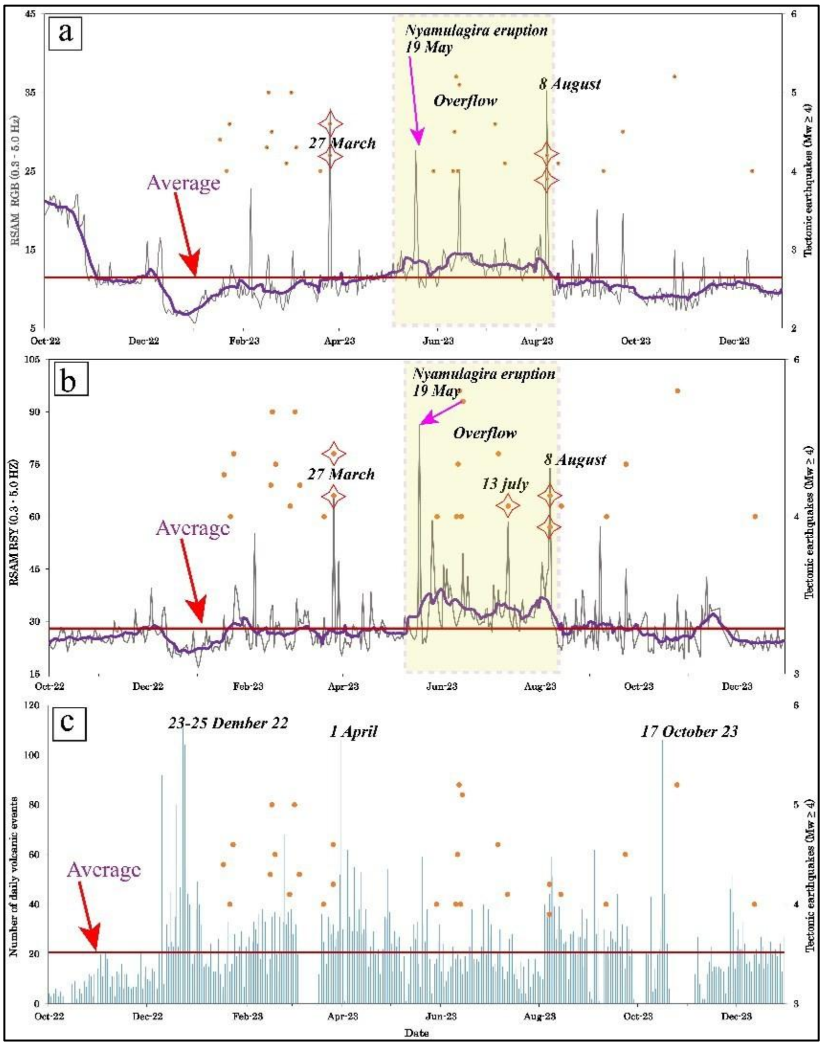


*Fig. 4. Temporal evolution of seismic parameters recorded from october 2022 to December 2023: (a) Daily RSAM values at RGB and (b) Daily RSAM values at RSY (0.3-5Hz band) black curve, with a 15-days moving average (purple). (c) Dail count of volcanic earthquakes (light blue bars). Major regional tectonic earthquakes (M≥4) are marked with orange dots and highlighted with red star symbole when directly influencing RSAM. The horizontal red line indicates the average over the intire period. The onset of the eruption on 19 May 2023, associated with lava overflow, is indicated in the yellow shaded zone, along with additional overflow events on 8 august*

### 3.3 CORRELATION BETWEEN RSAM AND SEISMICITY

Normalized RSAM curves from RGB2 and RSY2 showed a similar overall pattern (Fig. 5a). However, their correlation was moderate ($R^2 = 0.40$; Fig. 5b), reflecting both shared and local influences on seismic amplitude. Correlation between RSAM and the number of daily volcanic earthquakes was negligible ($R^2 < 0.04$; Fig. 5c–d), indicating that RSAM and earthquake count track different volcanic processes—one energy-based, the other event-based.

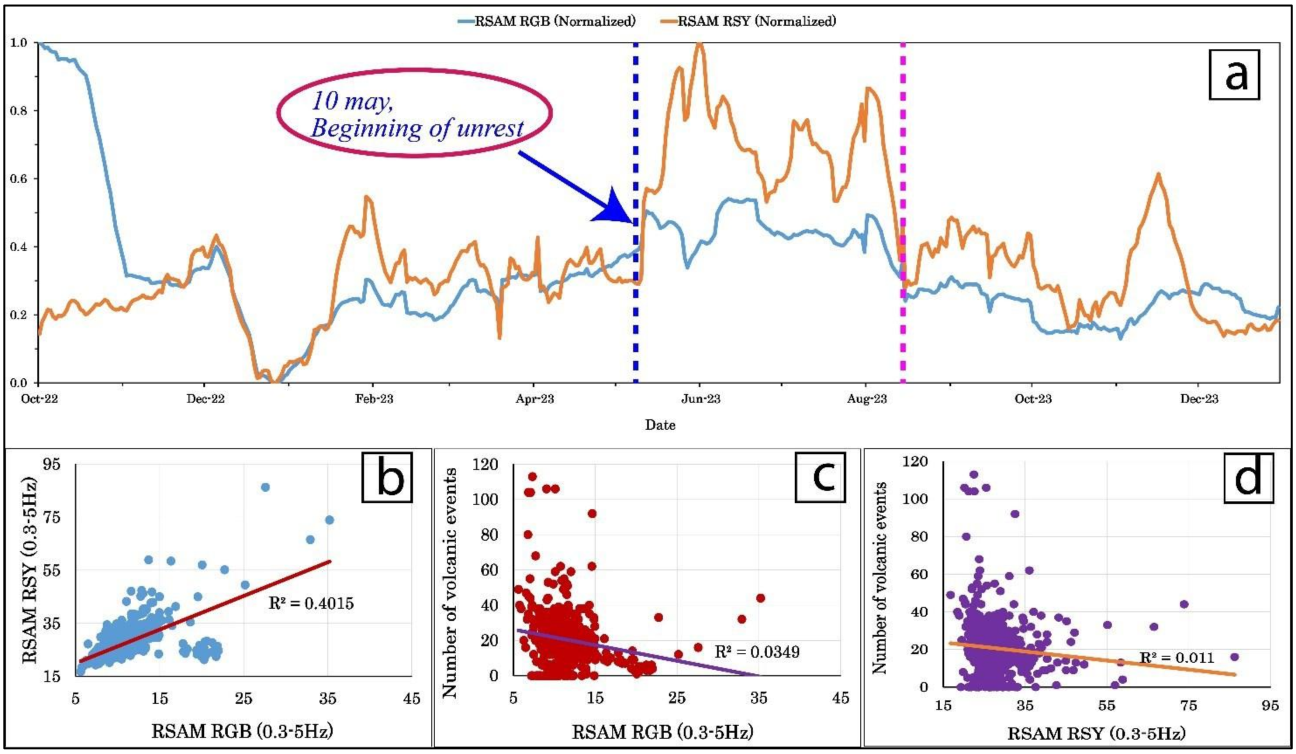


***Fig. 5. (a) Normalized RSAM value from stations RGB (blue) and RSY (orange) between October 2022 and December 2023. A progressive increase starting around 10 May (first vertical dashed line) and the second vertical line (pink) marks the end of unrest period (overflow event) in August. (b) Scatter plot of RSAM values from RGB versus RSY, showing a moderate positive correlation, indicating partial coherence in seismic amplitude trends between these stations. (c) Scatter plot of RSAM RGB versus the number of daily volcanic events and (d) RSAM versus the number of daily volcanic events***

### 3.4 PRE-ERUPTIVE SEISMIC SWARM AND EVENT ANALYSIS

An important seismic swarm was recorded between 22: 00 on May 18 and 02: 00 on May 19 (4 hours of duration) (Fig. 6). This swarm, observed across all three components at both stations, consisted primarily of volcano-tectonic (VT) events, with long-period (LP) signals. Spectral analysis of selected events confirmed dominant low-frequency peaks (~1 Hz) for LP events and higher frequencies (>5 Hz) for VT events (Fig. 6). This swarm preceded the eruption onset by approximately 17 hours. These observations support the interpretation of magma migration and overpressure leading to the lava overflow observed later on 19 May at from 19: 00 (local time) where an intense glow was observed all night.

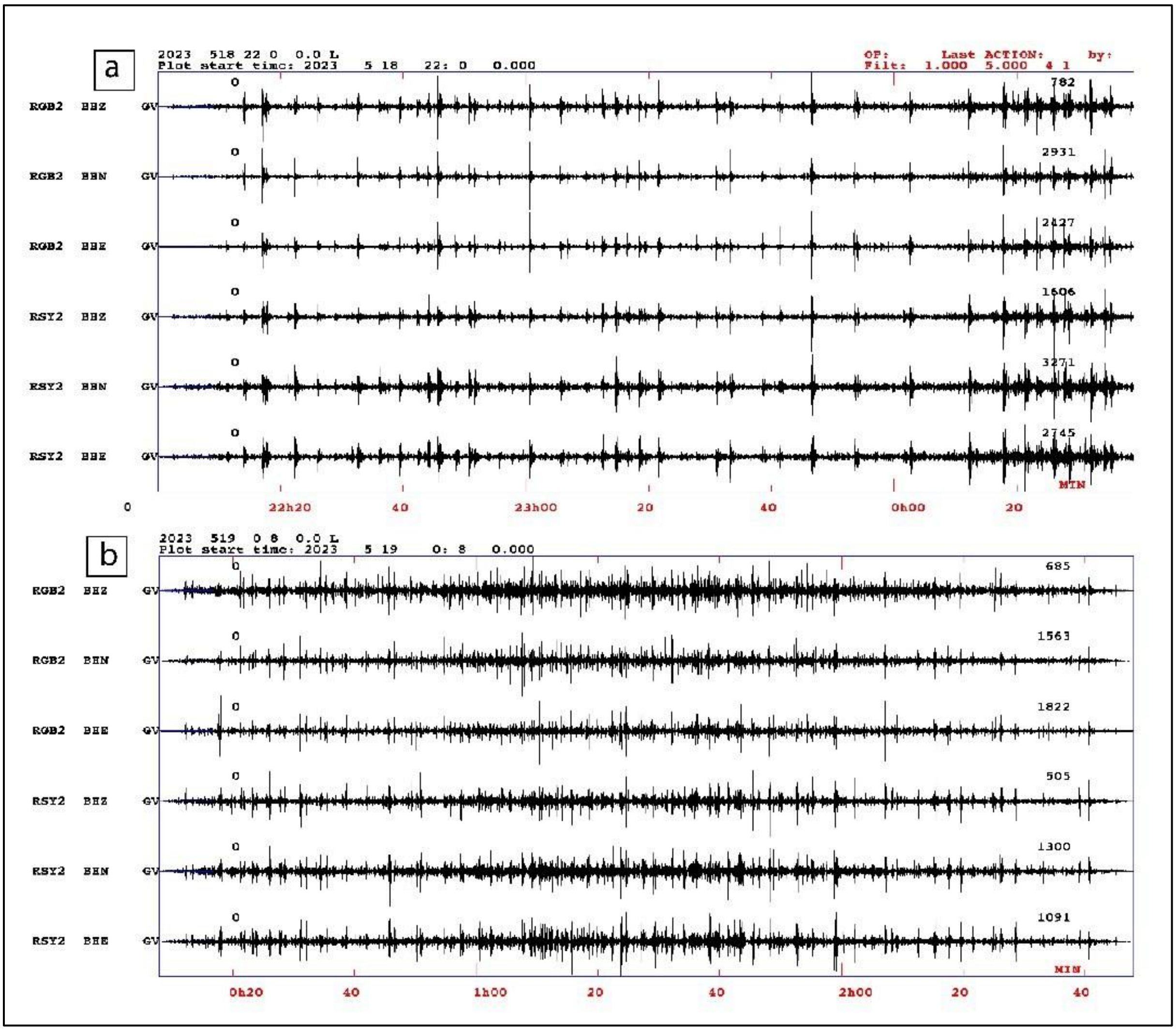


*Fig. 6. Pre-eruptive seismic swarm recorded on 18-19 May 2023: (a) seismic waveforms recorded at RGB2 and RSY2 stations (three components each) between 22: 00 on 18 May to 00: 40 on 19 May and (b) Continuation of the swarm from 00: 20 to 02: 40 on 19 May*

The LP events are characterized by ermergent waveforms a dominant low frequency energy between 1-3Hz, as shown in their corresponding sprectarl plots (Fig. 7a-b). The VT events recorded on 19 May 2023, exhibiting impulsive and frequency content above 5Hz (Fig. 7c-d) while the tectonic earthquakes show a higher amplitude and broader spectral content typical of regional tectonic events (Fig. 7d).

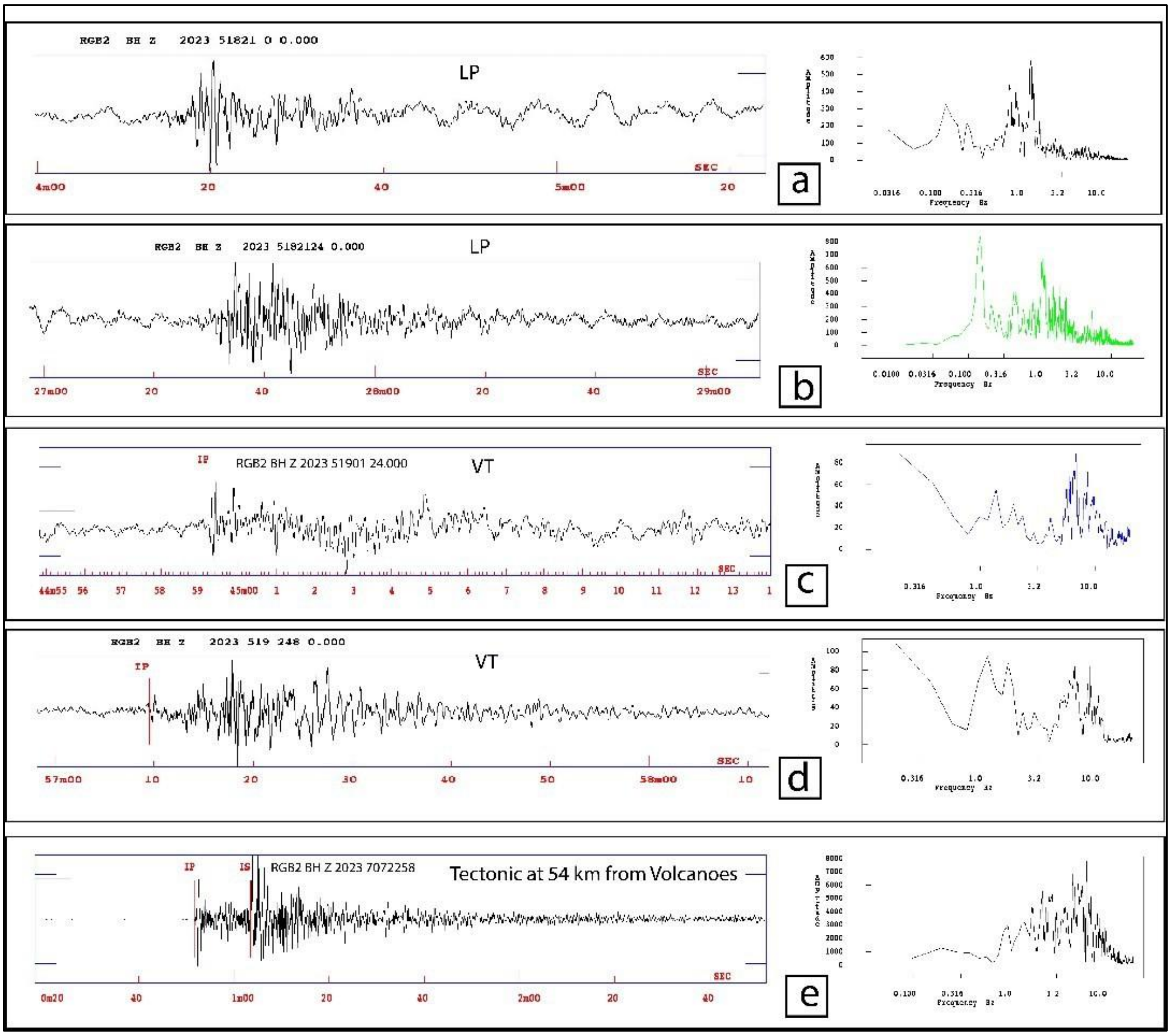


***Fig. 7. Examples of seismic events recorded during the swarm and regional erthquake, Vertical component at RGB station: (a) and (b) LP events, (c) and (d) Volcano-tectonic (VT) events and (e) tectonic earthquake (Mw≥4) located at about 54 km from the volcanic area***

## 4 DISCUSSION

On May 19-20, 2023, strong magmatic activity characterized the Nyamulagira volcano. A strong glow was observed at the summit of the crater; the lava having overflowed from the crater to flow on the northern flank of the volcano. Based on seismic data, GVO (Goma volcano Observatory) report indicate a shallow magma activity at Nyamulagira volcano since February (The Bulletin of the Goma Volcanological Observatory of February 19, 2023 n.d.). On March 14, 2023, lava fountains and a plume gas reach 1.5 km above the crater. A large thermal anomaly was observed on March 18, reports VAAC (Volcanic Ash Advisory Center of Toulouse) indicating the presence of the lava lake. (Global Volcanism Program, 2023. Report on Nyamulagira (DR Congo) (Venzke, E., ed.). Bulletin of the Global Volcanism Network, 48: 5. Smithsonian Institution. n.d.). All these observations were clear precursors to the May 19, 2023, event marking the beginning of the Lava Lake Activity series characterized by an overflow eruption followed by a short lava flow on the northwest flank of the volcano.

Analysis of seismic activity at Nyamulagira between October 2022 and December 2023 reveals a progressive evolution of the volcanic system, culminating in the effusive eruption of May 19, 2023. RSAM data, volcanic earthquake counting, and waveform analysis identified a consistent pre-eruptive sequence. A notable signal is the increase in RSAM, starting on May 10, 2023, approximately 9 days before the eruption, consistently observed at both RGB2 and RSY2 stations, although variable in magnitude due to site effects, indicates increasing unrest related to summit remobilization of magma. This phenomenon has been recognized as a precursor to effusive eruptions in other systems, such as at Pinatubo (Pilippines) in June 1991 and Mt St.

Helens (USA) en May 1985, where a slow rise of the RSAM precedes the final crisis, (Endo and Murray 1991; Endo et al. 1996 and Cornelius and Voight (1996) describe RSAM variations at Mt St. Helens. According to the authors, the first peak in RSAM occurred during doming in May 1985, followed by exponential increases that heralded imminent volcanic activity, correlated with rising magma in the dome.

Two major volcanic seismic swarms were observed before the eruption: on 23–25 December 2022 and 1 April 2023. These episodes indicate that the Nyamulagira magmatic system was under pressure for several months before the eruption, reflecting progressive instability. The recurrence of the seismic swarms suggests accumulation of magma at depth, with periodic energy releases. Several regional tectonic earthquakes, notably those of March 27, 2023, generated abrupt peaks in RSAM at both stations, without initiating a sustained increasing trend. Their effect on the RSAM curves manifests itself as brief pulses, suggesting a transient influence of seismic waves. However, these earthquakes were followed by a significant volcanic swarm on April 1, suggesting an interaction between magmatic and tectonic activity. In a continental rift setting such as this, the upwelling of magma from the crust causes regional stresses that can generate tectonic earthquakes (Wright et al. 2006; Ebinger et al. 2010). On the other hand, tectonic earthquakes can modify the stress state of the volcanic system, contributing to the reactivation of pre-existing structures and the release of magmatic fluids (Wong et al. 2019; Acocella 2021; Brauner et al. 2024).

Statistical analysis showed a moderate correlation between RSAMs from both stations (R2=0.40), reflecting a partially common response to similar sources, but also local influences (orientation, substrate, distance). In contrast, the correlation between RSAM and the number of volcanic earthquakes is almost zero (R2<0.04). This dissociation highlights that RSAM, and discrete seismicity reflect different processes: RSAM is sensitive to long signals (tremor, LP), sometimes non- localized, linked to fluid mobilization, while discrete volcanic earthquakes (VT) are more associated with brittle fracturing. Magmatic agitation phases can be expressed either by seismic swarms or by tremor-type signals, without these two manifestations being simultaneous. This reflects the complexity of the interactions between magmatic overpressure, fracturing, and system resonance. In periods when the RSAM is high, seismic noise can mask certain discrete volcanic earthquakes, artificially reducing their number in the catalogs.

Analysis of waveforms and spectra (Fig. 6–7) shows an intense volcanic swarm, dominated by VT events and some LPs, occurring between 22: 00 on May 18 and 02: 00 on May 19, less than 24 hours before the eruption. These signals reflect a rupture of the internal walls of the conduit, or a terminal pressurization, facilitating the final ascent of the magma. In an already open system, as is the case here with a lava lake active since 2022, this type of swarm is often the last precursor signal before an overflow, as observed in other volcanoes with permanent lava lakes (e.g., Chouet et Matoza 2013; Matoza et al. 2015; Thelen et al. 2022). However, the observed seismic signals (LP swarm + some VT) reveal a transition from a passive effusive regime to a dynamic instability regime, generally interpreted as fluid (gas or magma) mobilization (LP) and fracturing associated with increasing overpressure linked to a rapid magma rise or pressure change in the upper chamber. These signals reflect a progressive rupture of the conduit walls or a rapid remobilization of magma beneath an already active lava lake. The swarm thus represents an immediate precursor to the eruption, revealing a transition to a critical state in an already open magmatic system.

Our seismic analysis reveals a progressive RSAM increase starting on May 10, followed by a short seismic swarm on May 18-19, wich preceded the lava overflow observed at 19: 00 (local time) on May 19. These precursory seismic signals contrast with the findings of of (Polcari et al. 2025), who reported no significant ground deformation prior to the eruption using Sentinel-1 SAR coherence data. Their results support the interpretation of Nyamulagira as an open-system volcano, where magma ascent does not necessarily induce measurable surface deformation. This comparison highlits the value of combining seismic and satellite data, as seismic observations may provide earlier, immediate and very close precursors insight into pressurization or conduct dynamics that are not detactable via InSAR.

## 5 CONCLUSION

The May 19, 2023 eruption of Nyamulagira was preceded by a progressive increase in RSAM, 9 days before followed by a short but intnse seismic swarm just hours before the lava overflowe. Despite the absence of measurable ground deformation reported by InSAR studies, seismic indicators, particularly RSAM revealed clear signs of escalating volcanic unrest. We analysed the RSAM at two stations and noticed that their amplitudes are very different due to heterogeneous source processes, distance from the source or local site effects. In addition, analysis showed a lack of correlation between RSAM and the number of volcanic earthquakes suggests that seismic amplitude and event count reflect different processes: RSAM likely captures continuous magma movement, while discrete earthquake counts represent brittle failure in the surrounding rock. Therefore, we cannot directly compare the RSAM variations with the number of earthquakes, due to the overlap and the large number of seismic events that complicate the counting.

The analysis allowed several conclusions to be drawn, in particular:

1. RSAM was essential to analyze changes in activity at Nyamulagira volcano for the period October 2022 to December 2023. Fluctuations in the RSAM curve signal upcoming unusual events, with high peaks coinciding with lava movement in the upper part of the crater.
2. Variations in RSAM indicate the volume of magma supplied and pressure fluctuations at the supply source. An increase in RSAM signals a large volume of magma under pressure, while a decrease indicates a smaller volume. A constant curve at high levels suggests a continuous supply under stable pressure into the magma system.
3. RSAM is more reliable when seismic stations are close to the volcano, as this allows for the detection of seismic amplitude variations and the recording of a wide range of frequencies to better analyze those that influence RSAM.
4. Earthquake swarms were observed prior to the lava lake overflow on 19–20 May 2023. The evolution of hypocenters towards superficial areas in late 2022 suggests magmatic displacement towards the crater surface.

These results hihglith the importance of combining multiple seismic indicators for effective eruption forecasting in open-conduit systems like Nyamulagira. Particular attention should be paid to progressive RSAM increases and seismic swarms, which may provide more reliable precursors than the absolute number of volcanic events.

## Data availability

The data used in this work cannot be shared with third parties for a period defined by the organization (Goma Volcano Observatory). However, they can be accessed through the corresponding author’s contact for more credibility. The authors declare that there is no conflict of interest regarding these data.

## Competing interests

We declare that there is no competing interests.

## Acknowledgments

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