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RESEARCH ARTICLE

Detecting sources of shallow tremor at neighboring volcanoes in the Virunga Volcanic Province using seismic amplitude ratio analysis (SARA)

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Abstract

Volcano monitoring requires simple techniques to rapidly identify the cause of volcanic unrest. The so-called RSAM (real-time seismic amplitude measurements) technique, used in many observatories, is a good example of extracting information from seismograms with minimal processing. Built on a similar principle, the more recent seismic amplitude ratio analysis (SARA) technique allows locating migrating seismicity at high frequency (> 2 Hz, e.g., due to dike intrusions) under certain assumptions. However, such analysis generally requires a dense distribution of stations close to the seismic sources (depending on the magnitude) and/or station sites undisturbed by human activity. In a more straightforward and qualitative approach, computing amplitude ratios between station pairs can also allow for the detection of temporal and (2D) spatial changes of volcanic activity. In this work, we adopt such a simplified approach of SARA in order to characterize seismic tremors originating from two open-vent neighboring volcanoes, Nyiragongo and Nyamulagira, in the Virunga Volcanic Province (VVP) in the Democratic Republic of the Congo (DRC). In contrast with previous studies, we focus here on the low-frequency band (0.3–1 Hz), free from anthropogenic noise and sensitive to shallow volcanic tremors linked to intermittent or permanent intra-crater eruptive activity recorded through the large-aperture local network. We apply for the first time the SARA methodology for volcanic sources predominantly generating surface waves and propagating over long distances. The analysis is performed on more than two years of continuous seismic data. Seismic amplitude analysis in this frequency band is strongly influenced by the short-period microseisms originating from nearby Lake Kivu. Despite this diurnal to seasonal amplitude variability, SARA successfully detects continuous volcanic tremor activity and its arrest at both volcanoes. In light of these findings, we discuss the applicability of the method to the continuous, real-time detection, and characterization of long-period shallow volcanic tremor sources in this region.

Keywords Virunga · Nyiragongo · Nyamulagira · Volcanic tremors · Lake microseisms · SARA

Résumé

La surveillance des volcans actifs fait souvent appel à des techniques simples pour détecter les changements ou évaluer rapidement les causes d'une activité soutenue. La technique appelée RSAM (Mesure des Amplitudes Sismiques en temps Réel), fréquemment utilisée dans les observatoires volcanologiques, est un bon exemple d'extraction d'informations par analyse minimale de séismogrammes. En se basant sur un principe similaire, la récente technique d'Analyse des Rapports d'Amplitudes Sismiques (SARA) permet, sous certaines conditions, de localiser la migration de la sismicité à haute fréquences (> 2 Hz) liée, par exemple, à une intrusion magmatique. Cependant, cette méthode d'analyse nécessite une distribution dense

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des stations sismiques proche de la source (selon la magnitude) et/ou des sites d'enregistrement faiblement impactés par l'activité humaine. Dans une approche très directe et qualitative, le calcul des rapports d'amplitudes sismiques entre paires de stations permet également de détecter des variations temporelles et spatiales (2D) de l'activité volcanique. Dans ce travail, nous adoptons une version modifiée de SARA afin de caractériser les trémors volcaniques sur deux volcans voisins à systèmes ouverts : le Nyiragongo et Nyamulagira, situés dans la Province Volcanique des Virunga (PVV) en République Démocratique du Congo (RDC). Contrairement aux études existantes, nous nous focalisons ici sur la bande de fréquence basse (0.3-1 Hz). Cette dernière, est réputée comme non contaminée par le bruit anthropogénique, tout en restant sensible aux trémors volcaniques superficiels liés à l'activité volcanique intermittente ou permanente détectable sur toute l'étendue du réseau sismique local. Nous appliquons pour la première fois cette méthode SARA pour l'étude de sources volcaniques principalement dominées par des ondes de surface et se propageant sur des longues distances. La présente étude a été réalisée avec un peu plus de deux ans de données sismiques continues. L'analyse des amplitudes sismiques dans cette bande de fréquence est fortement influencée par les microséismes de courtes périodes provenant du Lac Kivu. Malgré cette variabilité diurne et saisonnière des amplitudes, SARA détecte de façon satisfaisante différents épisodes de l'activité des trémors volcaniques sur les deux volcans. A la lumière de ces résultats, nous discutons de l'applicabilité de cette méthode pour détecter et caractériser en continu et en temps réel des sources superficielles de trémors volcaniques à longues périodes dans cette région.

Mots clés : Virunga, Nyiragongo, Nyamulagira, trémors volcaniques, microséismes du Lac, SARA

Introduction

Due to their location in the western branch of the East African Rift in the Kivu rift and Virunga Volcanic Province (VVP), the cities of Goma and Gisenyi are threatened by several geological hazards (volcanic eruptions, earthquakes, floods, etc.). With more than 1 million inhabitants (Syavulisembo Muhindo et al. 2021) Goma and its surrounding areas are permanently exposed to Nyiragongo volcano, located at ~ 15 km distance, and, to a lesser extent, Nyamulagira volcano at ~ 30 km distance (Fig. 1). Nyiragongo, an open-vent stratovolcano, hosts one of the largest permanent lava lake on Earth at its summit. This lava lake was drained during each of the three known historical eruptions, i.e., in 1977 (Tazieff 1977), 2002 (Komorowski et al. 2002), and 2021 (Smittarello et al. 2022). The three eruptions were characterized by fast basaltic lava flows erupting from fissures on the volcano's flanks. These flows reached the city of Goma in 2002 and 2021, and Lake Kivu in 2002 (Komorowski et al. 2002). Nyamulagira is a very active shield volcano characterized by about 30 eruptions during the twentieth century (Smets 2015), the last one occurring in 2012. These eruptions are also effusive and start either in the large ~ 2 km wide caldera or on the flanks through vents and fissures (Fig. 1c) (Wauthier et al. 2015).

In such a context, capacity reinforcement of volcanic earthquake monitoring by a permanent and telemetered network is of the utmost importance. Abnormal seismicity (e.g., increase of the number of events, appearance of tremor) is often among the first signs of a resurgence or a change of volcanic activity which can lead up to an eruption (Tilling 2008). Following the 2002 Nyiragongo flank eruption, the first digital seismic network of the Goma Volcano Observatory (GVO) has been deployed in the VVP between 2004 and 2012 with up to 7 stations (Pagliuca et al. 2009). Unfortunately, these data have been little exploited due to insufficient data completeness caused by technical and transmission issues (Mavonga 2010). Since mid-2013 to June 2022, a new telemetered broadband seismic network called KivuSNet has been progressively developed in the area under the initiative of international and cross border local institutions (Oth et al. 2017), leading, since October 2015, to the densest seismic network ever installed in the Kivu region (up to 20 stations), thus offering opportunities to better understand the seismicity in the VVP (Fig. 2a).

Alongside recent research-based developments and findings in the VVP (e.g., Oth et al. 2017; Barrière et al. 2017, 2018, 2019, 2022), it is also of primary importance that low computational cost and user-friendly methods become general practice at GVO. Notably, techniques consisting in computing the variation of seismic amplitude through a network have become a standard approach since the pioneering study by Endo and Murray (1991) (Wassermann 2012). Since then, the RSAM, which stands for real-time seismic amplitude measurement, and related calculations, are commonly implemented at volcano observatories worldwide, including GVO. Here we intend to apply the SARA method (seismic amplitude ratio analysis), which is based on the calculation of amplitude ratios between station pairs (Taisne et al. 2011). Originally developed for detecting magma migration, SARA relies on the decay of seismic wave amplitude along the source-receiver travel path. Because magma movement to the surface is often accompanied by seismicity known as volcano-tectonic (i.e., a fracturing of the surrounding rock), the SARA technique has been generally used in a rather high-frequency band (e.g., 2 to 15 Hz), which is typical of this kind of source processes (Caudron et al. 2018). Recently, Tan et al. (2019) set up the so-called Red-flag SARA to track magma migration in the context of real-time volcano monitoring

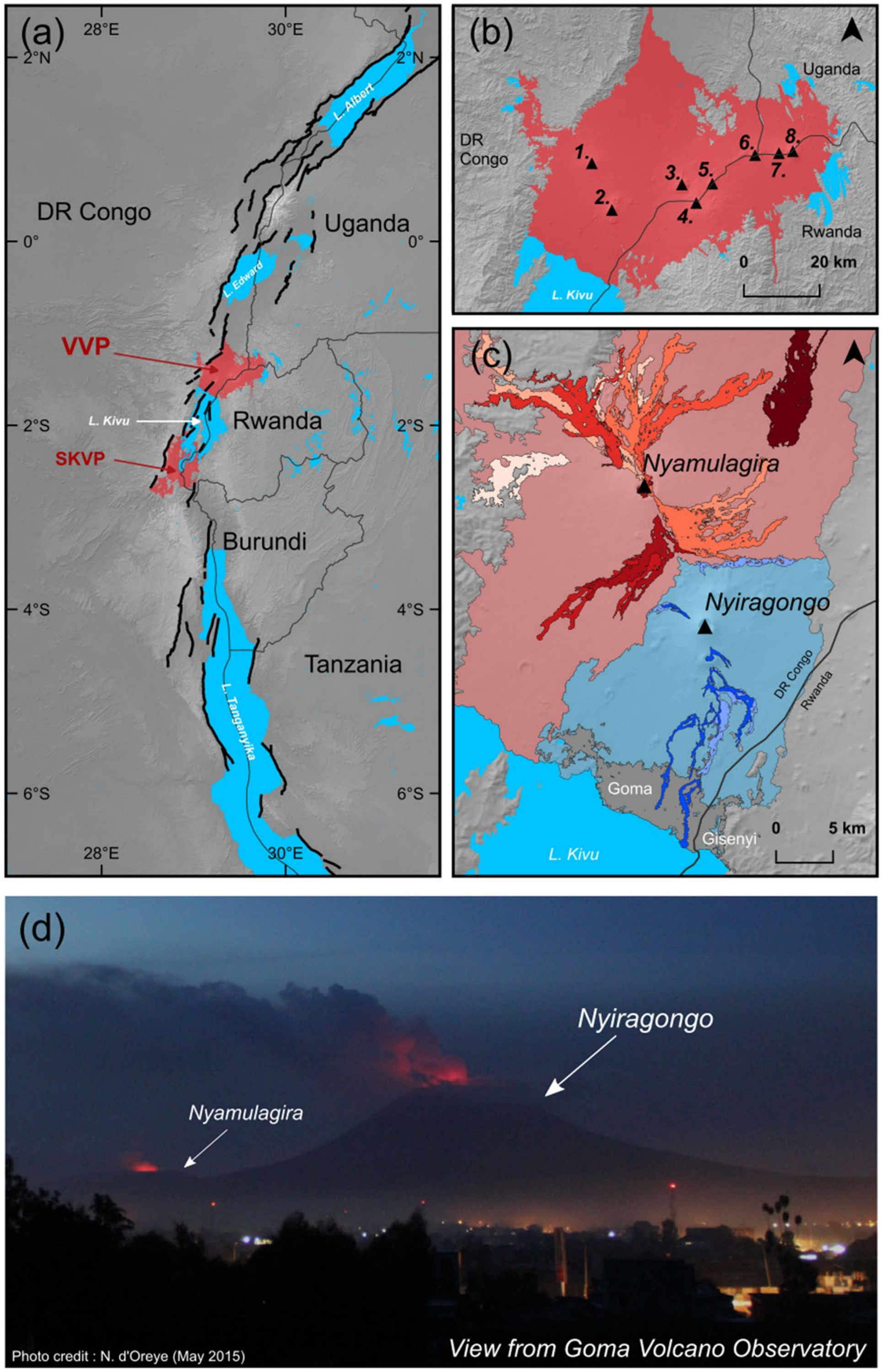


Fig. 1 **a** The Virunga Volcanic Province (VVP) and the South Kivu Volcanic Province (SKVP) within the East African Rift system (EARS). It borders many different countries: Rwanda, Burundi, the East of the Democratic Republic of Congo (DRC), the south-west of Uganda, and the north-west of Tanzania, and it is located in the middle of a topographical uprising called the Kivu Dome. **b** Zoom in the VVP (red color) with the eight main volcanic edifices (1: Nyamulagira, 2: Nyiragongo, 4: Karisimbi, 3: Mikeno, 5: Visoke, 6: Sabinyo, 7: Gahinga, 8: Muhavura). The two major active ones are Nyiragongo and Nyamulagira. **c** The different volcanic fields and some recent eruptions (lava flows are shown) are associated with the two volcanoes, the ones from Nyiragongo in lavender and magenta colors affecting the cities of Goma and Gisenyi at the north of the lake Kivu. All shape files of the lava flow are from Smets et al., (2010). The background hillshade topography is derived from the SRTM 3 arc seconds (NASA/USGS), which is made available from the US Geological Survey. **d** Picture of Nyiragongo and Nyamulagira taken from the Goma Volcano Observatory in May 2015 by N. d'Oreye. At that time, there was two active lava lakes in the Virunga

without event locations. Compared to the original study at Piton de la Fournaise by Taisne et al. (2011), the KivuSNet is a local network with a large interstation distance (~ 10 to 100 km). Due to the unstable political situation in the region, stations cannot be deployed between the volcanoes. Their locations are restricted to secure places (e.g., GVO, UN military compounds, etc.). As a consequence, most of the seismic records exhibit a strong anthropogenic noise level at high frequency (above 2 Hz, see the "Overview of the 2-year-long seismic data used" section). Put together, the sparse geometry of the network and the high level of human-induced seismic noise hamper the classical use of

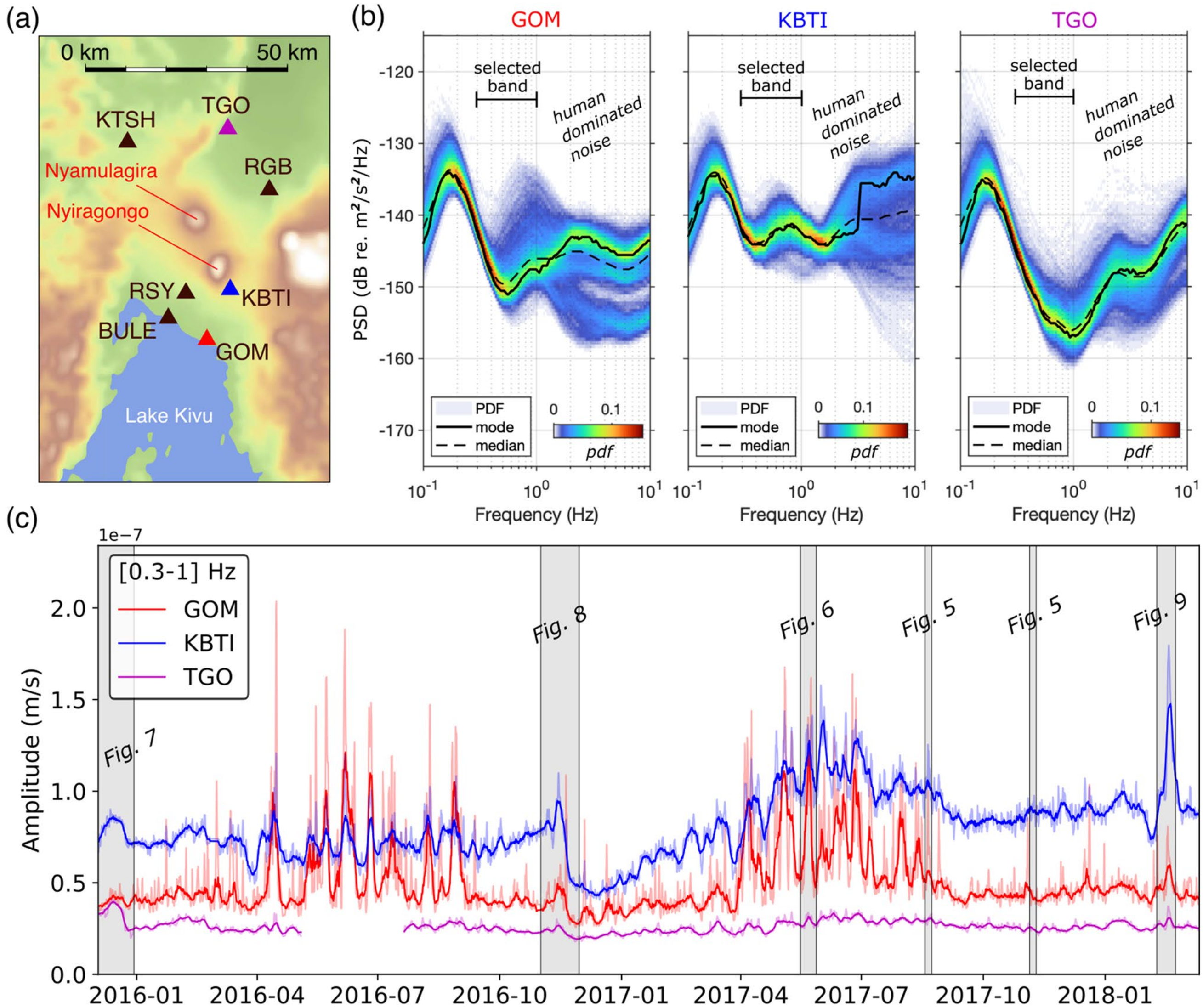


Fig. 2 **a** Seismic stations used in this study displayed on a topographic map of the Virunga Volcanic Province. The colored triangles (GOM, KBTI, and TGO) show the locations of the seismic stations close to Lake Kivu, Nyiragongo, and Nyamulagira respectively on which we performed the power spectral density (PSD). **b** Evaluation of the seismic background noise level using PSD (in dB re $m^2/s^2/Hz$) analysis at GOM, KBTI, and TGO stations. **c** Two-year-long time-series of the seismic amplitudes (in 10^{-7} m/s after correction of the instrumental response) smoothed using 1 day (light colored lines) and 7 days (dark colored lines) rolling median calculated between 0.3 and 1 Hz at GOM, KBTI, and TGO stations. The grey bands represent the short-term variation on the seismic amplitudes associated with magmatic or non-magmatic events discussed in Figs. 5, 6, 7, 8, and 9. The map has been generated with the GMT software using the ETOPO Global relief Model, which is made available from the NOAA

the SARA approach for locating high-frequency seismic sources.

Here, we test the applicability of the SARA technique within a different context. The main goal is the assessment of this method in a particular range of low frequencies corresponding to the shallow volcanic signal observed in the time period between flank eruptions at both volcanoes. One of the particularities of the VVP is the dominant, permanent background seismic signal generated by Nyiragongo's lava lake at low frequency (< 2 Hz) within its central crater and propagating as surface waves that are detectable throughout the entire network (Barrière et al. 2018). Tracking changes of this dominant seismic source in the VVP may therefore be relevant to monitor Nyiragongo's activity. Moreover, Barrière et al. (2017) have shown that Nyamulagira exhibits a similar low-frequency signature during intra-caldera eruptive activity (lava lake and fountaining). We thus explore in this paper if this alternative application of SARA at low frequency could be an efficient monitoring solution of the long-lasting summit effusive activity at Nyiragongo and/or Nyamulagira. The advantage of the proposed approach is its capability for detecting and interpreting changes of eruption dynamics in the Virunga with limited field records and minimal data processing. The main limitation of the method is, however, the overlap with non-volcanic signals at similar low frequencies caused by Lake Kivu's microseisms that can temporarily hamper the straightforward interpretation of continuous (real-time) seismic amplitude time series.

The VVP and its seismicity

General context

The VVP is a transition zone between the Lake Kivu and Lake Edward rift basins, in the central part of the western branch of the East African Rift System (EARS) (Fig. 1a) (Ebinger 1989; Smets et al. 2016). In this part of the EARS, the extension rate reaches 2.8 mm/year (Saria et al. 2013; Ji et al. 2017). The VVP comprises eight main volcanic edifices, with two major active ones, which are Nyiragongo and Nyamulagira (Fig. 1b, c). These two volcanoes are among the most active in Africa, and even on Earth (Wright et al. 2015) (Fig. 1d).

Nyiragongo (1.53° S, 29.25° N) has the shape of a stratovolcano and culminates at 3470 m with a 1200-m-wide main crater (Smets et al. 2017). The main edifice is also characterized by two satellite cones: Baruta on the northern flank and Shaheru on the southern flank. Its eruptive activity is mostly characterized by persistent lava lake activity in its summit crater, sometimes becoming the largest lava lake surface on Earth (Smets et al. 2016). Only three flank eruptions have been documented since the arrival of the first European explorers in the nineteenth century. These eruptions occurred in January 1977 (Tazieff, 1977), January 2002 (Komorowski et al. 2002), and May 2021 (Smittarello et al. 2022). Nyiragongo lavas have the lowest viscosity ever observed for terrestrial silicate lavas (Dawson et al. 1990; Morrison et al. 2020).

Nyamulagira (1.41° S, 29.20° E) is a shield volcano located about 15 km to the north-west of Nyiragongo and is mostly characterized by phases of summit eruptive activity (1913–1938, 2014–present) and phases made of flank eruptions (before 1912, 1938–2012) occurring every 1–4 year(s) (Smets et al. 2015). The main edifice culminates at 3058 m above sea level and is topped by a 2 × 2.3 km wide caldera. The characteristics of flank eruptions of Nyamulagira mostly vary according to their location (Smets et al. 2015). The Nyamulagira lava flows have a low viscosity and can cover long distances of up to several tens of kilometers (Smets et al. 2014, 2015).

Characteristics of the seismicity

The group of seismic signals encountered in the VVP are similar to those commonly detected at other volcanoes (Chouet and Matoza 2013). They are classified into four families based on their waveform characteristics: short-period (or high-frequency, often classified as volcano-tectonic), long-period (or low-frequency), hybrid events (i.e., low-frequency event with high-frequency onset), and tremors (Tanaka 1983; Lukaya et al. 1992). Long-period (LP) earthquakes, also called low-frequency (LF), are generally interpreted as the consequence of fluid migration in the magmatic plumbing system while low-frequency volcanic tremors are indicators of sustained magma movement (Chouet and Matoza 2013). However, no manual classification has been routinely performed at GVO, notably due to the lack of modern instruments maintained operational in the region in the past decades. A first long-term seismic monitoring database at GVO, obtained from the deployment of the telemetered seismic network KivuSNet in the Kivu rift region, has been available since late 2015. To date, this new insight into the Virunga volcanoes' seismicity has allowed to highlight a persistent background tremor source with a dominant frequency below 1 Hz (Oth et al., 2017; Barrière et al., 2017). This continuous low-frequency signal is attributed to the lava lake spattering activity (Barrière et al. 2018, 2019), which is recorded at a long-distance range (up to ~ 100 km) across the local seismic network. Barrière et al. (2022) showed that seismic activity at Nyiragongo is often associated with swarm sequences associated with magmatic intrusion (i.e., deeper than 10 km below sea level). These swarms are synchronous with large lava lake drops and contain many events with characteristics similar to hybrid events (i.e., high-frequency onset up to 10 Hz and low-frequency wavetrains). Additionally, seismic activity at this volcano is characterized by a cluster of daily repetitive events (more than 5000 between September 2015 and 2018) that suggest a non-destructive source beneath Nyiragongo (Barrière et al. 2019). These events are located at large depths (11–15 km) and are characterized by higher frequencies (2–10 Hz) than the low-frequency content generally observed for repetitive events attributed to magmatic movements. However, brittle failure can hardly explain their highly repetitive nature. Fluid-related movement is thus the probable source mechanism of such high-frequency excitation, as observed for instance by Caplan-Auerbach and Petersen (2005) at Shishaldin volcano. The last May 2021 eruption was also the first eruption at Nyiragongo well monitored by numerous broadband instruments, which allowed drawing a clear seismic picture of the flank eruption and the shallow dyke intrusion beneath the city of Goma

(Smittarello et al. 2022). At Nyamulagira, the detected seismicity has been mostly characterized by a dominant long-period signature (LP events, tremors) in the 0 to 20 km depth range, either inferred from recent observations during intra-crater lava lake/fountaining activity (Barrière et al. 2017) or using available pre- and syn-eruptive digital data from a dismantled network (Mavonga et al. 2006, 2010).

Overview of the 2-year-long seismic data used

We used data from the KivuSNet seismic stations (FDSN network code KV), which was a recent broadband seismic network installed in the region (Oth et al. 2017), comprising seismic and infrasound stations. The network was gradually deployed and operational between September 2013 and June 2022, the first station installed being GOM located in the GVO grounds. Our study is based on data collected from late 2015 coinciding with the main deployment phase of the KivusNet and the start of the operational telemetry (Oth et al., 2017). The data are both telemetered (sampled at 50Hz) and stored locally on a hard drive (sampled at 200 Hz). Six key stations with long-lasting records are selected around the volcanoes. They are all located between approximately 6 to 35 km away from both active volcanoes. Hereafter, we discuss the results from analyses based on seismic amplitude variations recorded between December 2015 and March 2018.

The locations of the selected stations are plotted in Fig. 2a. Power spectral density (PSD) between 0.1 and 10 Hz obtained from the entire records (Dec. 2015–Mar. 2018) at 3 stations are plotted in Fig. 2b. These 3 stations depict site properties typical of those encountered in the VVP:

- The station GOM is located close to the shore of Lake Kivu in an urban environment. Nyiragongo's and Nyamulagira's summits are located respectively around 17 and 30 km away toward the north.
- Station KBTI is located in a rural place affected by human activities (main road and villages), but it is also the closest station to one of the active volcanoes (~ 6 km away from Nyiragongo's inner crater).
- The station TGO is located in a military compound (UN base camp) in a remote place though affected by the nearby military activity. Its location to the North of the Virunga remains highly strategic in terms of volcano monitoring despite its distant location (~ 23 to 35 km from Nyamulagira and Nyiragongo, respectively), its difficult accessibility and its location in a region affected by strong insecurity.

In light of the abovementioned site descriptions, one can better gauge the 2-year-long PSDs obtained as these three stations plotted in Fig. 2b (represented as probability density functions, further called pdf). The processing follows the one described in McNamara and Buland (2004) using a main time window of 2^{19} samples with a sampling rate of 50 Hz (~ 175 min), overlapped by 50% and subdivided into 13 segments overlapping by 75%, thus resulting in sub-windows of 2^{17} samples (~ 44 min). The final PSDs are smoothed along 1/16th octave intervals.

The only similar pattern between the three PSDs is the oceanic secondary microseism peak (0.15–0.2 Hz) recorded everywhere on Earth (with regional and seasonal amplitude variations depending on the source properties) (McNamara and Buland 2004). Above 0.3 Hz, strong dB level differences between the three stations (spaced by ~ 50 km at maximum between GOM and TGO) point out local source and/or site effects. According to Barrière et al. (2018), the peak between 0.3 and 2 Hz at KBTI is due to the Nyiragongo lava lake activity nearby, generating a stable and persistent tremor. Available records at the summit during expeditions or from a station deployed on the crater rim in the course of the year 2018 (not shown here) depict a lava-lake tremor with a broadband signature up to 10 Hz (Barrière et al. 2019). In the [0.3–2] Hz frequency range, this lava lake signal does not clearly stand out at stations GOM and TGO. At both stations, the power increase above 1 Hz is mainly due to human activity (so-called cultural noise) where the spreading of the pdf is mainly due to diurnal variations (McNamara and Buland 2004). For all stations, anthropogenic noise sources are dominant above 2 Hz. At GOM, another peak is noticeable between 0.3 and 2 Hz, which do not correspond to the maximum mode (black line). We will see later in the "Variations of low-frequency seismic amplitudes in the VVP" section that this signal overlapping the volcanic tremor band is mostly due to short-period microseisms from Lake Kivu. The term "short-period," in accordance with the study of Xu et al. (2017) analyzing several lake microseisms signatures across the globe, refers to the [0.5–2] Hz frequency band, higher than the one characterizing the oceanic microseisms.

We conclude that analyzing the continuous amplitude of the seismic signals above 1 Hz at relatively large distances (i.e., tens of kilometers away from both volcanoes) could be too strongly affected by unwanted noise sources. Selecting a band between 0.3 Hz, above the ocean microseismic band, and 1 Hz, below the dominant anthropogenic noise sources, would successfully highlight seismic amplitude variations generated, at least partially, by volcanic tremor sources. This frequency band also corresponds to the one chosen by Barrière et al. (2017) for detecting and locating Nyiragongo's and Nyamulagira's tremor across the network (up to 100 km away from the edifice) based on seismic interferometry principles. In this case, the amplitude information is lost due to pre-processing procedures such as time-domain normalization and spectral whitening.

Thus, for the specific analysis presented in this paper, we bandpass filter the data in the [0.3–1] Hz frequency band. The obtained amplitude variations either correspond to magmatic processes at one or both volcanoes, or to other unknown sources. The 2-year-long seismic amplitude records from GOM, KBTI, and TGO, whose calculation details are provided in the "Variations of low-frequency seismic amplitudes in the VVP" section, are plotted in Fig. 2c. Between December 2015 and March 2018, we identified two categories of variations. The first ones are short-term changes associated with rapid variation of seismic amplitudes (1 day to few weeks) possibly indicative of fast changes in volcanic tremor activity or other phenomena in the region. The second ones are long-term changes, more prominent for GOM records, that extend over several months. This long-term trend of the GOM timeseries, which appears to be seasonal, is discussed in Fig. 4. Five short-term changes are analyzed separately in five figures (gray boxes in Fig. 2c), corresponding either to the largest amplitude variations (Figs. 7, 8, and 9) or to repetitive amplitude peaks (Figs. 5 and 6) clearly noticeable between April and October at GOM and KBTI. We already note that the overall low-frequency seismic amplitude at TGO (located in the countryside) is significantly lower than at KBTI (close to Nyiragongo) and GOM (close to Lake Kivu).

Applicability of the SARA method in the VVP

The SARA method was defined by Taisne et al. (2011) for characterizing and locating the seismic signature of magmatic intrusion at the Piton de la Fournaise. The method requires defining the theoretical decay of seismic wave amplitudes along the source-receiver travel path. Such an amplitude-based location approach was originally proposed by Battaglia and Aki (2003) for seismic events and eruptive fissures on the same volcano. After assuming that velocity and attenuation remain constant during the migration and based on a simple attenuation law, Taisne et al. (2011) used the following expression for the seismic amplitude ratio between two stations i and j:

$$\frac{A_i}{A_j} = \left(\frac{r_j}{r_i}\right)^n \exp\left(-B\left(r_i - r_j\right)\right) \tag{1}$$

with

$$B = \frac{\pi f}{Q\beta} \tag{2}$$

where r is the distance of the stations i and j from the source, A is the amplitude at the stations i and j, $n = 0.5$ for surface waves or 1 for body waves, β is the shear wave velocity, Q is the quality factor for attenuation, and f is the frequency.

Johnson and Aster (2005) pointed out the difficulty of estimating the radiated seismic energy in heterogeneous volcanic systems, where the seismic wavefield is constituted by both body and surface waves and where near-surface Earth structures can create strong local site responses. Thus, the SARA technique may be affected by site amplification factors and a non-isotropic wave radiation pattern. Taisne et al. (2011) have hypothesized that the radiation pattern is isotropic for a body wave propagation regime, which allowed them to invert for the depth of the magma propagation based on simple modeling (Eq. 1). They also indicated to be able to locate shallow volcanic tremor after assuming surface wave propagation. In addition, Battaglia and Aki (2003) successfully detected volcanic tremor sources after assuming an amplitude decay of either surface or body waves in a homogeneous medium. More recently, Caudron et al. (2018) applied the SARA approach for tracking the 2014–2015 Holuhraun dike propagation. They analyzed high-frequency body waves (> 2 Hz) because the assumption of an isotropic radiation pattern only holds at sufficiently high frequency due to path effects (Takemura et al., 2009).

Here, we do not indent to locate the tremor sources using the amplitude-based method applied in SARA (i.e., the "full" SARA methodology described in Taisne et al., 2011). Instead, when considering the characteristics of the ambient seismic noise in the VVP ("Overview of the 2-year-long seismic data used" section) and the sparse geometry of the KivuSNet, we rather follow the simpler SARA approach of Caudron et al. (2015) or Tan et al. (2019). The method basically consists of computing ratios of seismic amplitude between station pairs to qualitatively infer temporal and spatial variations of the volcano-related seismicity. This procedure does not correct for potential site amplification factors at each station and therefore implies that the variations of the seismic amplitude ratios can only be discussed qualitatively. Interpreting spatial amplitude variations at low frequency (< 1 Hz) cannot rely on the aforementioned assumption of an isotropic radiation pattern due to path effects and can be affected by the possible source anisotropy. Defining which type of waves dominates the recorded seismic amplitude remains essential for better interpreting the results from SARA and assessing their reliability. Our seismic recordings exhibit low ([0.3–1] Hz) frequency signals triggered by coherent shallow volcanic tremor sources from Nyiragongo and Nyamulagira, generating a wavefield dominated by surface waves (Barrière et al. 2017, 2018). These signals can be compared for instance with the ones observed at Masaya volcano by Métaxian et al. (1997), who detected a continuous and dominant surface waves signature from a shallow seismic source located close to its lava lake conveying a

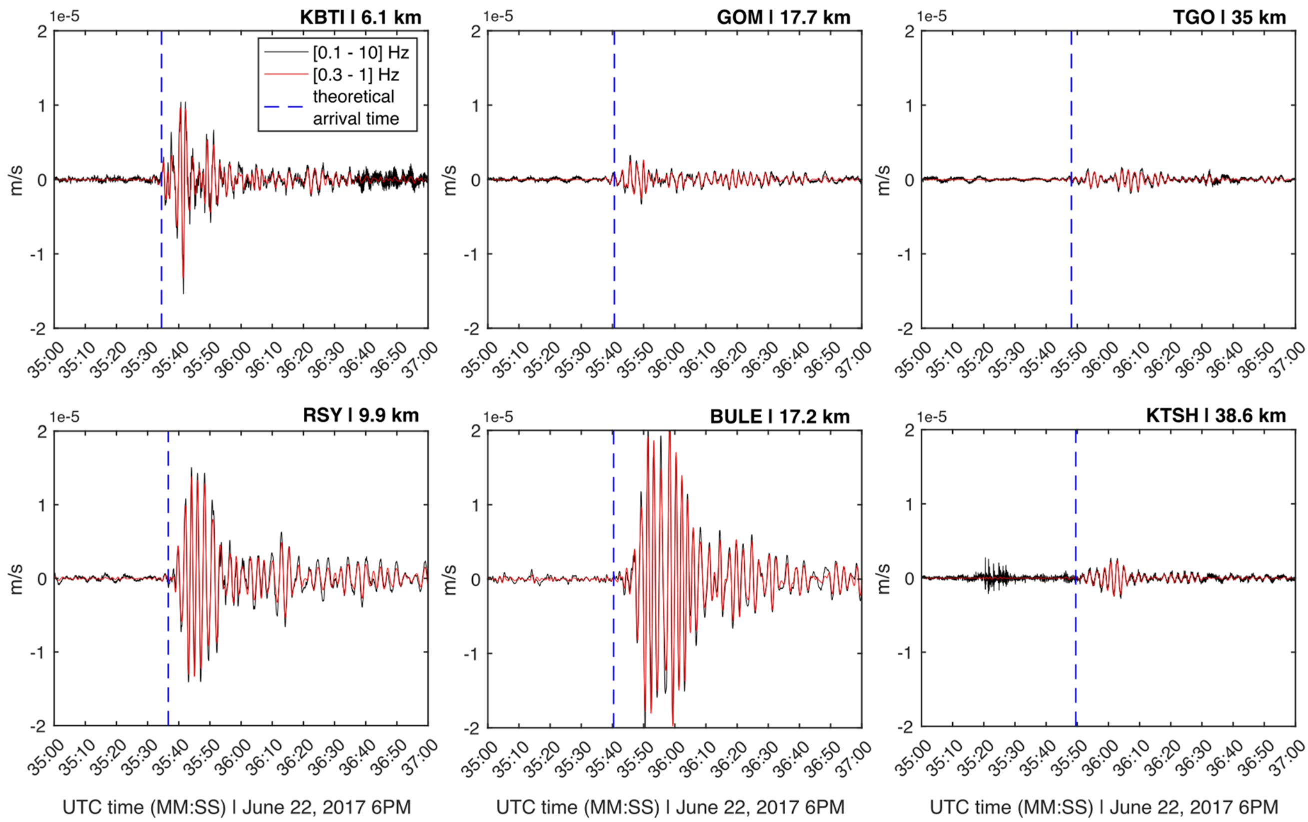


Fig. 3 Two-minute-long seismograms (in 10^{-5} m/s) at KBTI, GOM, TGO, RSY, BULE, and KTSH starting on June 22, 2017, at 6 PM (UTC time) depicting a shallow LP seismic event originating from Nyiragongo's crater. The seismic traces plotted in black are the broadband traces filtered between 0.1 and 10 Hz and the ones plotted in red are obtained with a bandpass filtering between 0.3 and 1 Hz. The dashed blue lines represent the theoretical arrival times of a seismic signal originating from Nyiragongo's lava lake using the surface wave velocity model obtained by Barrière et al. (2017) and KBTI as reference station (i.e., the theoretical arrival time is set to the observed arrival time at this station)

superficial magmatic activity at this volcano at that time. At Piton de la Fournaise, Aki and Ferrazzini (2000) observed low-frequency tremor below 2.5 Hz whose amplitude decay with distance can be fitted by the theoretical decay of surface waves (after correction of site factors).

We illustrate the motivation behind the chosen approach by analyzing a long-period (LP) "lava lake's event" at Nyiragongo occurring on June 22, 2017 (Fig. 3). At that time, only the station RGB was unavailable. Barrière et al. (2018) showed that this seismic signal has a dominant frequency around 0.5 Hz and elliptical particle motion typical of Rayleigh surface wave. It also has an acoustic counterpart and comes from Nyiragongo's crater, thus having all characteristics of a very shallow source generated at the lava lake such as a large explosion. This event can be seen as a discrete form of the shallow tremor from Nyiragongo's lava lake. This continuous tremor is detected across the entire KivuSNet network and is adequately located after assuming a lateral propagation velocity model defined by a simple power-law equation (Barrière et al., 2017). The theoretical travel-times obtained from this velocity model explain the observed arrival times of the LP event (blue dashed lines in Fig. 3), confirming the common origin of the lava-lake tremor and this single LP event. As expected, we observe a pronounced decay of the surface wave amplitude between the closest station to the lava lake (KBTI, 6.1 km away from Nyiragongo's crater), GOM (17.5 km), TGO (35 km), and KTSH (38.6 km). However, we do also note important site effects at RSY and BULE, which are both located in a subsiding area affected by significant CO_2 degassing (Wauthier et al. 2018). It is therefore important to keep in mind these two strong site-dependent effects when analyzing amplitudes from RSY and BULE. Yet, analyzing amplitude ratios in the frequency band [0.3–1] Hz as a function of source-receiver distance remains relevant and should be useful for detecting temporal and spatial variations of magmatic activity in the Virunga.

The SARA processing is performed using the python-based software MSNoise (Lecocq et al. 2014) following the procedure described by Taisne et al. (2011). The continuous seismic amplitudes (envelopes) were computed by taking the absolute value of the analytic signal of the traces

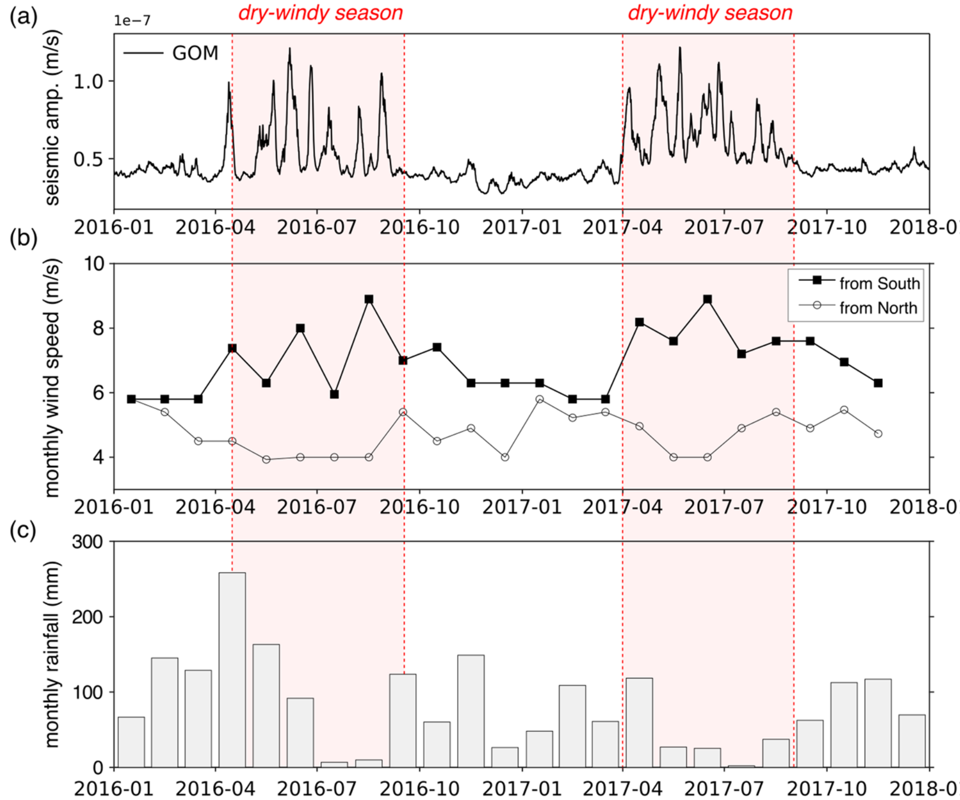


Fig. 4 **a** Two-year-long seismic amplitudes timeseries (7-day median) at GOM seismic station (in 10^{-7} m/s). **b** Monthly wind speed (97.5th percentile per month) split in two dominant wind directions, i.e., coming from the south (black line and squares) and from the north (grey line and circles). **c** Monthly cumulative rainfall data. Meteorological data are collected from a station located at GVO. The red dashed box corresponds to the maximum extent of the dry-windy season inferred from wind and rainfall data

filtered between 0.3 and 1 Hz after removing the instrumental response and using a bandpass, 4-poles zero-phase Butterworth filter. The obtained envelopes were then decimated to 1 min using a median filter in order to remove the transient spikes, and smoothed using a centered moving median of one day. The amplitude ratios for each station pair were computed from the 1-min decimated amplitude time series and smoothed using a centered moving median of 1 day. The choice of the window length for the smoothing operation (i.e., 1 day in this study) depends on targeted sources. The network characteristics (in terms of stations distribution and performance) control the strength of the temporal smoothing needed. For example, with a dense network around the main edifice allowing high temporal/spatial resolution, Taisne et al. (2011) took 5 min for reducing the influence of big earthquakes in the amplitude ratios before the signal inversion for tracking magma propagation. On another hand, in a more qualitative approach using a sparser network, Caudron et al. (2015) chose a value of 6 h to capture the main characteristics of stress migration at the Klyuchevskoy volcano group. In our study, we tested several window sizes to better gauge the influence of this critical smoothing operation on the final result and interpretation. It appears that a 1-day smoothing window is needed to better visualize and understand significant changes in seismic amplitude ratio across the VVP. A 1-day window allows to capture the main fluctuations of the continuous tremor activity in the VVP while shorter windows (e.g., 10 min) emphasize erratic, non-volcanic amplitude variations, such as the Lake Kivu's microseisms discussed later. For the 2-year-long time series plotted in Fig. 2c, an additional 7-day moving median filter is applied to capture the main amplitude variations over this long-time frame, which are analyzed in more detail in Figs. 4, 5, 6, 7, 8, and 9.

Variations of low-frequency seismic amplitudes in the VVP

Long-term (seasonal) variations due to Lake Kivu microseisms

Figure 4 a shows the 4-year-long GOM time series (7-day median) plotted in Fig. 2c. In Fig. 4b, c, we provide monthly wind speed and monthly cumulative rainfall retrieved from a meteorological station also located at GVO. The wind speed dataset is split into winds coming from the south (mostly Lake Kivu) and from the north (inland). In order to only highlight the highest wind speeds, we selected the 97.5th percentile per month. The highest wind speeds occur during low rainfall periods, in accordance with observations at Lake Kivu (Kranenburg et al. 2020) or at another African Great Lake, Lake Tanganyika, located about 200 km southward from Goma

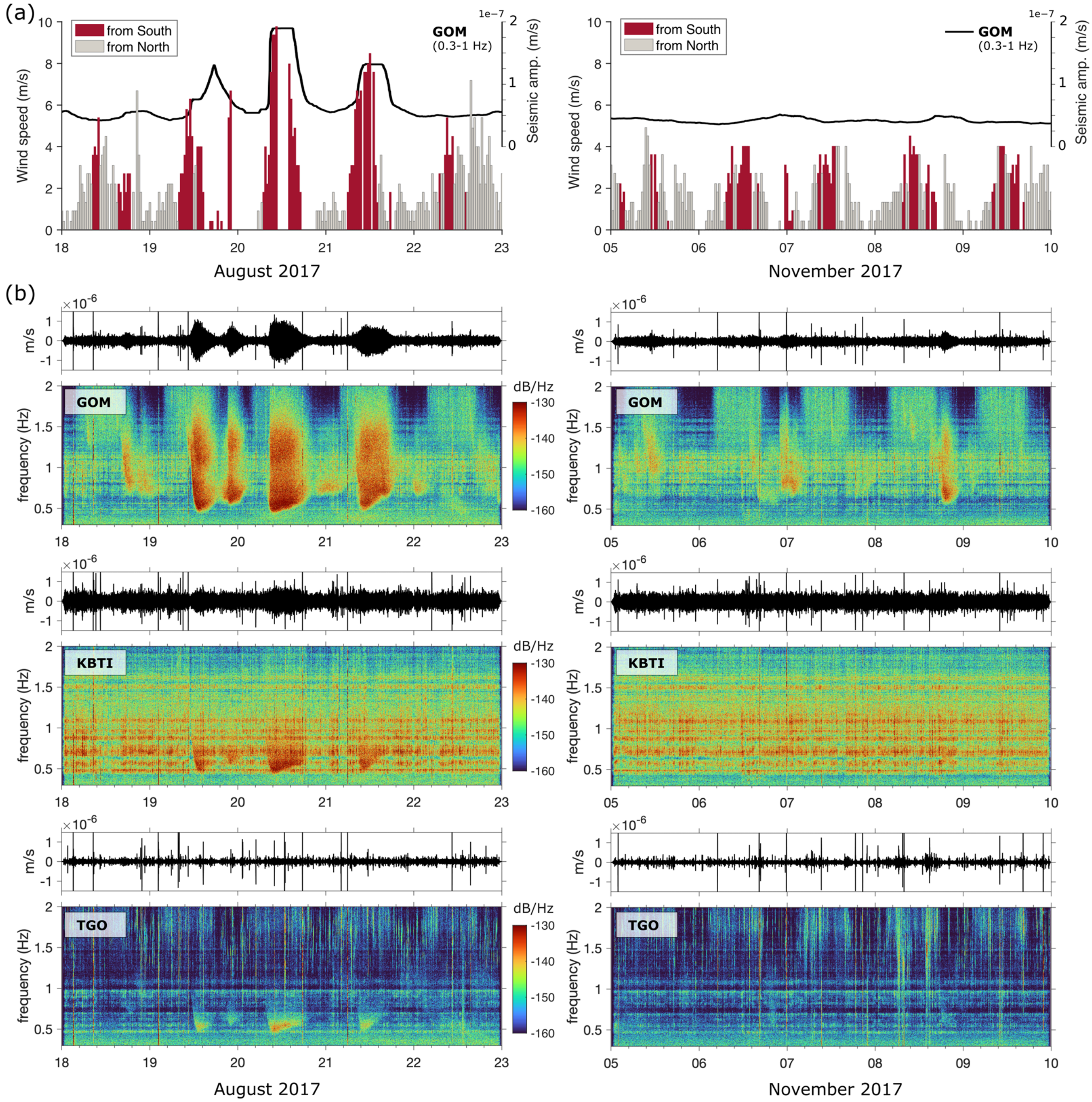


Fig. 5 **a** Wind speed and seismic amplitudes in 10^{-7} m/s (GOM station) comparison at GVO between two 5-day periods during the dry season (18–23 August 2017; left) and the wet season (5–10 November 2017; right). The wind speed data (in m/s) has a temporal resolution of 30 min and are split in two dominant wind directions, i.e., coming from the south (red histograms) and from the north (grey histograms). **b** Filtered seismic traces (in 10^{-6} m/s) in the frequency band [0.3–2] Hz and corresponding spectrograms (in dB/Hz) at GOM, KBTI, and TGO stations for the same time periods depicted in **a**)

(Docquier et al. 2016). The dry season in the Lake Kivu region generally starts in June and ends in September (Thiery 2015), which is confirmed by the local rainfall data obtained at Goma (Fig. 4c). This bimodal seasonal cycle is also obvious through the fluctuations of wind speed associated with the lake breeze (i.e., from south) starting to increase in April, which is 2 months earlier than the start of the dry season inferred from the rainfall. On a monthly basis (Fig. 4b), the winds coming from the South are also stronger than those coming from the North (i.e., land breeze) all year long. Kranenburg et al. (2020) pointed out strong variations of the preferential wind speed

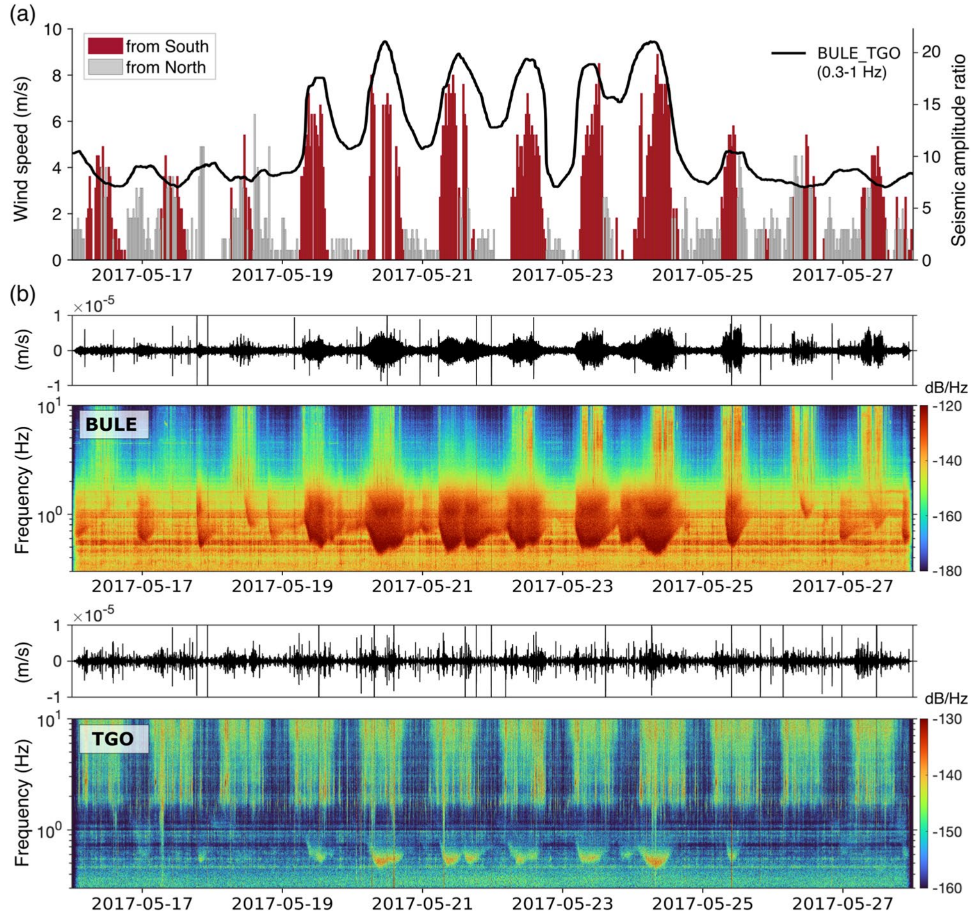


Fig. 6 **a** Comparison between the seismic amplitude ratios for a station pair (BULE/TGO) and wind speed (red histograms for wind coming from the south and grey histograms from the north) obtained at GVO at the beginning of the 2017 dry season. **b** Filtered seismic traces (in 10^{-5} m/s) in the frequency band [0.3–10] Hz and corresponding spectrograms (in dB/Hz) at BULE and TGO stations for the same time periods depicted in **a**)

direction depending on the location in the Lake Kivu region. From this study based on 2013–2016 data from a measurement station off the coast of the city of Gisenyi (Rwanda) next to Goma, the dominant wind direction is from the north and the wind speed range of the lake breeze (from south) is overall higher. Comparing Fig. 4 a and b, we observe here that the long-term variations of the seismic amplitude follows at first order the seasonality of the Lake breeze, thus being potentially at the origin of unwanted seismic noise in the considered frequency range.

Wind is known to be an important factor affecting the seismic noise at frequencies above 2 Hz (Smith and Tape 2019). Tan et al. (2019) noted that this spurious noise source can hamper the use of SARA at high frequencies. However, in the frequency band of interest (0.3–1 Hz), this effect should be mitigated. A strong local site effect might be an explanation but these marked long-term patterns are also observed at KBTI station (Fig. 2c). Barrière et al. (2019) also pointed out such seasonal variability of the seismic noise below 2 Hz after analyzing data from the station BULE located on the shore of Lake Kivu, close to the station GOM (see stations map in Fig. 2a). Following recent studies about the generation of microseisms from Great Lakes across the globe (Xu et al. 2017; Anthony et al. 2018), we assumed that this seasonality in the frequency band [0.5–2] Hz was most likely due to nearby Lake Kivu. Despite some potential similarity with the shoaling process of the primary ocean microseisms or the wave-wave interaction process of the secondary ocean microseisms, it is still unclear what exact mechanisms generate such short-period microseisms (Anthony et al. 2018) and this question remains beyond the scope of this paper. The key role of wind speed variations in modulating the amplitude of the Lake microseisms appears however obvious, similarly to the ocean microseisms (Kerman and Mereu 1993). Moreover, as evidenced in Fig. 4b, a surface wind speed coming from the south with respect to GVO (lake breeze) higher than from the north (land breeze) could enhance the coupling into seismic energy during swell periods in Lake Kivu.

In order to support this hypothesis, we bring in the following section a new detailed investigation between wind speed and seismic amplitude data in the Virunga. Beyond the observed seasonal fluctuations, it is well known that the wind speed variations are also diurnal (Thiery 2015; Kranenburg et al. 2020). Thus, we analyze two selected periods of a few days when seismic amplitude and wind speed can be compared with high temporal resolution. These specific periods are plotted in Figs. 5 and 6.

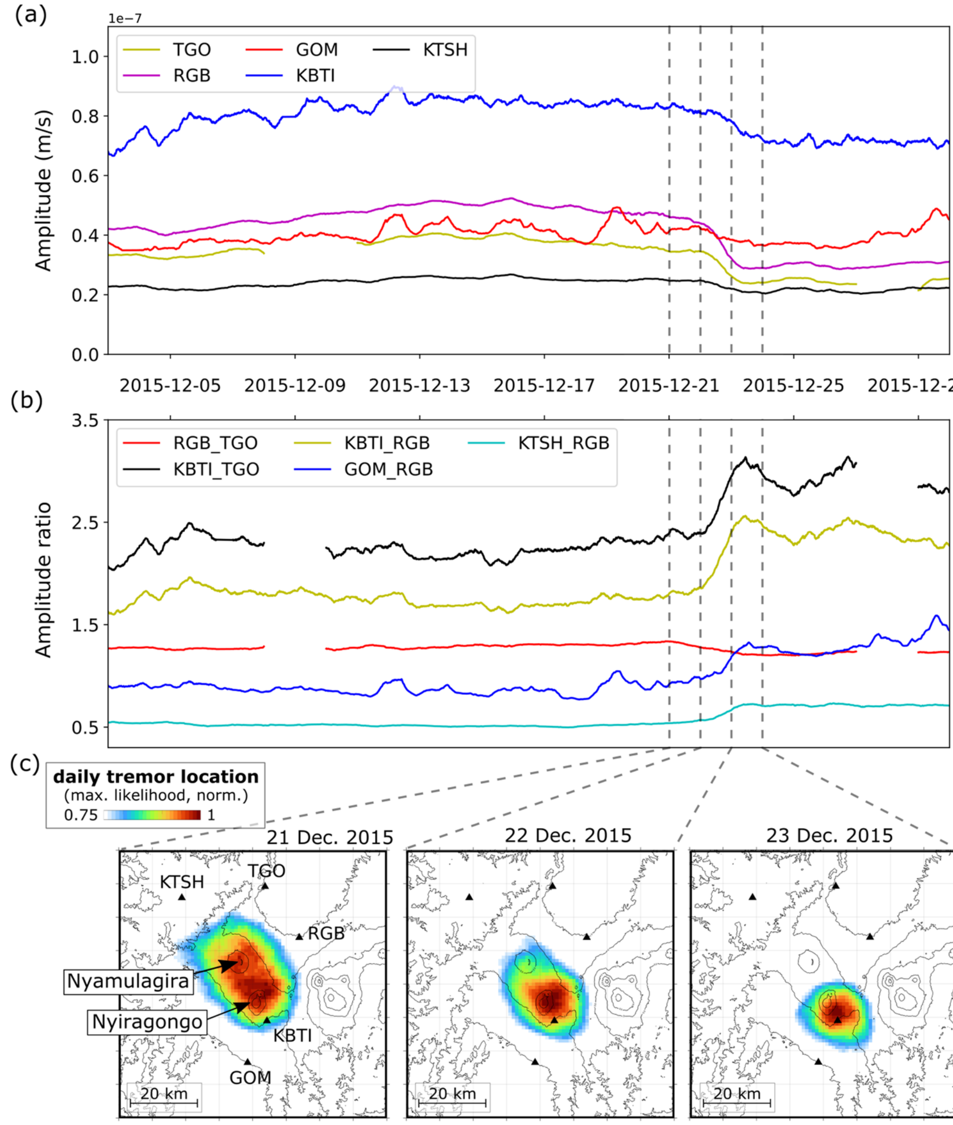
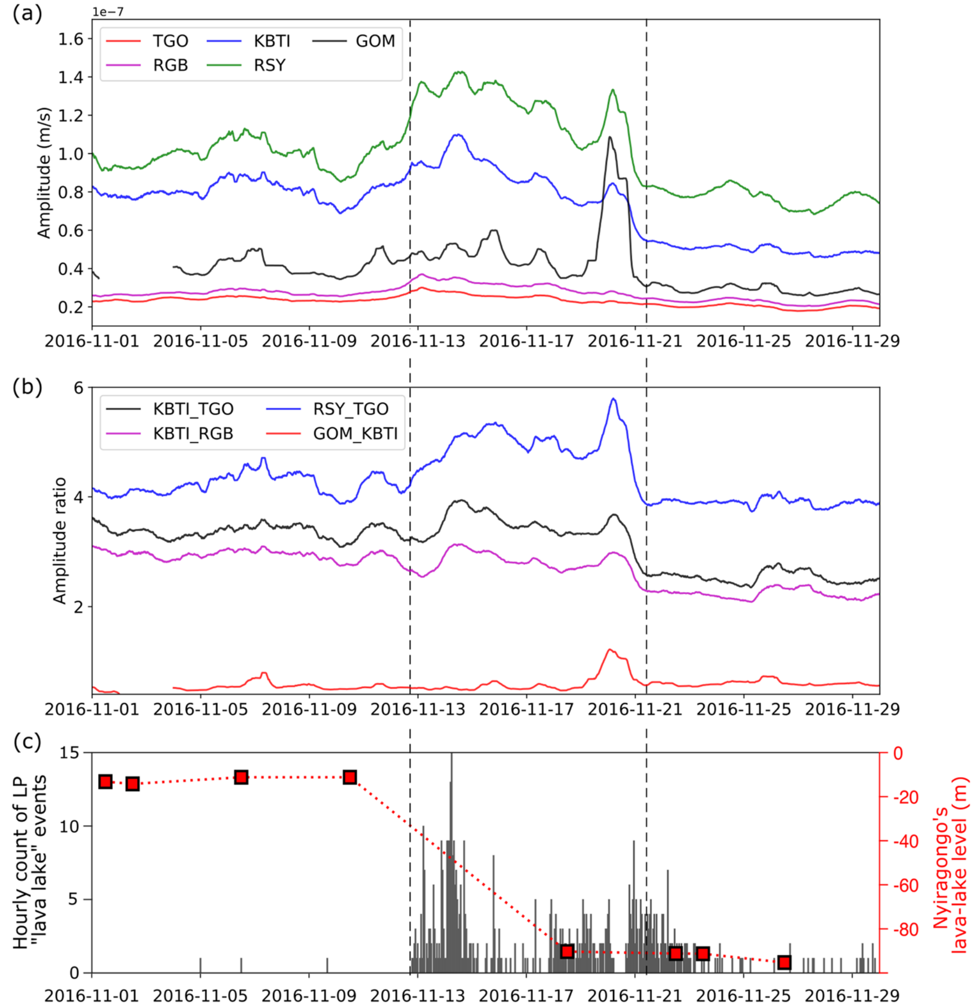


Fig. 7 (a) Seismic amplitude (in 10^{-7} m/s) at TGO, RGB, GOM, KBTI, and KTSH between 3 and 30 December 2015. (b) Amplitude ratios for the station pairs RGB/TGO, KBTI/TGO, KBTI/RGB, GOM/RGB, and KTSH/RGB. (c) Daily location maps of the dominant continuous shallow volcanic tremor sources in the VVP between 21 and 23 December 2015. Both seismic amplitude timeseries (a, b) and location maps (c) are obtained from seismic signals filtered in the same frequency band [0.3-1] Hz (see text for details)

Short-term (diurnal) variations due to Lake Kivu microseisms

Figure 5 compares two 5-day periods during the dry season (18–23 August 2017) and the following wet season (5–10 November 2017). Figure 5 a represents the wind speed with a temporal resolution of 30 min coming from the south (lake breeze) and from the north (land breeze). The seismic amplitude at GOM is plotted against these histograms. A striking observation is that the seismic amplitude peaks in August 2017 coincide with the highest wind speed from the south. As described in the "Applicability of the SARA method in the VVP" section, the sliding window used is 1 day and the resulting seismic amplitude time series are strongly smoothed. Therefore, it is also interesting to plot the full seismic records and their corresponding spectrograms to better gauge the temporal relation between the wind speed and the level of seismic noise. In Fig. 5b, we plot the spectrograms for the stations GOM, KBTI, and TGO for the two selected periods, pre-filtered in the frequency band [0.3–2] Hz. Seismic traces (in m/s) and spectrograms (in dB/Hz) at GOM, KBTI, and TGO are plotted with the same scale. The continuous (background) seismic tremor from Nyiragongo's lava lake is seen on all records, notably at KBTI across the full frequency range [0.4–2] Hz. On top of that, numerous transients are detected, which are due to the anthropogenic activity in most cases (see TGO above 1.5 Hz). Some local and regional earthquakes simultaneously recorded at all stations are also detected. Finally, the Lake Kivu microseisms are obvious on the August 2017 spectrograms and form bursts of seismic energy lasting a few hours between 0.5 and 2 Hz and concentrated around 0.5–0.7 Hz at KBTI and TGO. The reduced frequency range and amplitude for

Fig. 8 **a** Seismic amplitude (in 10^{-7} m/s) at GOM, KBTI, RGB, RSY, and TGO between 1 and 30 November 2016. **b** Amplitude ratios for the station pairs KBTI/TGO, KBTI/RGB, GOM/KBTI, and RSY/TGO. **b** Left, hourly count of LP events originating from Nyiragongo's lava lake (from Barrière et al., 2018). Right, lava lake level with regards to the lava lake rim (red squares connected by a dashed line) estimated from SAR space-based measurements (Barrière et al., 2022). The magmatic event corresponding to the drop of the lava lake level is encompassed between the two black vertical dashed lines (12–21 November)



stations further away from the Lake Kivu (KBTI and TGO) confirm a source region closer to GOM. Such patterns are recorded all year long and are more prominent during the dry season, being responsible for the seasonal amplitude increase at GOM observed in Fig. 4a. The case of November 2017 illustrates an example of low wind speed from both directions (north and south). Some weak microseisms decorrelated from the wind speed measured at GVO are recorded at GOM only, thus conveying again a source region closer to this station.

The seismic records at BULE, which is also on the shore of Lake Kivu close to the station GOM (see Fig. 2a), often exhibits similar signature of lake microseisms (Barrière et al. 2019). In Fig. 6, we compare the seismic amplitude ratio between BULE and TGO and the wind speed obtained at GVO. A time period of 12 days is selected between May 16 and 28 at the beginning of the 2017 dry season. Here, the seismic traces and the spectrograms are filtered between 0.3 and 10 Hz, which allows for a better visualization of the influence of the anthropogenic noise above 1.5 Hz. Once more, we observe an excellent temporal agreement between the strongest wind speed from the south and the low [0.3–1] Hz frequency seismic amplitude peaks related to the lake microseisms. The amplitude ratio BULE/TGO (Fig. 6a) shows clear diurnal variations synchronous with the occurrence of strong southerly winds while the attenuation of the signal between BULE and TGO is obvious, thus conveying a source region closer to BULE. Only the strongest microseisms (between May 19 and 25) are detected at TGO between 0.5 and 0.7 Hz. The correlation observed between the seismic records at BULE and the wind speed measured at GVO implies that the microseisms recorded at GOM and BULE share the same source, though the variability of the wind speed along the shore of the Lake Kivu can be significant (Kranenburg et al. 2020). It also emphasizes that the wind speed recorded at GVO is well representative of the lake breeze at the origin of the Lake Kivu microseisms recorded by

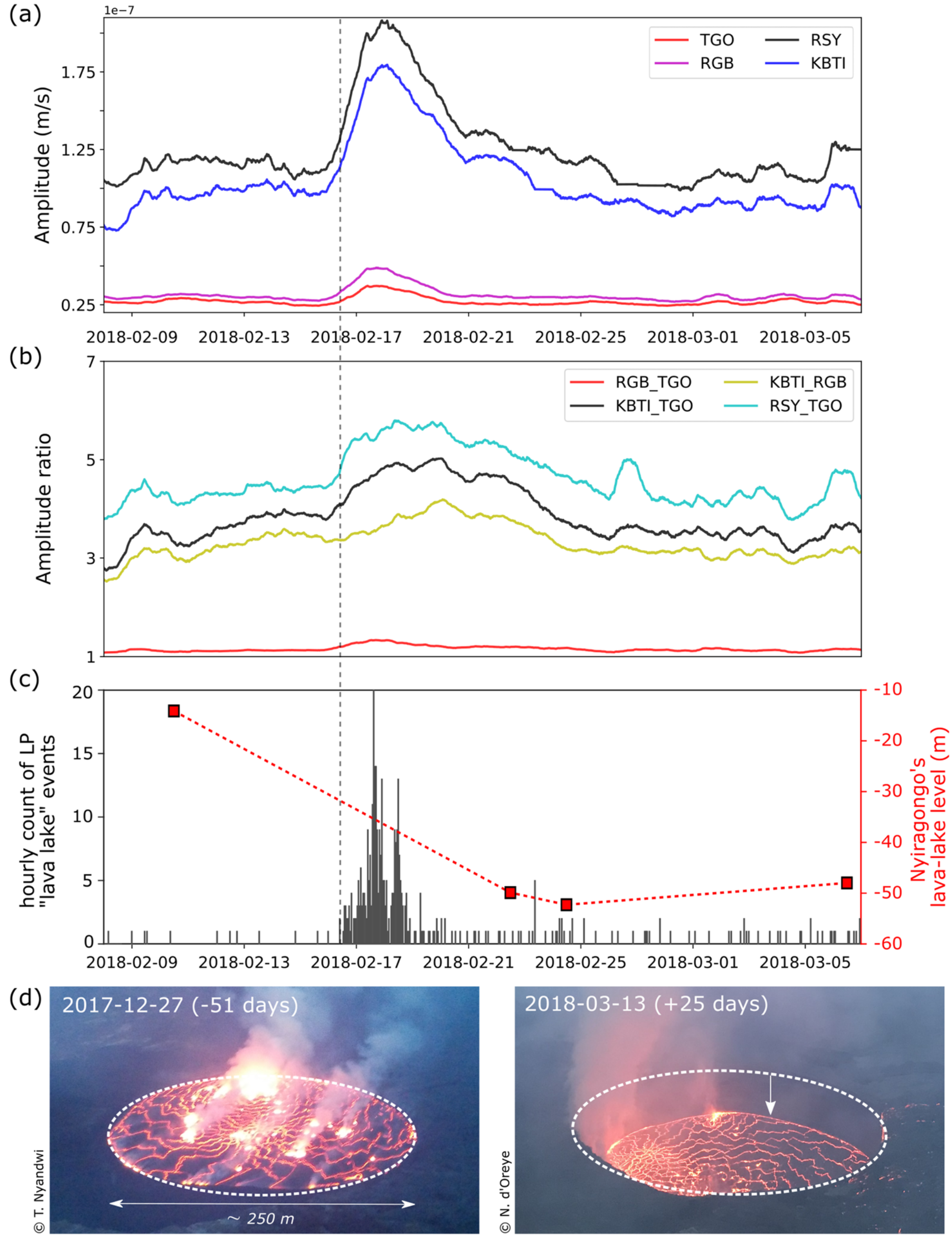


Fig. 9 **a** Seismic amplitude (in 10^{-7} m/s) at TGO, RGB, KBTI, and RSY between 8 February and 7 March 2018. **b** Amplitude ratios for the station pairs KBTI/TGO, KBTI/RGB, RSY/TGO, and RGB/TGO. **c** Left axis and grey bars: hourly count of LP events originating from Nyiragongo's lava lake. Right axis and red squares: lava lake level (with regards to the lava lake rim) estimated from SAR space-based measurements (Barrière et al., 2022). The start of the magmatic event corresponding to the drop of the lava lake level is identified by the black vertical dashed line on 16 February 2018. **d** Two pictures of Nyiragongo's lava lake before (− 51 days) and after (+ 25 days) the lava lake drop on 16 February 2018

the seismometers deployed on its shore. Nonetheless, other minor microseismic events observed at BULE are not clearly associated with variations of the wind speed measured at GVO (see before May 19 and after May 26), similarly to the observations of weak microseisms at GOM in November 2017 (Fig. 5). Thus, the source at the origin of the lake microseisms cannot be explained solely by an increasing lake breeze even if the highest wind speed from the lake region appears to play a fundamental role. The source of these signals appears to be a complex process and its mechanism remains elusive, though our analysis paves the way for further investigations comparing the atmospheric changes and the lake dynamics with seismic records around the Lake Kivu.

Detecting the intermittent sources of tremor at Nyamulagira

A typical case of magmatic movements detected by SARA in the low-frequency band is presented in Fig. 7. This kind of short-term event lasting approximately 1 day took place from 22 to 23 December 2015. Amplitudes at stations to the north of VVP near the Nyamulagira volcano (RGB, TGO, KTSH) have decreased much more than at the southern stations (KBTI, GOM). For example, the amplitude at RGB decreased about twice as much as at KBTI (Fig. 7a). Hence, the amplitude ratios for pairs using the northern stations as reference (denominator) clearly increased (Fig. 7b) while the ratio between two northern stations (RGB/TGO for instance) does not exhibit any significant variation. In that case, one can only observe that the amplitude decay is slightly stronger at TGO than at RGB. On another hand, the ratio KBTI/TGO shows a stronger decay at TGO. Since all stations recorded an amplitude decrease, stronger in the north than in the south, this suggests that a persistent source in the northern part of the region, possibly associated to Nyamulagira, stopped around 23 December.

This hypothesis is further supported by other independent observations suggesting changes in the Nyamulagira eruptive activity. The volcanic tremor location obtained by Barrière et al. (2017) in the VVP following the interferometry approach of Ballmer et al. (2013) helps to refine the observations made with SARA (Fig. 7c). On these daily location maps, the maximum location likelihood for the sources of continuous shallow tremor is highlighted in red. Since we applied a grid-search strategy assuming tremor sources as point sources, multiple active sources during a day could result in multiple regions colored in red. The accuracy of the final solution is constrained by the network layout and the ability to detect coherent noise sources at each station, enhanced by specific pre-processing procedures of the continuous records (see Barrière et al. 2017 for more details). Thus, in Fig. 7c, the exact location (grid point) of the global maximum is not relevant. Instead, these daily location maps mainly tell us if the dominant tremor source region in the VVP is predominantly located at Nyamulagira, Nyiragongo or both. Hence, on 21 December, continuous tremors were both detected at Nyamulagira and Nyiragongo. Between 22 and 23 December, we observed a dominant source region toward Nyiragongo, reflecting the lava lake activity. After this date, the background persistent signature of Nyiragongo's lava lake, as illustrated by the tremor location on 23 December 2015 in Fig. 7c, persisted up to the 22 May 2021 when the lava lake drained during the last flank eruption at Nyiragongo (Smittarello et al. 2022).

A wrong interpretation of the tremor location maps depicted in Fig. 7c would be a shift of the tremor source due to magmatic movement from Nyamulagira to Nyiragongo. Instead, the SARA analysis indicates that a shut-down of the powerful shallow tremor source occurred at Nyamulagira. The surface effusive activity at Nyamulagira persisted a few months after this event in December 2015. Barrière et al. (2017) showed that this shallow signal was replaced by the occurrence of deeper LP events having similar frequency content. However, in the [0.3–1] Hz frequency band considered, the continuous amplitude ratio time series across the network did not exhibit this deeper seismic signature. Activity depicted in the time series is rather dominated by the Nyiragongo shallow persistent tremor due to its lava lake activity. Because these shallow tremor sources are very energetic when active lava lakes are present both at Nyiragongo or Nyamulagira, a change in depth as highlighted at Nyamulagira with a tremor-LP transition requires complementary methods to be detected (e.g., detection/location of single events, template matching of repetitive clustered events). Together with the SARA-based results, these complementary observations can be interpreted as a sudden decrease in magmatic activity in the shallow part of the Nyamulagira edifice.

Monitoring the background lava-lake tremor at Nyiragongo

Figures 8 and 9 are related to magmatic events evidenced by SARA in November 2016 and February 2018, respectively. Looking at Fig. 2c, these two amplitude variations are the strongest ones recorded at KBTI during the selected 2-year-long period. An interesting pattern in Fig. 2c between KBTI, GOM, and TGO is the clear amplitude decay between these three stations, corresponding to an increasing distance from Nyiragongo. We focus in this section on these two specific events to support the hypothesis that we detect some relevant changes at Nyiragongo.

The November 2016 event (Fig. 8) lasted approximately 9 days. At the beginning of the event on November 12, we observe increasing amplitudes at the southern (GOM, RSY, KBTI) and northern (RGB and TGO) stations further away from Nyiragongo. The largest amplitudes are observed at the two stations near Nyiragongo (RSY and KBTI) (Fig. 8a). From November 14 to 21, all amplitude timeseries decrease, then stabilize. The overall level of seismic amplitude at all stations is significantly lower after than before November 21 (up to twice lower than the maximum reached a few days before). There is also a large peak the day before November 21, which is much stronger at GOM and RSY than at KBTI while it is barely noticeable at northern stations RGB and TGO.

The amplitude ratio between stations located close and far from Nyiragongo help to better understand the overall trend of amplitude variations over the whole month as well some changes more limited in time such as the large peak on November 20. Three amplitude ratios plotted in Fig. 8b compare stations close to Nyiragongo (KBTI, RSY) and further away (TGO, RGB). A fourth ratio compares GOM on the shore of Lake Kivu with KBTI on the flank of Nyiragongo. The three ratios between "Nyiragongo's stations" (KBTI, RSY) and "northern stations" (TGO, RGB) depict roughly the same pattern, though more prominent for the station pair RSY-TGO: a rather constant trend during the week before November 12, a smooth increase and decrease between the 12th and 19th, then a marked peak ending with a significant decay reaching a new lower constant level. This new seismic amplitude level is the lowest one ever recorded during the full 2-year period (see Fig. 2c). Since these ratios closely follow the trend of the seismic amplitude curves at KBTI and RSY, we can infer that the main amplitude variations are due to changes close to these stations, that is close or at Nyiragongo. The ratio GOM-KBTI brings another piece of information where the most prominent feature is the large peak on November 20. It is clear that this sharp increase of amplitude ratio between GOM and KBTI indicates a source predominantly located to the south toward Lake Kivu, thus suggesting lake microseisms. This is confirmed by looking at the decaying amplitude of this large peak compared to the background level over an increasing distance from the Lake Kivu (i.e., GOM > RSY > KBTI). In turn, we can conclude that the main amplitude change of magmatic origin only occurred on November 12-13 and that the following days exhibited a progressive decrease of the seismic tremor amplitude overlapped on November 20 by a non-magmatic event.

In Fig. 8c, two other independent observations confirm this interpretation: the level of Nyiragongo's lava lake obtained from space-based measurements (Barrière et al. 2022) and the hourly count of LP seismic events identified as being generated by the lava lake spattering activity (Barrière et al. 2018). On 12 November, a large drop (~ 80 m) of the lava lake level occurred in response to a deep dyke magmatic intrusion, which was inferred from the detection and location of a synchronous seismic swarm of high frequency events at large depth (> 10 km b.s.l.) (Barrière et al. 2019). The variations of the continuous seismic amplitude in the frequency range [0.3–1] Hz as plotted in Fig. 8a only reflect the more intense spattering activity at the surface of the lava lake as evidenced by the occurrence of numerous LP seismic events at the lava lake location plotted in Fig. 8c (Barrière et al. 2018). It should be noted that these particular LP events also have a counterpart acoustic signature, thus confirming a very shallow source process. As exemplified for Nyamulagira in Fig. 7, the SARA results in this low frequency band thus highlight surface processes and additional observations are needed in order to infer the complete picture of the targeted magmatic event.

The February 2018 event described in Fig. 9 is due to a similar drop of the lava lake level in response to a deep magmatic movement (Barrière et al. 2022). The seismic amplitudes at KBTI and RSY clearly show a tremor peak lasting a few days (17–20 February) related to the more intense surface activity of the lava lake during its drop, as confirmed again by the large occurrence of LP "lava lake" seismic events (Fig. 8c). This peak is well noticeable on all stations and the amplitude ratios between southern (KBTI, RSY) and northern stations (RGB, TGO) help to constrain changing activity at Nyiragongo. The increasing ratio RGB/TGO also allows to infer a changing activity at Nyiragongo since RGB is the closest station of the pair (but still more than 20 km away from the central crater). Two pictures of the lava lake before and after the ~ 40-m drop on February 17 are shown in Fig. 9d to illustrate what changing surface activity within Nyiragongo's crater these amplitude peaks convey.

Conclusion and perspectives

Former studies using the SARA method, either through qualitative (i.e., trend of the amplitude ratios) or quantitative (i.e., source location) approaches, generally focused on volcano-tectonic signals in a high frequency band (above 2 Hz) during magmatic migration (e.g., Caudron et al. 2015, 2018, Tan et al., 2019). Considering the specificities of the ambient seismic noise sources in the Virunga, we provided here a benchmark to assess the application of the SARA technique in monitoring Nyamulagira and Nyiragongo volcanoes at low frequency (0.3–1 Hz). We show how we can use it to highlight temporal changes of shallow tremor sources at long distance (several tens of kilometers).

We identified that the nature of the volcanic seismicity in the VVP and the distribution of the available stations in the region (i.e., no dense network in close vicinity to both volcanic edifices) are best suited to detect magma movements using seismic amplitude ratios under 1 Hz, this low-frequency band being rich in information related to the superficial magmatic activity. The seismic wavefield below 1 Hz is dominated by the propagation of surface waves from persistent volcanic sources conveying summit eruption dynamics at both volcanoes. We qualitatively discuss the temporal and spatial variations of the seismic amplitude ratios in the VVP assuming isotropic radiation pattern and neglecting site effects. We showed that this simple approach applied in the low frequency range remains relevant since the decay of amplitude from the source (i.e., Nyiragongo, Nyamulagira, Lake Kivu) is well noticeable at the considered stations. However, strong site effects at two stations (RSY, BULE) are also noticed, which hamper the straightforward analysis of amplitude ratios involving one of these stations. We used more than two years of seismic data recorded by telemetered stations from the KivuSNet broadband seismic network. The technique seems sensitive to the intermittent sources of tremor at Nyamulagira volcano and to amplitude variations of the background tremor at Nyiragongo volcano. The six stations used in the present study correspond to the best ones available at that time in terms of station performance, data availability and distance to the volcanoes (see Oth et al., 2017). To date, in addition to a station deployed at the summit in early 2018, these stations remain among the most relevant for the monitoring of Virunga volcanoes. KBTI station best tracks the large level fluctuations in the lava lake at Nyiragongo. For Nyamulagira, RGB and TGO stations can be used to track tremor changes. However, it is noteworthy that TGO does not exist anymore (withdrawal of UN camp where the station has been installed since September 2015), which leaves a gap at the North of the Virunga.

Records at GOM and BULE stations located on the shore of Lake Kivu can be largely influenced by microseisms originating from Lake Kivu. As observed for other Great Lakes around the world (Xu et al., 2017), this effect decreases as the distance to the lake increases. The dominant non-magmatic source detected by SARA in this low-frequency band (i.e., < 1 Hz) is related to the seasonal patterns of lake-generated microseisms, which are studied here in detail for the first time at an African Great Lake. On this particular aspect, this study brings additional clues about the source mechanisms as being strongly related to the lake breeze and swell periods. One should note that analog records (from Kinemetrics instrument) at BULE station were claimed to exhibit volcanic tremors for several months prior to 2002 Nyiragongo eruption while synchronous records from the other available station located at the North of Nyiragongo did not record any tremor (Kavotha et al. 2002). In light of the results presented here, one can question whether diurnal to seasonal variations of short-period Lake Kivu microseisms were also potentially recorded at that time at BULE station.

In the context of real-time monitoring, we thus identify the main limitation of the method in this frequency band as being influenced by lake microseisms, which are associated predominantly to southerly winds over Lake Kivu. This effect is more pronounced during the dry season and is dominant for stations deployed close to the shore of Lake Kivu. These seasonal to diurnal seismic amplitude variations can mask volcanic signals since the microseismic signature can remain significant for stations closer to the volcanic edifices like RSY and KBTI, both located less than 15 km away from the Lake Kivu. This also implies that interpreting signal at a single station during these unfavorable periods should be done with caution. The SARA approach combining records at different locations is of particular interest in this case. Having several stations located over an increasing distance to the lake allows gauging easily the most likely source region between Lake Kivu's microseisms and Nyiragongo/Nyamulagira's volcanic tremors. The main advantage of this method is thus its ease of implementation and interpretation. In this context, it offers the possibility of detecting changes in the volcanic tremors caused by unrest at Nyamulagira or Nyiragongo. It is also efficient in detecting major variations related to eruptive dynamics at both volcanoes and can provide decisive real-time information from limited field records (i.e., a few station pairs), as it may happen for volcanoes monitored with ground sensors deployed in remote areas. Considering its simplicity, computing continuously the seismic amplitude ratios between relevant pairs of stations constitutes an interesting complementary tool to the Goma Volcano Observatory for monitoring the summit effusive activity at both volcanoes, alongside other monitoring solutions.

Finally, it is worth noting that the work presented here was completed before the intense seismic crisis associated with the dyke intrusion occurring during the last May 2021 flank eruption at Nyiragongo and remarkably well recorded by the seismic network KivuSNet network over an entire week (Smittarello et al. 2022). In turn, we did not analyze in this paper this particular period, which will be dedicated to further investigations. In that case, the more standard approach of the SARA technique focusing on high-frequency volcano-tectonic signals could be well suited to track the progression of this major dyke intrusion with the KivuSNet available at that time. If possible, in the future, a denser deployment of stations around the edifices would be obviously beneficial for applying the full SARA methodology for tracking magma movement in the VVP.

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Availability of data and material Data archiving and accessibility from KivuSnet is ensured through the GEOFON program of the GFZ German Research Centre for Geosciences (https:// doi.org /10.14470/XI058335) under the KV FDSN code (http://www.fdsn.org/networks/detail/KV/).

Code availability The MSNoise software is available at https://github.com/ROBelgium/MSNoise.git.

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Declarations

Conflict of interest The authors declare no competing interests.

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