American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)

ISSN (Print) 2313-4410, ISSN (Online) 2313-4402

http://asrjetsjournal.org/

Classification of Volcanic Earthquakes Observed at Nyamulagira and Nyiragongo Volcanoes Reference on Frequency Analyses and its Implication in Volcano Monitoring

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Abstract

Identification of the types of seismic signals is the basic of the seismo-volcano analysis, because it allows to have information on the magmatic activity prevailing in the crater. Modern analysis for this work identifies the frequency observed in the evaluation of the signals that can lead to a proper classification following groups arranged in specific spectral bands. This frequency analysis was applied to seismic data that preceded the eruption of Nyamulagira Volcano of 6 November 2011 and the persisted lava lake within Nyiragongo Volcano. The data analyzed covered a period of two years, from January 2010 until November 2011. The work consisted to analyze the frequency content of the signals and to deduce the type of the signals reference to the general classification made by Lahr and his colleagues. [1], Miller and his colleagues. [2] and White and his colleagues. [3]. The work resulted on a classification ranging signals into 5 groups including: (1) Earthquakes whose frequency band row from 10 Hz and over, which were identified as volcano-tectonic earthquakes or A-Types, (2) Earthquakes whose frequency band row between 3 and 10 Hz identified as Hybrid earthquakes or B-Type earthquakes, (3) Earthquakes whose frequency band row between 1 and 3 Hz identified as Long Periods earthquakes or C-type earthquakes, (4)) Earthquakes whose frequency band row between 0.25 and 1Hz identified as Very Long Period, VLP earthquakes and (5) Continuous signals marking the same values as the Long Period earthquakes identified as volcanic tremors.

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It was eventually found that swarms of Long period and hybrid earthquakes are those related to magmatic intrusions, and thus can lead to volcanic eruptions. At other hand, there are only VLP and A-type earthquakes which are observed in the period of persisted Lava Lake. This classification can be used in the monitoring of the volcanoes.

Keywords: Frequency band; Types of earthquakes; Nyamulagira Volcano; Nyiragongo Volcano.

1. Introduction

The volcano Nyamulagira and its neighbor Nyiragongo in the Democratic Republic of Congo, are located inside the western branch of the East African Rift [1] and more specifically in the western part of the Virunga volcanic chain. Nyamulagira is the most active volcano of the African continent with a rate of one eruption each 2 or 3 years in these recent decades [2]. Eruptions from Nyamulagira are feed by dykes and cracks, and many of them come out of the flanks of the Volcano [1]. The study of the seismicity at active volcanoes is a very important tool because it is the main sign informing about the state of the magmatic activity which passes inside the volcano. Identifying types of earthquakes which occur at a volcano is the first point and remains ahead of all the points that help to seismo-Volcanologists to understand seismic activity of a volcano.

Analysis of ``volcanic earthquakes'' recorded by many scientists at Japanese volcanoes in 1960s, evidenced the great potential of seismic observations, and quickly, it became the main instrument for monitoring volcanoes. Reference [3] , who established the Asama Volcano Observatory in Japan, proposed the first classification of volcanic ``earthquakes'' according to their location, their relationship to eruptions and the nature of the earthquakes recorded. With time, many new volcano observatories born in volcanic areas around the world, and after Reference [3] 's pioneer work which is still a reference up to today, many classifications have been proposed, being generally focused to classify and describe typical events from specific volcanoes and/or based on seismogram appearance [4], including the frequency content of the signal in the classification of the events. This feature, joined with the formers Reference [3]'s and Latter's classification schemes, sets up the more general base of classification currently used in most volcano observatories to discriminate volcanic seismic signals at first glance. In this paper, the seismic signals collected at the digital stations of Kibumba (at about 18Km east of Nyamulagira and at about 4 Km East of Nyiragongo) and of Katale (at about 5 Km North-east of the two volcanoes), were analyzed in order to assess their frequency content and lead to a modern classification which can help the good monitoring of these volcanoes.

2. Seismic activity of Nyiragongo and Nyamulagira volcanoes

The seismic activity of Nyiragongo and Nyamulagira volcanoes was been studied by references [5, 6, 7]. Nyiragongo and Nyamulagira are two neighboring volcanoes separated by only 15 km, direction NW-SE. These volcanoes are often in rash and eruptions are always preceded by significant seismic signatures. Eruptions are often preceded by swarms of Long Period earthquakes, about ten months before [7]. The classification of seismic signals collected on these active volcanoes of the Virunga region was been made by references [5, 6]. The two authors use a one component seismometer with To=1s, and their classification is based on the

Waveform similarity. Their results can be summarized in three groups of earthquakes:

The first group is composed by earthquakes having clear P and s waves, and high frequency component. Theirs S-P are less than 5 seconds. They are temporarily called Tectonic earthquakes by reference [5] and A-type volcanic earthquakes by reference [6]. The second group is composed by earthquakes having obscure P and S phases, and low frequency component. Their S-P are larger than five seconds for reference [5] because he frequently observed them at LWI station located at 80 Km of the Virunga region. They are called volcanic earthquakes by reference [5] , and B-type volcanic earthquakes by the same Author reference to the Minakami's (1960) classification in Japan, B and C-type volcanic earthquakes by reference [6]. The third group is composed by Volcanic tremors, which are long period (LP) events that last much, that is to say a seamless continuity that appear on the seismograms as irregular sinusoids. These types of events are expected to occur as a result of a mount or descent movement of the magma in the crater without intrusion tendency.

3. Data acquisition and methods

Seismograms used in this study come from the Katale (KTL) and Kibumba (KBB) stations, which are two of the seismographic stations of the seismic network of the Goma Volcanological Observatory, which consists of 8 stations (with different categories and sensitivities: the Lenartz, T0 = 5s , the Guralps T0 = 40s the Guralps T0 = 60s and the Guralps T0 = 120s), around the Nyiragongo and Nyamulagira volcanoes. The KTL and KBB stations were chosen for this study because they are more sensitive (T0 = 120s and T0 = 60s) to record even the smallest disturbance, they are also closed to the two volcanoes (KTL is located at about 5 Km from Nyamulagira and Nyiragongo, and KBB at about 4 Km from Nyiragongo). These stations were deployed by the Goma Volcano Observatory in the 2008s. The KTL station was deployed through an Africa Array project; during this time it was called DRC01. In 2014, the station was been taken in charge by a Belgian project and from that moment it was known as RGL1.

This work consists of the spectral analysis of seismic signals to evaluate the frequency content, and reach to different groups according to the spectral bands well chosen. The characteristics of the different groups are compared to the classification based on the waveform that was already been made in the region and to the international classification, in the end result in the general classification of modern seismic signals recorded in the region. Using Volcanalysis Software under MATLAB, the seismic signals (seismograms) were filtred in the frequency band of 0.3-3 Hz, and cuted at a scale estimated in correlation with the duration of the seismic event. The spectral amplitudes of the vertical component of ground velocity were computed for each window and contoured for the frequency range 0-20 Hz and time range 0-30 s.

These contour plots, or spectrograms, are normalized to a peak value of 15 counts, with contours every unit and bold contours every 5 units. Such spectrograms are useful in appraising the spectral content of the body phases and later coda waves. Spectra of the vertical component of ground velocity were also computed for the entire 30-s seismograms (Fig. 2). Although these spectra lack the detailed time resolution of the spectrograms, they provide further useful information for our classification.

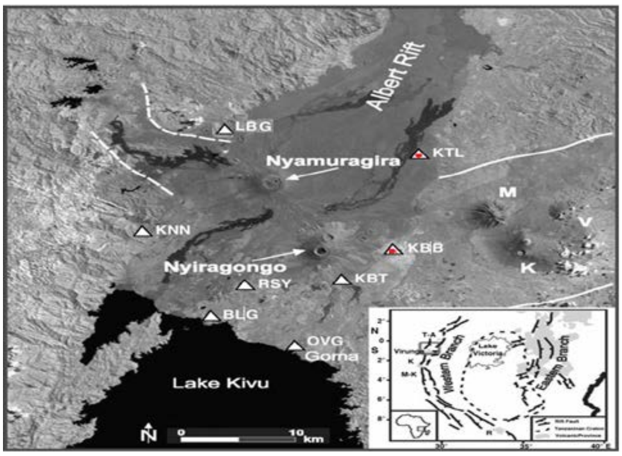

Figure 1: Map of the seismic Network of the Goma Volcano Observatory in the Western part of the Virunga volcanic province north of Lake Kivu. Nyiragongo and Nyamuragira volcanoes in the western part stay the only active volcanoes. The other Volcanoes: K-Karisimbi, M-Mikento, V-Visoke are asleep. Seismic stations are marked by white triangles (Goma-OVG, Kunene-KNN, Rusayo-RSY, Bulengo-BLG, Kibumba-KBB, Kibati-KBT,Luboga-LBG, and Katale-KTL. The KTL and KBB stations used in this study are marked by white triangles with red dots). Inset shows the East African Rift System with its eastern and western branches. Volcanic provinces in the western branch: T-A-Toro-Ankole, K-Kivu, M-K-Mwenga-Kamituga, R-Rungwe. Modified after [8 and 9].

4. Results

4.1. Detected families

A total of six families of volcanic earthquakes were detected in the region **:** The Volcano-Tectonic earthquakes, Shallow, type VT-A, the Volcano-Tectonic earthquakes, deep, type VT-B, (C) the Hybrid earthquakes, (D) the Long Period earthquakes LP, (E) the Very Long Period earthquakes VLP, and (F) the Volcanic Tremors.

a) The Volcano-Tectonic earthquakes, deep, type VT-B: They are local earthquakes generated within the volcanic edifice. In the Virunga Volcanic field, they usually display S-P times smaller than 5s. These earthquakes are dominated by a double-couple mechanism, and often characterized by impulsive P-wave onsets, and clear S arrivals. The spectral content is broad with energy between 5 and 15 Hz. In Fig 3 (A1) we plot an example of a VT-A type earthquake. In the Virunga field, these events are usually shallow, with low magnitude. However, some earthquakes with magnitude greater than 3 are evident to occur in the region, because of the Rift actions. The source of VT-A earthquakes is associated to the brittle failure of parts of the volcanic edifice in response to changes in the distribution of local or regional stresses (Rift actions for example). The stresses may change for example due to interactions of water with hot materials or to the effects of shallow magma injections [10]. Typical short-period earthquakes, termed volcano tectonic earthquakes when they occur within or under a volcanic edifice, are attributed to brittle failure in response to stress changes associated with magmatic activity. For sources below a few kilometers depth, VT earthquakes have clear high-frequency P and S arrivals with peak frequencies above 5 Hz and are easily distinguished from LP events. The seismogram of a typical deep VT earthquake is dominated by the P- and S phases and a very short coda (Fig. 2d). The spectrogram shows broadband P- and S phases with peak energy between 6 and 8 Hz, and has a broadband coda with energy extending up to 15 Hz.

b) The Volcano-tectonic earthquakes, shallow, B-Type: The Shalow VT quakes larger than about M 0.3 generated stronger surface waves than the deeper VT earthquakes but were still distinguishable from LP events on recordings obtained at KTL. Notice the variation in dominant coda frequency with time in the seismogram and spectrogram of a typical shallow VT, from 1.5 Hz three seconds after the S phase to 3 Hz five seconds later; such variation is characteristic of a dispersed surface wave train. Shallow VT's smaller than about *M* 0.3 that occur within the coda of LP events cannot be easily distinguished from the latter, so that some of the smallest events located may be misclassified. All of the events were originally classified on the basis of their seismograms as either LP or VT.

c) The Long Period earthquakes (LP); they are volcanic earthquakes characterized by a quasi-monochromatic spectral content. The most frequent seismicity at Nyiragongo and Nyamulagira are the LP events, which constitute signals with a spindle-shaped envelop and durations smaller than 60s. In some cases, a high-frequency phase precedes these events. In Fig. 3 (C1 and 2), we show an example type of LP event with its spectral content which is between 1 and 3 Hz. The Source processes that generate the LP seismicity involve a volumetric component due to the resonance of fluid-filled cavities [11]**.**

d) Volcanic tremors are monochromatic signals with duration longer than that observed for the LP events. Episodes of tremors that last from minutes to several hours and days have been observed at Nyamulagira and Nyiragongo Volcanoes. In figure 3 (E1 and 2) and in Figure 2, we show samples of volcanic tremors. Models of tremors generation are based on degassing, fluctuations of the gas, resonance of conduits, etc. [12, 13, and 14]. Those models considering the resonance open conduits have been complicated by introducing different geometries of the resonance system. Some results, which integrate observations of tremor and LP, show evidences that both type of events share similar source regions and processes [15]. An LP event response to a sudden pressure transient within a fluid-filled crack, while tremor is the response to continuous fluctuations of pressure.

Figure 2: Helicorder of on day plot of the KTL records on 06/11/2011, the day of Nyamulagira eruption. In the records many volcanic tremors with detected hybrid events.

e) Hybrid events are signals that contain both double-couple and volumetric components. They are characterized by an initial high-frequency phase similar to a VT earthquake, followed by a monochromatic signal to those shown by the LP events. In some cases, LP events with an energetic initial high-frequency onset could be confused with hybrids. While the low-frequency signature is originated in both cases by resonance of fluid-filled cavity, in the case of hybrid events the initial pressure step that triggers the resonance is caused by a brittle failure process [15]. Their frequency content is located between 3 and 10 Hz. Hybrid events have more pronounced high-frequency onsets than LP events and show a mix of first motions characteristic of VT earthquakes. Their codas, however, are dominated by a non-dispersive harmonic wave train that is characteristic of LP events, hence the spectrograms of a hybrid coda and an LP coda are similar. We suggest that the hybrid events may result from brittle faulting in zones of weakness intersecting a fluid-filled crack and thus involve both double-couple and volumetric source components [16].

f) Very-long-period (VLP) volcanic events are events associated with unsteady mass transport, generating seismic signals over the range 2 to 100 s [17]. The VLP events generally exhibit a strong pulse of energy followed by decaying oscillations that last for a few to tens of cycles before receding into the background noise [17]. VLP seismicity often occurs during hours to days-long transient deflation or inflation episodes of the summit caldera [17]. At Kīlauea volcano the transients in magma transport are episodic in nature and the VLP seismic signals are generated through fluid–rock interactions where inertial volume changes in fluid-filled conduits occur [18, 19, and 20]. Very-long-period events were observed by [21] at Kīlauea Volcano, which is a volcano with a persisted lava lake as at Nyiragongo. They suggested that these events are associated with distinct processes: vigorous degassing, rockfalls onto the lava lake, transients in mass transfer that occur within the dike system. They suggested also that these events are induced by pressure and momentum changes at the top of the magma column that are transmitted downward to a source centroid ~1 km below the northeast corner of the Crater where the energy couples to the solid Earth at a geometrical discontinuity in the underlying dike system. The frequency band of these events are between 0.01-0.1 Hz. With the actual broadbands seismometers used at KTL, such events are observed and are associated to the same causes described by [21]. Figure 3 (D1 and 2), Illustrates an example type of a very long period event.

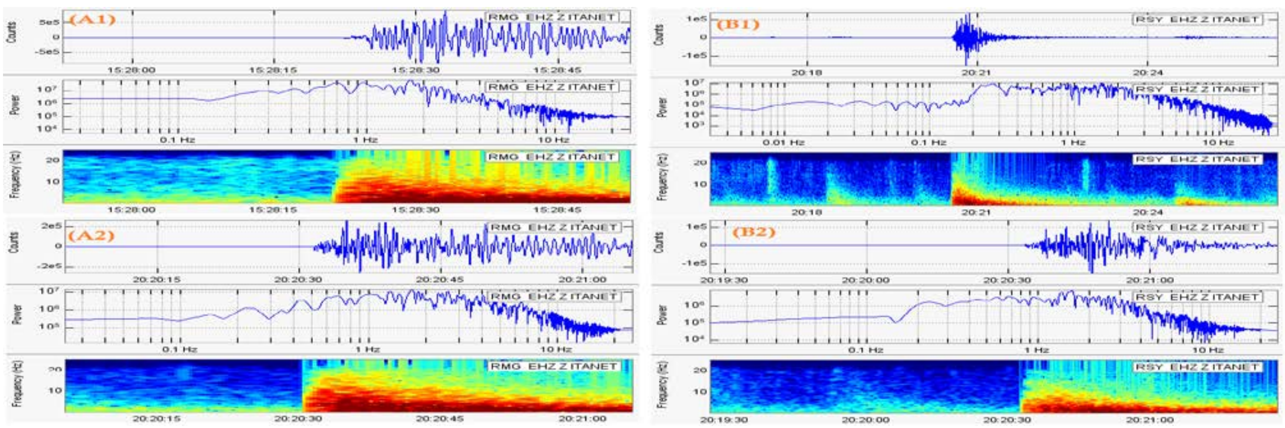

Figure 3: Spectrograms of the types of Earthquakes detected: (A1) Volcano-Tectonic earthquakes, Shallow type VT-A, (A2) Volcano-Tectonic earthquakes, deep type VT-B, (B1-2) Hybrid earthquakes, (C1-2) Long Period earthquakes LP,(D1-2) Very Long Period earthquakes VLP, (E1-2) Volcanic Tremors.

4.2. Volcanoes monitoring

The detected families of earthquakes described above and below can be used in the monitoring of volcanic eruptions. The volcano-Tectonic earthquakes can to some extent disrupt the activity of the volcanic edifice. The Hybrid earthquakes are trusted name like breaking earthquakes, they are a result of force exerted on the magma cracks when seeking the way to go out. At Nyiragongo and Nyamulagira volcanoes, magma intrusion dikes are usually marked by swarms of VT and Hybrid earthquakes. Long Period earthquakes are characteristic of an activity within the volcano, but their swarms can be dangerous. The tremors are linked to an upward, downward or horizontal movement even within the volcanic edifice. VLPs are characteristic of volcanoes with lava lake assets and can provide information on the ongoing activity within the building volcano. The Volcanoes Nyiragongo and Nyamulagira, usually erupt through fissures and eruptions are always preceded by swarms of earthquakes with a mixture of LP, Hybrid and VT events (see Figure 4).

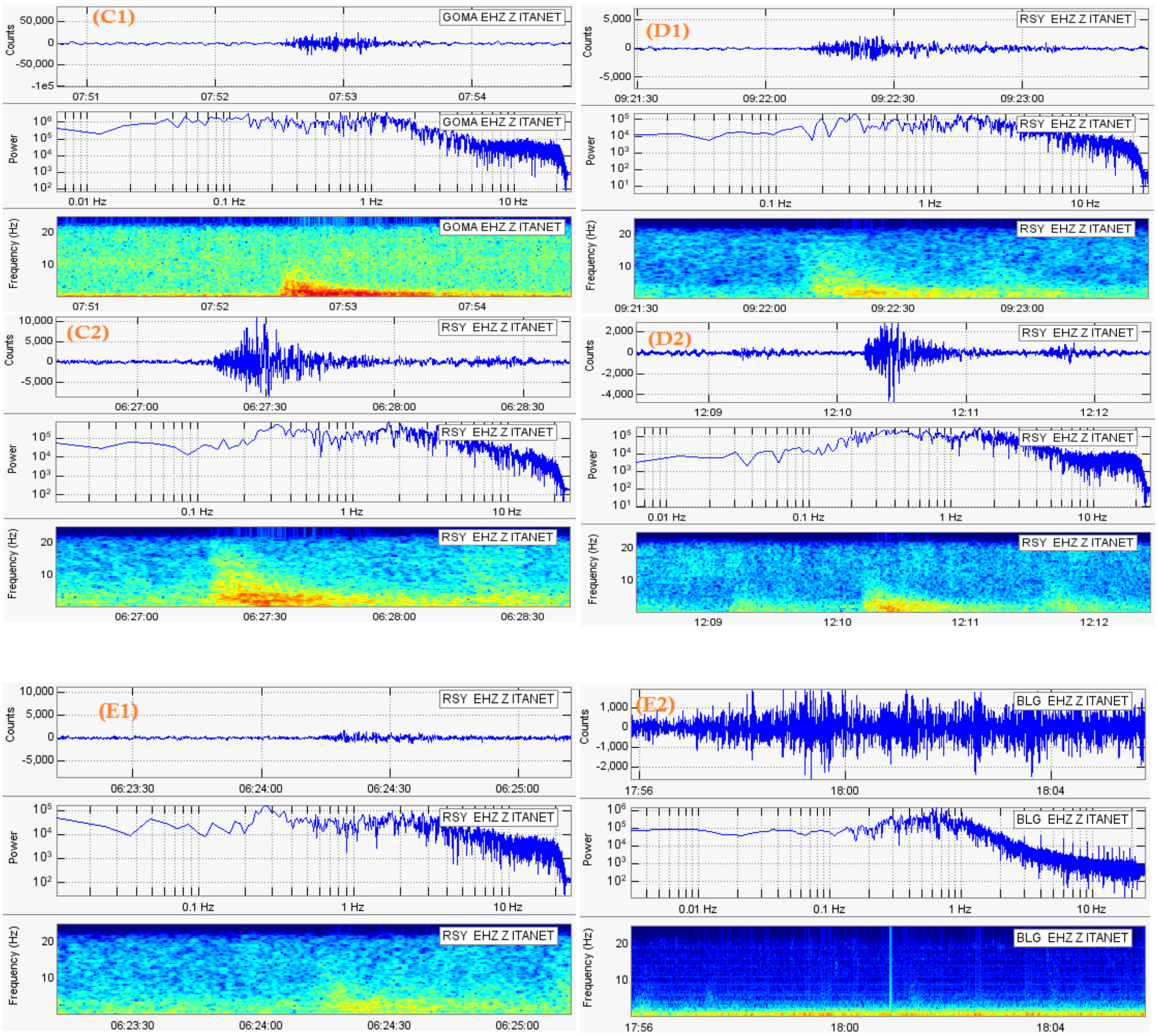

Figure 3 (continued)

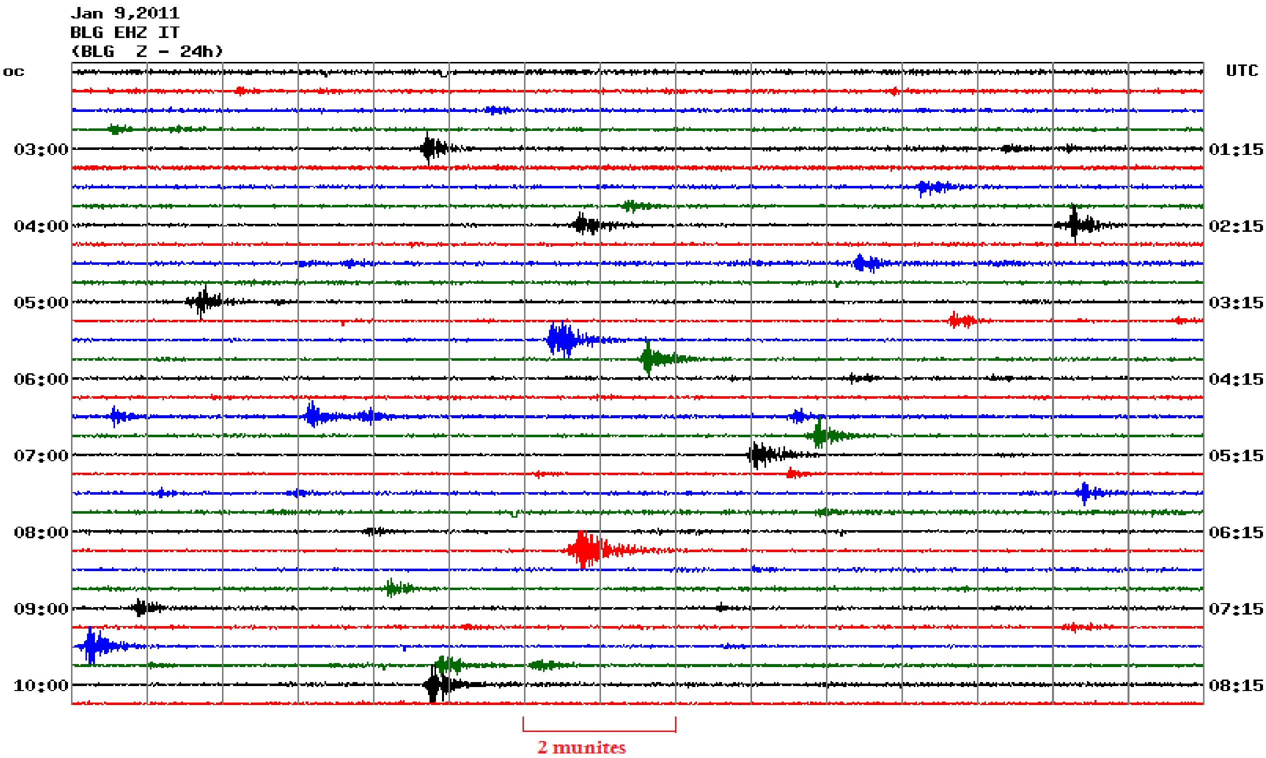

Figure 4: Helicorder of 09/11/2011, from the Vertical component. A swarm of volcanic earthquakes is observed, with predominance of Hybrid events. Such cases are results of dyke intrusions at Nyiragongo and Nyamulagira Volcanoes

5. Conclusion

The seismicity of the Virunga area was reviewed using very sensitive equipment. Six families of earthquakes were detected, reference to their frequency content with comparison to the international classification of volcanic earthquakes: VT-Shalow, the VT-deepper, Hybrids, LP, VLPs and volcanic tremors. This classification can be used in monitoring the Nyiragongo and Nyamulagira volcanoes.

Acknowledgements

We first thank the reviewers and editors for their careful reviews and helpful comments which significantly improved the presentation of this work. Thanks, are also extended to all the members of the department of seismology of Goma Volcano Observatory for their continuous efforts for hard work in analyzing data, their efforts made possible the composition of this work. We thank also the staff members of the Goma Volcano Observatory to maintain seismographic stations in the region.

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