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Seismic activity related to the June 2014 New lava Lake apparition at Nyamulagira volcano in the Western Branch of the East African Rift

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ABSTRACT: A lava lake activity is observed at Nyamulagira volcano during this last decade. The training process of this lava lake began in 2012 by the release of gas fumes that was been continuously observed in the crater of the volcano. However no change in seismic activity was observed compared to the usual activity of the volcano until April 2014. On 22 June 2014, an activity of glow was observed by the Goma Volcano Observatory and the inhabitants of the city of Goma. On July 3rd 2014, the United States's organization NASA (National Aeronautics and Space Administration) noted this situation by its satellite detection and published on his Web site the apparition of a new lava lake in the crater of Nyamulagira. Nyamulagira volcano (in its known history) logged again a lave lake from 1921 to 1938. Here are analyzed the seismic activity which preceded this new event at mount Nyamulagira. It was found that this event was been preceded by a significant swarm activity of Long Period earthquakes in April 2014, six hybrid earthquakes and volcanic tremors in June 2014. The April 2014 swarm of low frequency earthquakes lasted about four days and was been located in the North-Eastern part of the Nyamulagira crater (at the place where appeared the new lava lake) and was been interpreted as expressed by the precursor movements of the opening of the crater. The six hybrid earthquakes were been interpreted also as the events that led to a falling movement of the land masses and the opening of the crater. After the visibility of the lava lake in June 2014, the activity of LP events reduced, no swarm and hybrid events were been recorded from this period, but the number of Volcano-Tectonic events remained constant.

KEYWORDS: Lava Lake, Nyamulagira Volcano, Volcanic tremors, swarm of earthquakes, seismic activity.

1 INTRODUCTION

Nyamulagira Volcano (also known as Nyamuragira; 1.41°S, 29.20°E, 3058m) and its neighboring, Nyiragongo volcano, are located in the north part of Lake Kivu, in the western branch of the East African Rift (Fig. 1.a) and still the only active volcanoes of the Virunga volcanic chain, which is composed by eight principal volcanoes (Fig. 1.b). The currently dormant volcanoes of this chain are Muhavara, Sabinyo, Visoke, Mikeno, Karisimbi and Gahinga. Nyamuragira erupted twenty six times between 1938 and 2010 [1] at these eruptions we can add the November 2011 eruption which lasted four months. These current eruptions make Nyamulagira one of the world's most active and productive volcanoes [2]. This volcano erupted lava flows with a recurrence rate of 2-4 years [1]. Some of them are fissural and occur on the flank of the volcano [3]. Nyamulagira Volcano is characterized by Hawaiian eruption type, with very potassic lavas [4], [3], [5]. This very high basic lava is done by Basanites-tephrites and alkaline basalts [2].

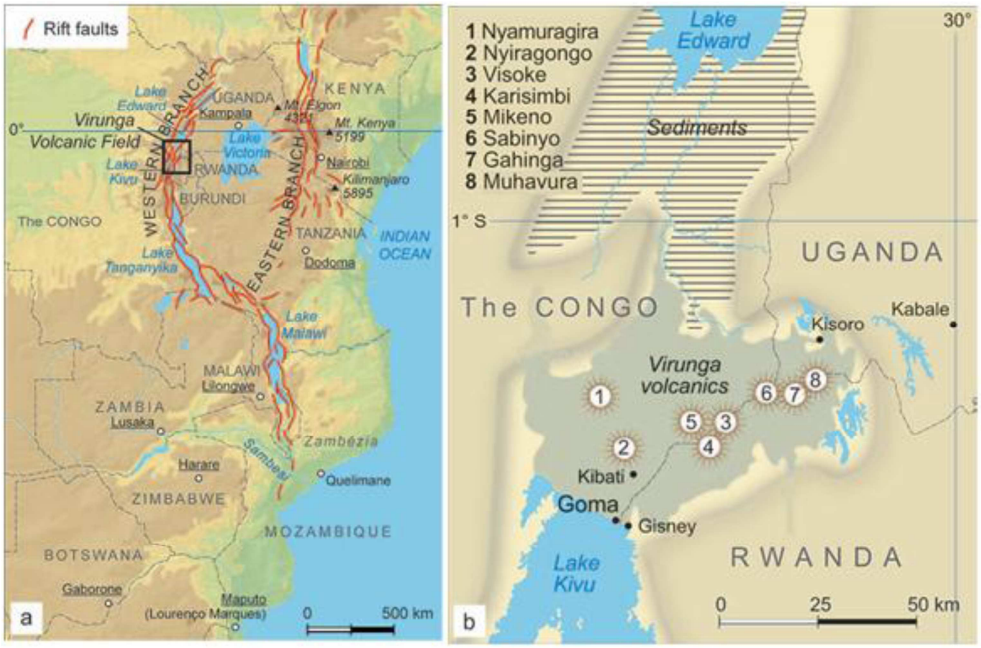

Fig. 1. Map showing the overview of the tectonic and volcanic manifestations of the study area. a. The East African Rift; This rift consists for two branches: The Eastern branch and the western branch. The Virunga Volcanic field is located in the Western branch as it is shown with the black rectangle. Red lines show the orientation of the Rift faults. b. The Virunga Volcanic Field, between DRCongo and Rwanda, with eight volcanoes aligned in the West-East direction. Nyiragongo (1) and Nyamulagira (2) are located immediately in the North of Lake Kivu.

Nyamulagira Volcano had a long-lived and permanent lava lake in the summit of its crater for about 17 years in the period 1921-1938 [3], [5]. On January 28th 1938, this lava lake was been drained by a very great eruption at the same time, a major flank eruption. This historical lava flows extend down at the southern flank of the volcano, more than 30 Km from the summit, reaching as far as Lake Kivu, destroyed a grand part of the Sake city and cut a small part of the Lake Kivu, which is now called Lake of Sake. No further documentations exist about this 1921-1938 former lava lake in Nyamulagira volcano, but oral records from the Sake Inhabitants report that this historical eruption duration (period of the lava flow draining) was for two years, from 28th January 1938 until 25th July 1940. In the night of 22 June 2014, a low intensity light was visible at the top of Nyamuragira volcano by the inhabitants of the city of Goma. The intensity of this light grew stronger from day to day until it became almost as that observed at Nyiragongo volcano. After some days many institutions of earth observation toward the world annoced the apparition of a new lava lake at Nyamulagira volcano.

In this Paper, the authors analyze the seismic activity expressed by the apparition of this new Lava Lake in Nyamulagira volcano, with special emphasis on the movement in the crater which conducted to the occurring of the seismic activity.

2 Apparition Of The New Lava Lake In The Nyamulagira Volcano Crater: Observations Of Different Institutions Toward The World

Two weeks after the visibility of the glow, on **July 3, 2014 Jesse Allen and Robert Simmon**, two analysts of satellite images of the Earth using Landsat data from the USGS explorer for National Aeronautics and Space Administration (NASA), had claimed data on June 30, 2014 acquired through observations and had published on the NASA website in reference [6], the apparition of a new lava lake in the summit crater of Nyamulagira Volcano. In their issue, they mentioned that their recent Landsat satellite image shown the new lava lake, and thermal anomalies as well as increased SO2 concentrations above the close-by Nyiragongo and Nyamulagira volcanoes. In another way, on 1st july 2014, the Global Volcanism Program (GVP) bulletin from the University of Hawaii information, reported that Moderate Resolution Imaging Spectro-radiometer (MODIS) satellite data detected thermal anomalies and issued MODVOLC alerts for the Nyamulagira volcano's North side. The bulletin explained that series of thermic anomalies (a total of 15), was been observed by MODVOLC at Nyamulagira volcano between 22nd june and 1st july 2014, all located in the north part of the caldera which opens its summit. The bulletin continue to explain that the incandescent glows were been observed and related to the presence of a potential lava lake within the crater of Nyamulagira volcano (See reference [7]).

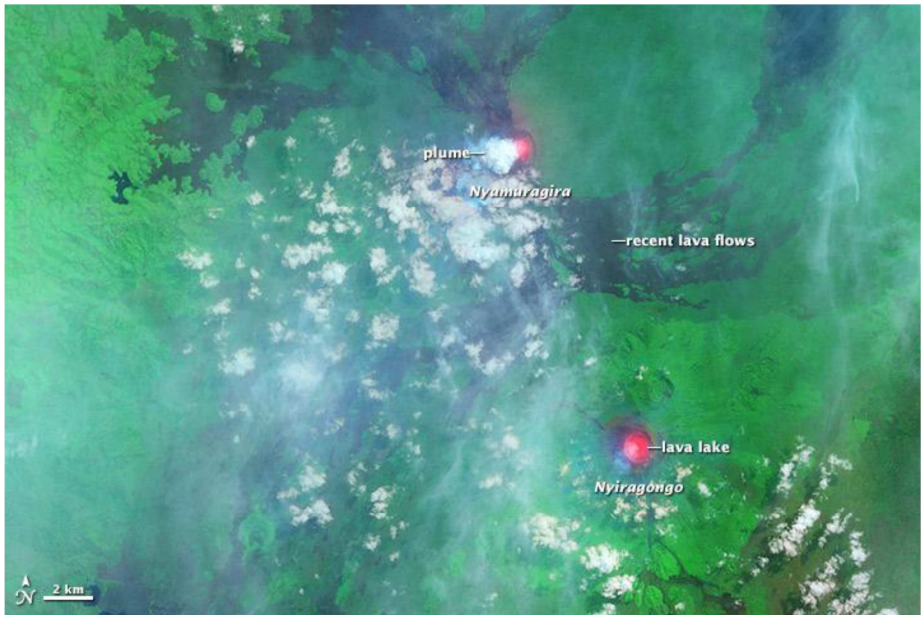

Fig. 2. Landsat image for the lava lakes within Nyiragongo and Nyamulagira volcanoes. The false-color image which combines shortwave-infrared, near infrared, and green light as red, green, and blue, respectively. Shortwave and near- infrared light penetrates hazy skies better than visible light, so more surface detail is visible in this image than would be in natural-color. Because of very hot surfaces glow in shortwave-infrared, the lava lakes within the summit craters of Nyamuragira and Nyiragongo appear bright red. The dark lava flows spreading from Nyamuragira were erupted within the past 50 years, some as recently as November 2011. Vegetation is bright green.

At the same time, the Goma Volcano Observatory (GVO) from DRCongo with the Rayal Museum of central Africa (RMCA) from Belgium and the National Museum of Natural History (NMNH) from Luxembourg, organized four expeditions with helicopter at this volcano on 5th July; 12th July; 13th September and 1st November 2014. Their records show that the glow activity in the crater which began on 22nd June 2014, increased gradually in the half-July as well as it was seen as a lava lake, but in the beginning of September 2014, this activity decreased slowly until the glow became smallest and at the end of October, the glow reappeared as well as it became biggest for all the period of November. Then it was noted that the decreasing of the glow intensity in September didn't explain the end of the activity of the Lava Lake. In this period the lava lake was active but with a smallest intensity of glow.

3 DATA ACQUISITION

The seismograms used in this study were provided by the seismological network of the Goma Volcano Observatory (GVO). The observation network began in 2002 and was composed by eight analog stations (Fig. 4) : Katale(KTL), Luboga (LBG), Kunene (KNN), Rusayo (RSY), Kibumba(KBB), Goma (OVG), Kibati (KBT) and Bulengo (BLG). Each station was equipped by a Short period (To= 1 sec) Kinemetric Vertical seismometer SS1, PMK-noVKtsujima connected to a PS2 Portable Recorder. On November 2003, the GVO began the deployment of three-component short-period Lennartz (LE-3D/5 s, To = 5 sec) seismometers coupled to an A /D convertiser at these stations. On May 2004, the Lennartz short-period seismometer at KNN and KBB was replaced with Nanometrics Trillium 40 broadband seismometers. Signals from these stations are locally digitized from a modular acquisition system (GAIA), specifically developed by the ''Instituto Nazionale di Geofisica e Vulcanologia (INGV)", with a sampling frequency of 50 Hz and an A/D resolution of 24 bits and are telemetered to the Goma base station where they are recorded in triggered and continuous files.

4 METHODS

Continuous waveforms from the GVO array were manually scanned and analyzed using the seismic analysis programs. The observations were made on both analog data and digital data. The counting of earthquakes was done manually on analog seismograms considering the identification based on the waveforms. The spectral analysis to evaluate the frequency content was made solely on the broadband 40s digital station of KNN and KBB using softwares: Swam [8] and SEISAN [9].

Fig. 3. Different observations of the new lava lake in the Nyamulagira crater from 5th July until 1st November 2014. A: July 5th 2014, the activity in the crater is seen as lava fountains in horizontal direction. B: July 12th 2014, the activity in the crater has increased and is seen very well as a Lava Lake. C: September 13th 2014: the activity of glow in the crater decreased and the light despaired gradually D: November 1st 2014, the activity of the lava lake generated a great intensity of glow and the light became biggest.

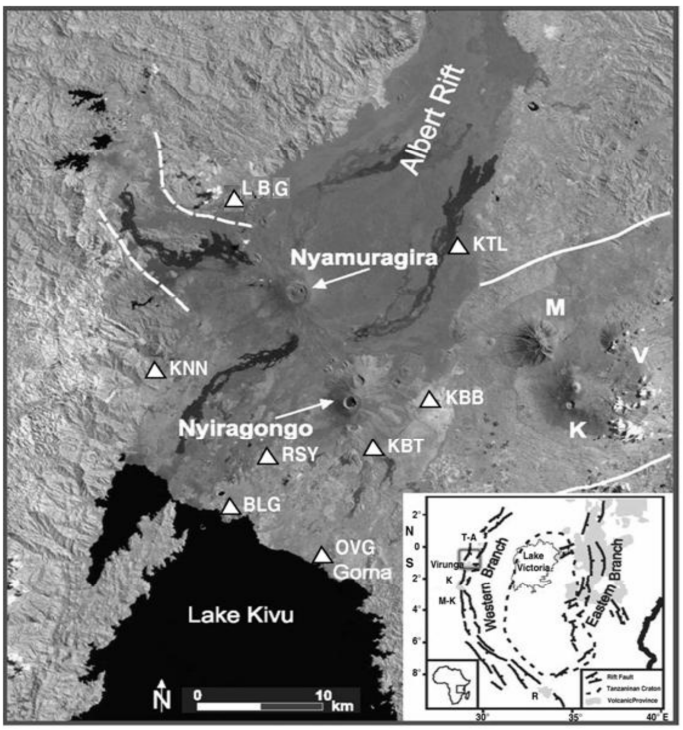

Fig. 4. Seismic network of the Goma Volcano Observatory. Seismic stations are marked by white triangles (Goma-OVG, Kunene-KNN, Rusayo-RSY, Bulengo-BLG, Kibumba-KBB, Kibati-KBT, Katale-KTL, Luboga-LBG).
Volcanoes: K-Karisimbi, M-Mikento, V-Visoke. Inset shows eastern and western branches of East African Rift System. Volcanic provinces in the western branch: T-A-Toro-Ankole, K-Kivu, M-K-Mwenga-Kamituga, R-Rungwe. Modified after References [30] and [31].

To locate earthquakes, P and S wave arrival times were picked manually on Butterworth filtered (0.5–15 Hz) vertical and horizontal components, respectively. P phase arrival times were assigned quality factors of 0, 1, 2 or 3 according to estimated measurement errors of 0.05 s, 0.1 s, 0.15 s, and 0.3 s, respectively. S wave quality factors of 0, 1, 2, and 3 were assigned to arrivals with estimated measurement errors of 0.1 s, 0.175 s, 0.25 s, and 0.3 s, respectively. The events were located using a 3-layer one-dimensional P wave velocity model of Reference [18] derived from earlier seismic studies in the Virunga region. Earthquakes recorded on 4 or more stations and with 4 or more P and/or S arrival time readings were used for location. To reduce bias due to uncertainty in the phase reading and velocity model, we considered only epicenters with standard error in latitude and longitude less than 5 km and a standard root mean square (rms) error on the travel time residual less than 0.7 s. It was thus revealed that the maximum accuracy on focal depth is obtained for erz=5 km.

5 SEISMIC ACTIVITY

The seismic data from the Goma Volcano Observatory (GVO) network have been analyzed since the last eruption in November 2011, until the appearance of the lava lake in June 2014. Throughout this period, two swarms of long period earthquakes were observed: one in November 2013 and another in April 2014. The swarm of November 2013 is not so interesting as it was of low intensity and lasted two day only. The swarm of April 2014 is the most interesting because it was intense and lasted four days. After the swarm of April 2014, the seismic activity remained normal and on behalf of June 2014, the lava lake became visible in the crater.

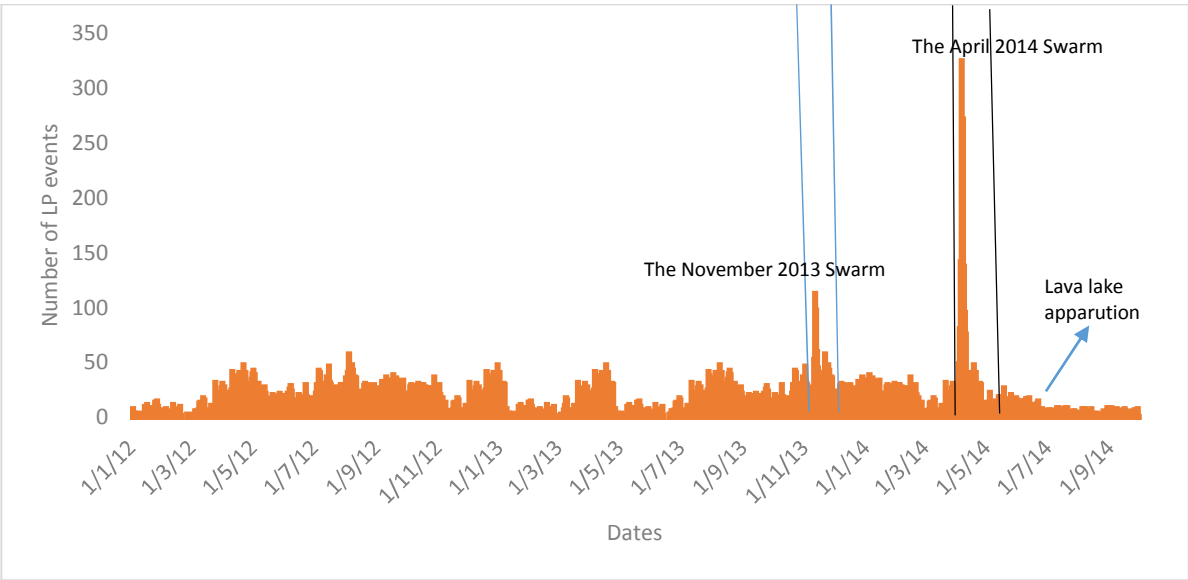

Fig. 5. Daily Count of LP events from January 2012 until September 2014. After the apparition of the lava lake, the number of LP events decreased.

5.1 THE APRIL 2014 EARTHQUAKES SWARM

From 6th until 9th April 2014 a Low frequency earthquakes swarm was been recorded by the GVO seismic network and was been located in the Northeastern part of the Nyamulagira crater (Fig. 6). At the second day of the swarm, on 7th , the number of Low frequency earthquakes increased as well as the office of GVO could annoce an imminent eruption, but two days ago, this activity decreased gradually, until it became normal (Fig. 5). At the Rusayo station (RSY) , the records were as fellow: on 06th April, 179 LP events, on 7th, 243 LP events, on 8th, 319 LP events (the highest level) and after this day, the number of LP events decreased as well as it became 171, 71 and 55 respectively on 9th, 10th and 11th April 2014. After this time, the seismic activity became normal (with an average of 25 LP events per day) until the date of the observation of the new lava lake. The swarm of April was located and almost all the earthquakes were located in the northeastern part of the crater at shallow depth except three only which were located between 12 and 20 km (Fig. 6). This situation attests that the activity of the magma was been characterized by a migration from the deep depth to the shallow. From the beginning of the

swarm until the end, no light or glow was been observed but this swarm was been noted as the precursor sign of the new lava lake apparition.

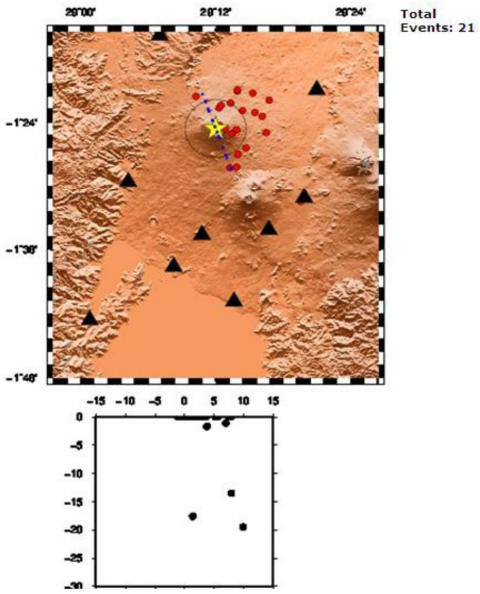

Fig. 6: Map of the locatable LP events of the Swarm of April 2014, although all the events are located in the Northeastern part of the Nyamulagira crater (Place were the new lava lake appeared in June 2014). Black triangles show the stations used for the location, the yellow star show the Nyamulagira crater, which areas are covered by a black circle. The red dots show the epicenter location, all of them are located in the Northeastern part of the crater.

5.2 THE JUNE 2014 ACTIVITY

After the swarm, the seismic activity remained normal until 20th June 2014 (Fig.5), at an average of 20 LP events per day. On 21st, four Seismic events were been registered on 8:42, 9:42, 5:04 pm and 7:20 pm respectively with volcanic tremors from 5:5 am until 5:4 pm (Fig. 8). On 22nd, two events occurred again: one at 0:17 and the other at 2:50 am. After 22nd, the seismic activity was been marked by volcanic tremors only, but the average number of the LP events recorded became low at about 10 LP events per day (Fig. 5). They were recorded on the Broadband Guralp seismometer (T0=120 s) at KTL station renamed actually RMG, and on the Lenartz seismometer (To= 5 s) at Goma station, as well as on other analog stations as RSY, GOM, KNN and LBG. The data analyzed here are from the records of KTL broadband. Based on their frequency contents and their waveforms (Fig. 7) these earthquakes were classified as hybrid earthquakes and have been interpreted as having been at the base of the downward movement which conducted to the failure of the land mass and then to the opening of the crater. These earthquakes have a clear and discernable P wave, but invisible S wave and S-P is less than 1s. Their frequency content is between 3 and 10 Hz. Continues volcanic tremors began at about 5:05 GMT of 21st. Their amplitudes increased on 6:00, and finished at about 17:04 GMT by a hybrid earthquake (Fig.8). Reference [10] mentioned in his issue that in the virunga region, volcanic tremors appeared just after a tectonic earthquake. Unlike his idea, on 21st june, the volcanic tremors appeared suddenly without a tectonic earthquake occurrence. This situation was been noted as all began in the magma chamber. The mounted of the magma in the conduit began early on 5:04 of 21st expressing by the volcanic tremors, until the first and second events occurred, continued again and stopped at the occurring of the third event (Fig. 8).

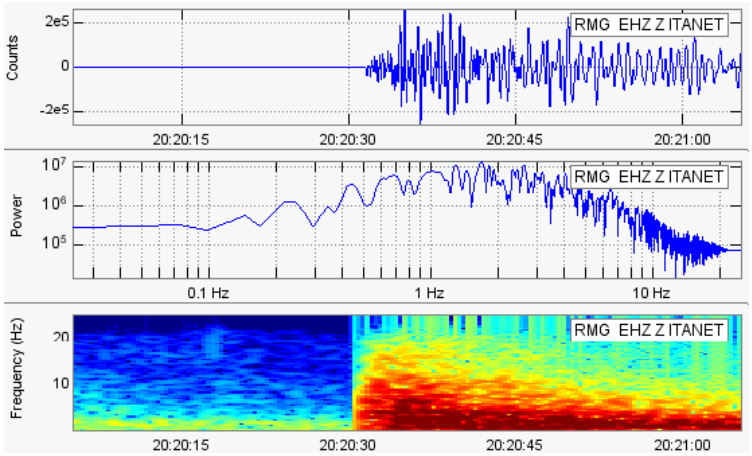

Fig. 7. Waveform, spectrogram and spectrum of a typical Hybrid event recored at Katale station renamed RMG after the deployement of the broadband 40s. the Frequency Contant reaches values about 8Hz.

Figure 8: Typical seismograms recorded at Rusayo Analog station. Hybrid earthquakes and volcanic tremors are shown. The volcanic tremors began on 5:05 AM of 21st and finished on 17:04 of 21st by a hybrid earthquake

6 CONCLUSION

We studied the eruptive activity of the June 2014 Nyamulagira lava lake apparition based on the analyses of the seismic parameters. The surface activities of June 2014 Nyamulagira new lava lake apparition began early in April with a dyke intrusion expressed by a LP earthquake swarm from 6th until 9th. This activity was been reactivated in June at about 5:05 am of 21st and finished at about 2:05 am of 22nd, during which time the following processes occurred successively:

(1) The dyke intrusion which took place in April was reactivated by physical conditions (variation of temperature and pressure).
(2) The quick mounted magma in the conduit of the crater expressed by the volcanic tremors occurrence happened early without any seismic event as exciter.
(3) Low motion on the ground surface (from the quick of the magma), from which the terrace collapsed slowly step by step to the bottom of the crater, causing the occurrence of the early four Hybrid earthquakes.

(4) High motion on the ground surface from which the terrace collapsed completely causing the last two events and the formation of a big hall crater with a depth of 350 m and diameter of 50m about.

Then it can be seen that the June 2014 Nyamulagira new lava lake apparition was continuously accompanied by four dynamic processes listed above. This lava lake actually observed in Nyamulagira volcano will probably finish by a surface eruption in the future days as the same situation was been observed in 1938.

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