Preliminary results from seismic monitoring at Nyiragongo Volcano (Democratic Republic of Congo) through telemetered seismic network, Goma Volcanological Observatory

N.M. Pagliuca[1], L. Badiali[1], M. Cattaneo[1], H. Ciraba[1], A. Delladio[1], M. Demartin[1], A. Garcia[1], A. Lisi[1], F. Lukaya[1], A. Marchetti[1], G. Monachesi[1], A. Mavonga[2], T. Sgroi[1] and D. Tedesco[3]

[1] *Istituto Nazionale di Geofisica e Vulcanologia*
[2] *Goma Volcano Observatory*
[3] *2ª Università di Napoli, Dipartimento Scienze Ambientali*

(Received: April 16, 2008; accepted: September 15, 2008)

ABSTRACT Following the January 17, 2002 catastrophic eruption of the Nyiragongo Volcano (Democratic Republic of Congo) located in the western branch of the East African Rift, a great effort has been devoted to the seismic surveillance of this volcanic area. The 2002 eruption destroyed one/tenth of the city of Goma, leaving more than 100,000 homeless. In order to correctly monitor the seismic activity at Nyiragongo volcano for both scientific and civil defence purposes, the Istituto Nazionale di Geofisica e Vulcanologia in cooperation with GVO (Goma Volcanological Observatory), between November 2003 and May 2004 installed a new telemetered seismic network consisting of seven digital stations. The network is operational and seismic signals are continuously recorded at the GVO. In this study, we focus mainly on two aspects: (1) the deployment, in the field, of this new digital seismic network and the related real-time data acquisition system, and (2) the first results from a preliminary data analysis based on 6-month seismic recordings. Based on the waveforms and spectral analysis, long-period and very long period events (both, tectonic and volcanic-tectonic earthquakes), have been detected. Furthermore, we succeeded in locating more than 100 earthquakes. These results should strongly encourage the use of such a network data for seismotectonic studies of the area.

1. Introduction

The East African Rift Valley System (Fig. 1), one of the most seismically active regions of the African continent, is divided, in its central part, into the eastern and western branch (Platz *et al.,* 2004). The western zone runs through the Democratic Republic of Congo's (DRC) eastern border region and neighbouring countries of Uganda, Rwanda, Burundi, Tanzania, including lakes Albert, Edward, Kivu, and Tanganyika, and joins to the south the eastern branch.

The central part of the Western Rift, between Lake Kivu and Lake Victoria, is the site of the Virunga volcanic chain which extends along the E-W direction for about 80 km perpendicularly to the rift valley. The range is formed by eight major volcanoes with the highest peak reaching 4,500 m. Only the most western and youngest volcanoes, i.e. the Nyiragongo and Nyamuragira ones, are active. While Nyamuragira Volcano is a typical shield volcano, comparable to Mauna Loa (Hawaii), the 3470-m high Nyiragongo Volcano displays the typical, characteristic steep

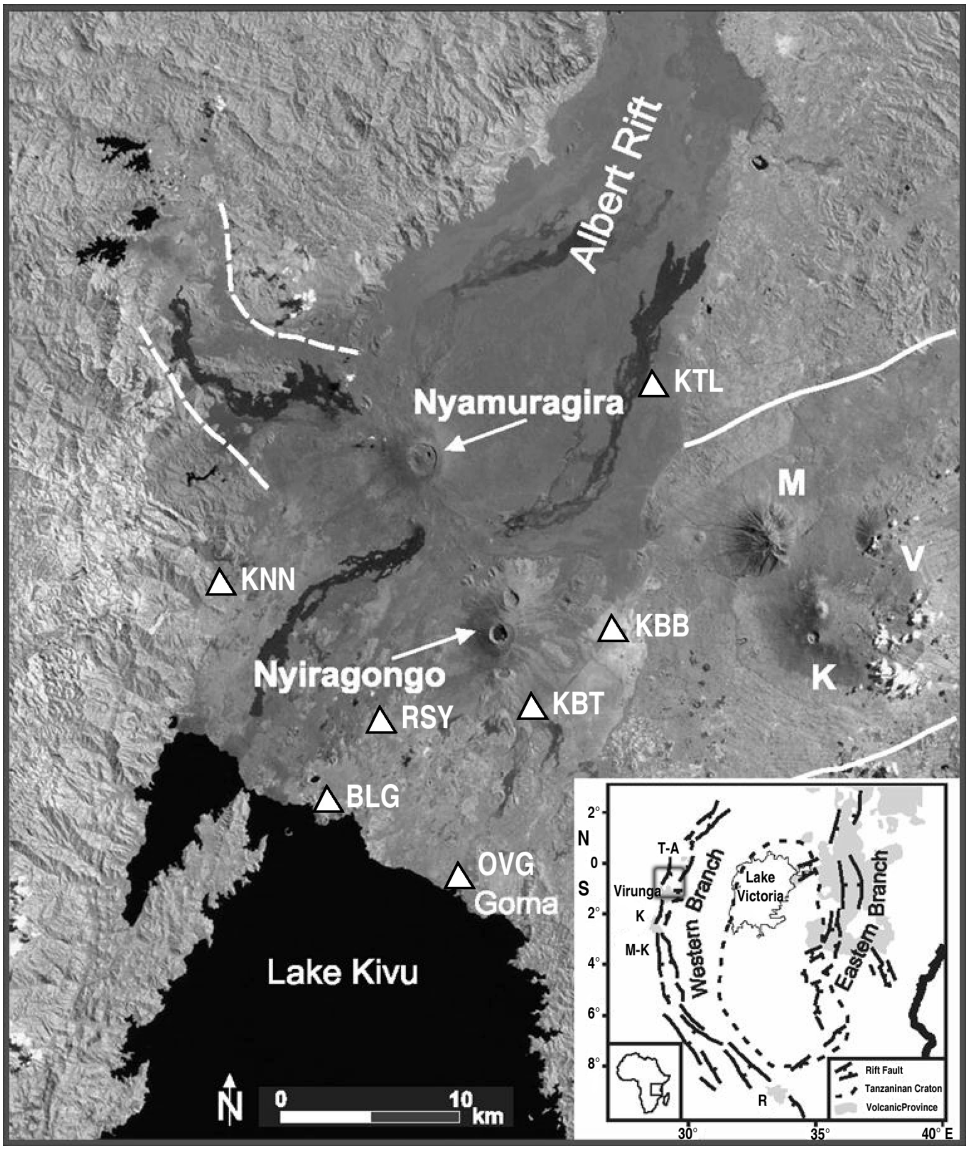


Fig. 1 - Western part of the Virunga province north of Lake Kivu. Nyiragongo and Nyamuragira volcanoes are situated on the active Albert rift floor. Lines mark Bay of Bufumbira (solid) and Kamatembe rift (dashed). Volcanoes: K-Karisimbi, M-Mikento, V-Visoke. Inset shows eastern and western branches of East African Rift System. Volcanic provines in the western branch: T-A-Toro-Ankole, K-Kivu, M-K-Mwenga-Kamituga, R-Rungwe. Seismic stations are marked by white triangles (Goma-OVG, Kunene-KNN, Rusayo-RSY, Bulengo-BLG, Kibumba-KBB, Kibati-KBT, Katale-KTL). Modified after Platz *et al.* (2004).

slopes of a stratovolcano (Simkin *et al*., 1981).

The Western Rift has experienced severe earthquakes and volcanic eruptions in recent historical times. Earthquakes with M≥ 6, although not frequent, caused significant destruction in the past (ISC, 2008; Vunganai *et al*., 1999). This activity occurs mostly in the tectonically-active Lake Kivu region (DR) and in neighbouring countries such as Uganda and

Tanzania. Recently, the region of Lake Kivu was hit by an M=6 earthquake on February 3, 2008 (http://earthquake.usgs.gov/eqcenter/eqarchives/poster/2008/20080203.php).

Nyiragongo Volcano is located about 20 km north of Lake Kivu, and only 15 km north of the city of Goma. The population growth in the area in the last 30 years has been extremely high, and the inhabitants of Goma increased from 50,000 in 1977 to almost 600,000 in 2007. Such a growth is mainly due to the greater insecurity in rural areas caused by social unrest and civil war. Obviously, most of the new population started building houses in areas already hit by the volcano getting increasingly closer to the volcano itself. Because of these new settlements, the seismic and volcanic hazard of the area today has increased exponentially.

Since its discovery in 1895, when first reported by von Gotzen (1895), Nyiragongo Volcano has been well known for its persistent active lava lake (Tazieff, 1979). After several eruptive episodes during 1977, 1982, and 1994, on January 17, 2002 a very important eruption generated about 20 milion m^3 of foiditic lava and two lava flows reached the city of Goma. About onetenth of the city was destroyed and tens of thousands of refugees fled to adjacent Rwanda. Furthermore, in the 5 days following the effusive activity, about 100 tectonic earthquakes (M > 3.5), located between Goma's Lake shore and Nyiragongo, were recorded. The strongest earthquake (M=5) struck at 00:14 (UT) on January 20, 2002 (Tedesco *et al.,* 2007a; 2007b). The seismicity was clearly felt as far away as Bukavu (60 km south in DRC), Kigali (Rwanda, 120 km east) and Kampala (Uganda, 150 km NE). The number of earthquakes gradually decreased with time but remained at abnormally high levels (Tedesco *et al.,* 2007b). Afterwards, the volcano erupted continuously from May 2002 up to now.

The events associated with the 2002 eruption were recorded by two local seismic stations (Bulengo and Katale; Fig. 1), of the local Goma Vulcanological Observatory (GVO). These two stations were not sufficient to allow any accurate earthquake location.

Therefore, despite the intense volcanic and seismic activity and the high density population, a seismic network was missing in the area; the MBAR station, belonging to the IRIS (International Research Institutions for Seismology) global network, located 200 km NE of Nyiragongo, was the closest station and the only one operating in this part of the African rift during this period (www.iris.edu). Unfortunately, the monitoring of seismicity in this area has not been an easy task with seismic stations repeatedly looted during the on-going social unrest and civil war. Therefore, because of the high volcanic and seismic hazard and for the extremely important location in the East African Rift, a well suited and fully operational seismic network was of fundamental importance for scientific research and for civil defence purposes.

2. The digital seismic network of GVO

The telemetered seismic network GVO (Fig. 1) was designed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) on the basis of the experience in digital seismic monitoring developed during the volcanic crises that occurred in the last years on active volcanoes in Italy and particularly at Stromboli (Italy). The network is composed of seven three-component stations: four stations are Lennartz 3D 5 s (LE3D/5s) seismometers, while the other three stations were equipped with a broadband Nanometrics Trillium 40 s sensor (Table 1). Nanometrics Trillium

Table 1 - The seismological network of GVO is composed of 7 stations: Bulengo (BLG), Kibumba (KBB), Goma (GOM), and Rusayo (RSY) which deploy Lennartz (LE3D/5s) seismometers and Katale (KTL), Kibati (KBT) and Kunene (KNN) where Nanometrics Trillium 40 s are used. Signals from these stations are digitized locally from a data logger 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.

Station	Location	Latitude	Longitude	Elevation (m)	Instrumentation
BLG	Bulengo	-1.6280	29.1380	1480.0	Lennartz LE3D/5s
KTL	Katale	-1.3247	29.3838	1600.0	Nanometrics Trillium 40 s
KBT	Kibati	1.5690	29.2770	2000.0	Nanometrics Trillium 40 s
KBB	Kibumba	-1.5190	29.3330	2029.0	Lennartz LE3D/5s
KNN	Kunene	-1.4800	29.0670	1800.0	Nanometrics Trillium 40 s
OVG	Goma	-1.6810	29.2270	1470.0	Lennartz LE3D/5s
RSY	Rusayo	-1.5780	29.1810	1694.0	Lennartz LE3D/5s

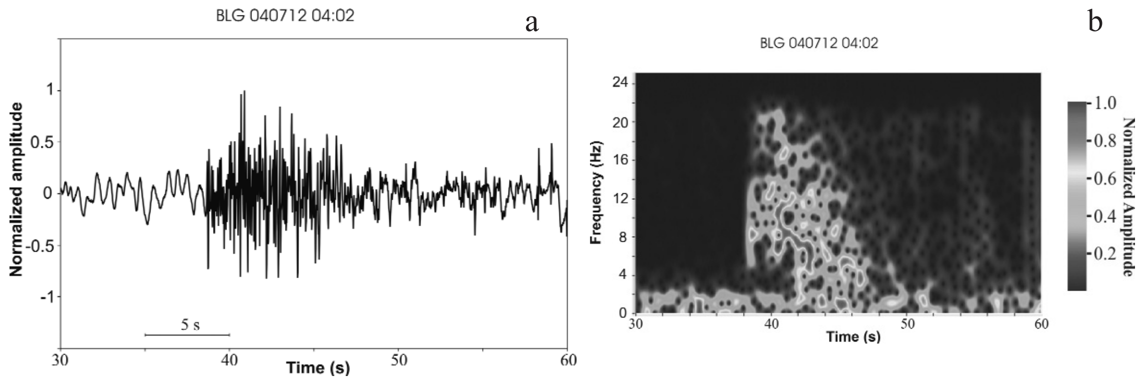
40 s broadband seismometers measure ground motion over a wide frequency range with flat response to velocity from at least 0.025 to 50 Hz, while Lennartz LE3D/5s is a sensor with the frequency range 0.2-40 Hz.

The sampling rate used by the network is 50 Hz. Furthermore, the network is composed of 24-bit A/D converters, a GPS synchronization at each remote station with a radio modem link on the 444-447 MHz frequency band, solar panels and batteries for power supply in the remote sites and a PC-based acquisition and analysis system.

The digitizing unit, named "Geophysical All Inclusive Acquisition" or GAIA system, is a very low noise, modular system, specifically developed by the INGV seismological unit for the National Centralized Seismic Network and it has been deployed in the field since 2002 (Salvaterra *et al.,* 2007). Its portable configuration is composed of two boards: the AGDF1 (the main board) and the GPS board, both placed in a waterproof box. The AGDF1 uses a 3 Crystal 24 bit ADC (analog-to-digital converters), one for each component, in order to transform the analogue signal from the sensor into a digital stream. The GPS guarantees a very accurate synchronization of the sampling clock.

The communication protocol over radio link uses a FSK (Frequency Shift Keying) and the radio-modem used is a Satelline 3A5 model by Satel. It is compact, low-power, and able to transmit a 19200 bps flow on a serial line using 25 KHz of bandwidth.

The very poor safety conditions of the area for both persons and goods, forced the installation of instruments in location easy to control. The technical staff of the GVO built seven concrete buildings, organized a very efficient, although costly, 24H surveillance service. Six remote sites are connected by radio link directly to the GVO. The Katale (KTL) station, located on the north-eastern side of the volcano (Fig. 1), needed a radio repeater along the road to Goma due to its specific location and morphology configuration. These sites did not operate till the end of 2004 for safety reasons. Therefore, after 2004 the GVO has been receiving digital data only from the



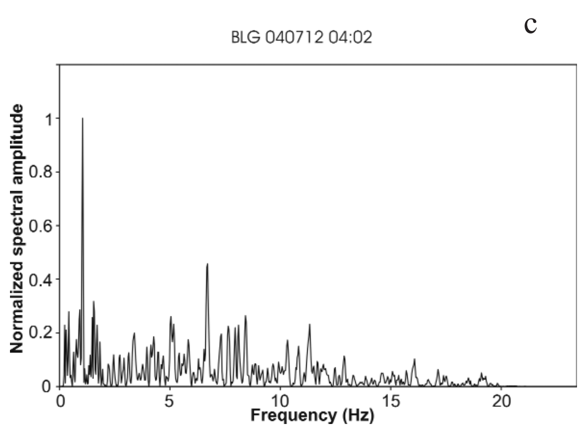


Fig. 2 - Waveform (a), spectrogram (b), and spectrum (c) for typical VT earthquakes observed on Nyiragongo volcano at station BLG. The spectrum is calculated for the whole period of the seismogram. The peaks in frequency at 0.5-3 Hz are observed. The light colour of the spectrogram defines the dominant spectral amplitudes while dark gray colour defines lower amplitudes, also for Figs. 4 and 5.

six centralized stations. Because of the improved safaty situation, we hope to re-establish the radio-connection in 2009.

The acquisition software we are using in Goma is a subset already used during the Stromboli volcanic unrest occurred in 2002-2003 and is a part of the INGV centralized acquisition software suite running at the Rome central base. The system can save waveforms as time series in SAC format as well as images in Portable Network Graphic (PNG) format. To save disk space, a scheduled task compresses all the folders into a file after the scheduled time has passed.

3. Preliminary data analysis

The spectral analysis was performed to characterize the short-scale temporal evolution of different seismic signals. The spectral analysis was performed computing the Power Spectral Density (PSD) on each seismogram. Moreover, to underline the distribution of spectral energy in signals, also spectrograms have been calculated. Each spectrogram has been computed using successive 2.56 s windows with 2.06 s of overlap. Each window has been smoothed with the use of Hanning window and individually normalised.

Based on the visual and spectral results, different seismic signals have been recognized.

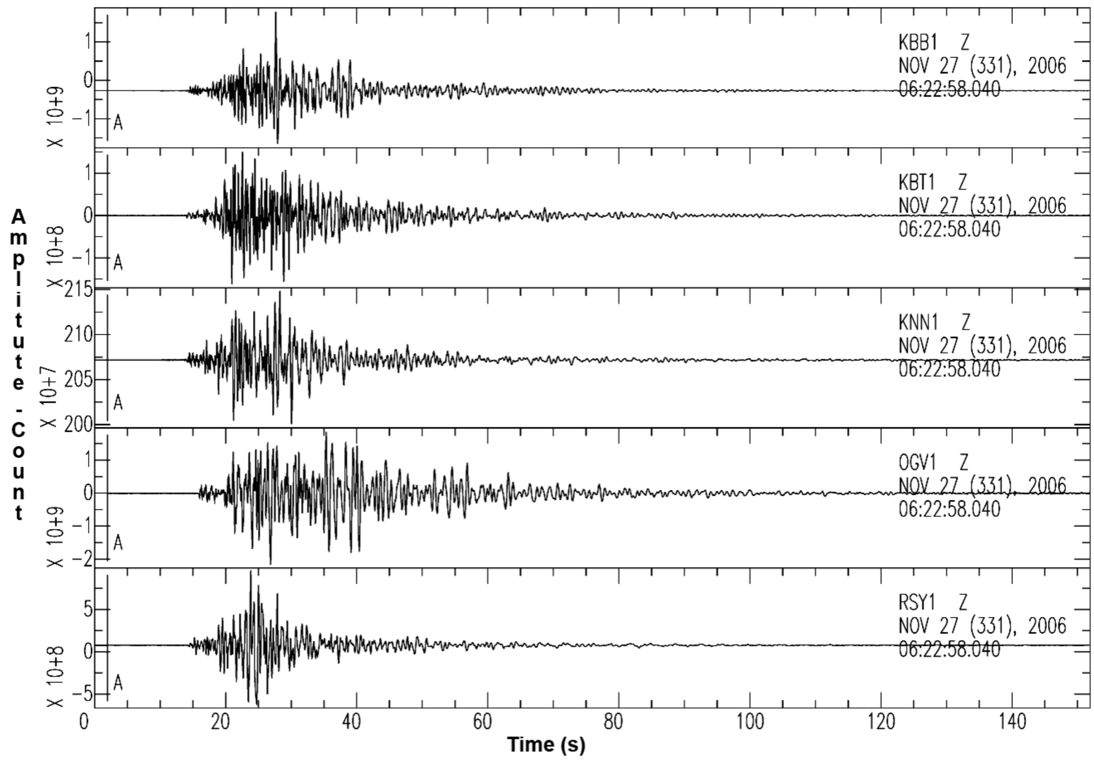
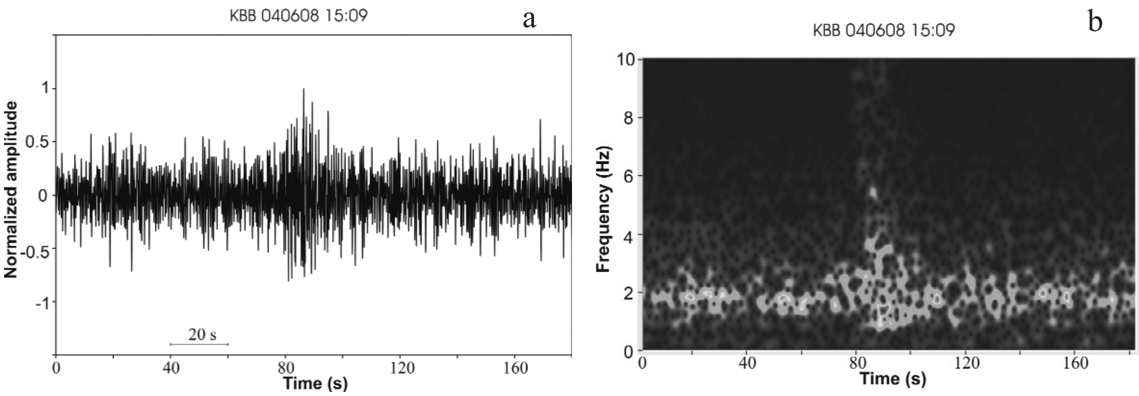


Fig. 3 - Waveforms for typical tectonic earthquakes (Ml=3.3) occurring in the Virunga area, located by ISC (2008): 2006/11/27; 06:23:11.82; Lat -1.8193; Lon 29.0729.

- Earthquakes (both tectonic and volcanic-tectonic, VT) characterized by an impulsive onset and a high frequency spectrum (greater than 5 Hz) with a progressive attenuation of the signal amplitude towards the coda. P and S waves are easily distinguishable (Fig. 2), with S-P times around 10 s. The VT earthquakes (Fig. 2) are related to brittle failure associated with the structural response of the volcanic edifice to the intrusion and/or withdrawal of fluids (e.g. Chouet, 1996; McNutt, 2005). Indeed, we believe that common tectonic earthquakes (Fig. 3) we recorded at Nyiragongo occur when rocks and/or magma in the Earth's crust break and move due to rift movement. This seems the case here at Nyiragongo volcano.
- Long-period (LP) events recognizable as longer signals than VT signals, are characterized by a weak emergent P onset and by the absence of the S phases (Fig. 4). Their predominant frequency content is in the range of 1-3 Hz with a dominant spectral peak around 1 Hz. LP events are attributed to resonance of fluid-filled cracks or conduits induced by pressure transients in the fluid (e.g. Chouet, 1996). Chouet (2003) suggested that LP events may reflect the response of the hydrothermal system to enhanced degassing associated with magma transport in the deeper conduits. However, in the area of Nyamulagira and Nyiragongo there is a lack of any superficial hydrothermal system. There is also evidence that such a system does not exist at depth (Tedesco *et al.,* 2007a). We then associate the LP



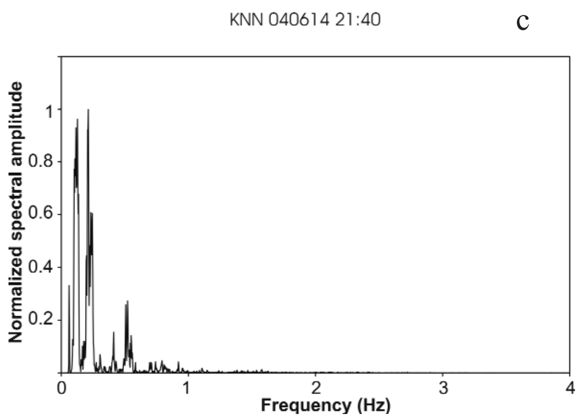


Fig. 4 - Waveform (a), spectrogram (b), and spectrum (c) for a typical LP event observed on Nyiragongo Volcano at station KBB. The spectrum is calculated for the whole period of the seismogram. A dominant spectral peak at 1.5 Hz is observed.

events to direct magma degassing at depth and resonance in close to surface crackes.

- We also detect very long period (VLP) events showing features similar to those associated to LP events but with lower frequency content (< 0.1 Hz) (Fig. 5). The VLP commonly observed beneath volcanoes represent the elastic response of the conduit's wall to volumetric changes associated with a mass (mostly gas) transport process.
- A volcanic tremor which appears as an irregular sinusoidal continuous seismic signal of long duration in comparison to a tectonic earthquake of the same amplitude.

In general, LP-type events include different volcanic transients with dominant frequencies in the range between 0.5 and 5 Hz, having sharply peaked spectra, showing generally a dominant peak and, sometimes, several subdominant peaks. The most common LP events recorded in volcanic areas face a main frequency peak around 1-2 Hz. Lower frequencies, from 2 s up to tens of seconds, are usually considered as VLP signals. So, using 5 s seismometers (four GVO's stations used LE3D/5s) it is possible to see a portion of this band (>1 s – 5 s) and then, at least technically, it is also possible to see VLP events if their frequency content lies in this range. Obviously, VLP events with periods larger than 5 s will not be observed using the 5 s seismometers. In our case, we observed VLP events with a clear peak around 2-3 s, so with frequencies laying into the (flat) frequency response of the 5 s seismometers.

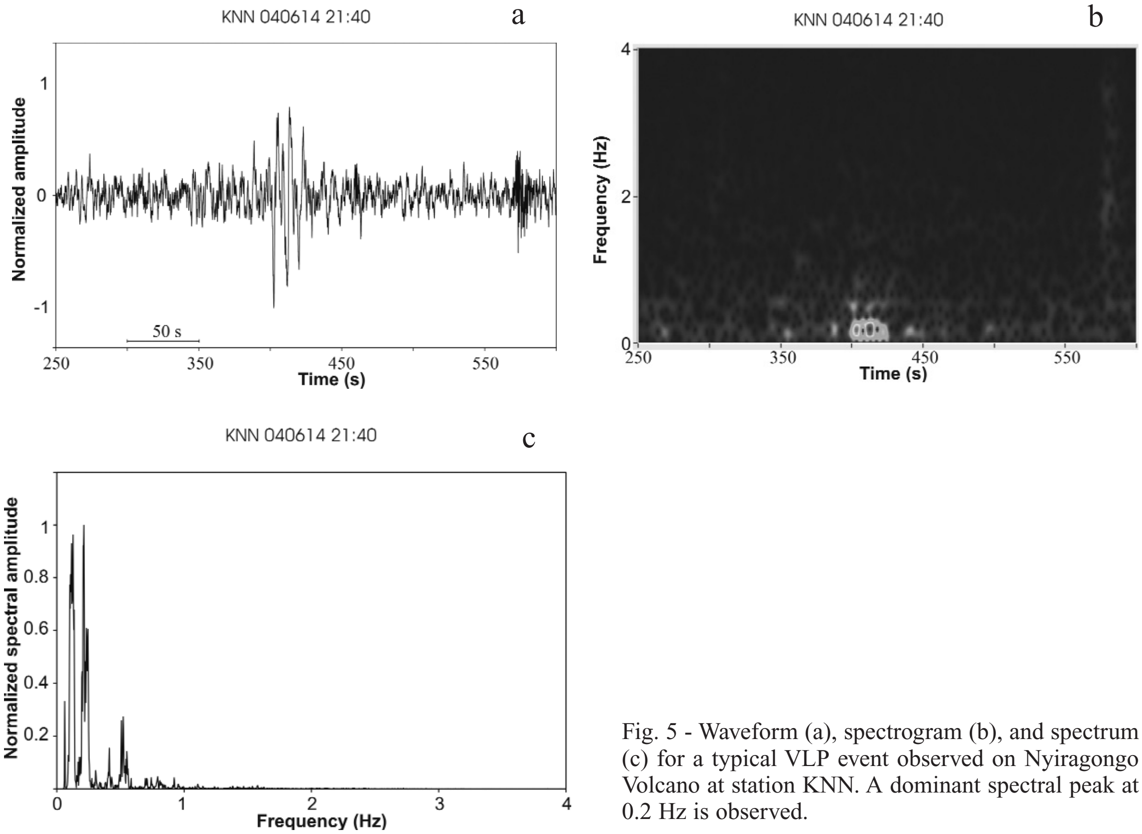


Fig. 5 - Waveform (a), spectrogram (b), and spectrum (c) for a typical VLP event observed on Nyiragongo Volcano at station KNN. A dominant spectral peak at 0.2 Hz is observed.

4. Discussion of data

The earthquakes we analyze occurred from February to July 2004. This period is characterized, at least through visual observations, by an intense volcanic activity within the crater, with lava fountains and growth of the lava lake.

From the whole available data set we selected local earthquakes that occurred around Nyiragongo Volcano using the following two criteria: (i) P and S waves arrival time clearly recorded at more than three stations and (ii) travel time differences between the P and S waves at each station less than 15 s. Those events were located with a HYPOELLIPSE code (Lahr, 1989).

Table 2 - One-dimensional P-velocity model in the Virunga volcanic area. The S-wave velocities are calculated using the Vp /Vs ratio of 1.73.

Depth (km)	P-wave (km/s)
0-3	4.0
3-20	6.0
20~30	6.7

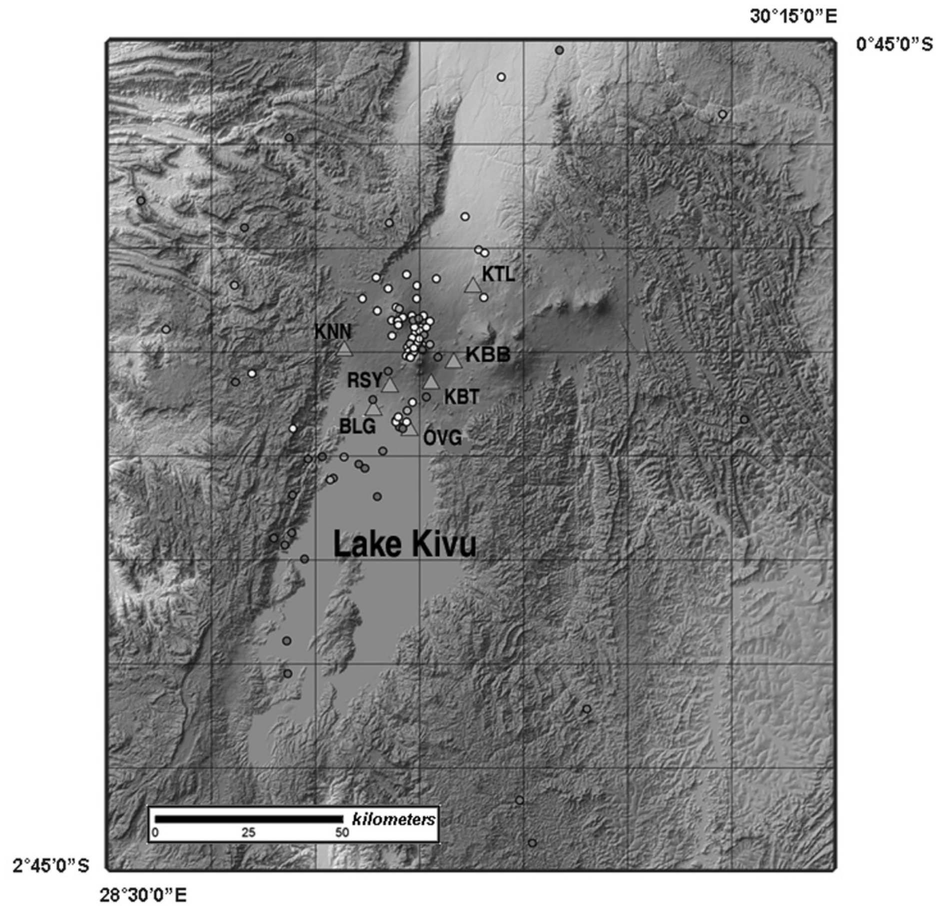


Fig. 6 - Locations of earthquakes that occurred in the Virunga area in February-July 2004. White circles = depth < 5 km; light grey circles = 5 ≤ depth ≤ 10 km; dark grey circles = depth > 10 km. Seismic stations are also reported with grey triangles.

The final data set consists of 108 precisely located earthquakes.

To calculate earthquake hypocentres we assumed a simple two-layer model (Table 2), which has proved to work well and it has been already adopted in previous works on the same volcanic area [Mavonga *et al*. (2006) and references therein], that incorporate gravity data results obtained from a survey in the western part of the Virunga volcanic complex (Zana *et al*., 1992).

From hypocenter's spatial mapping (Fig. 6) three distinct distributions of the earthquakes are put in evidence: 1) very shallow events (depths less than 5 km) located between Nyiragongo and Nyiramuragira volcanoes; 2) earthquakes with a depth of slightly more than 5 km, except few events deeper up to 40 km located beneath Lake Kivu; 3) a shallow depth cluster of events, located near and beneath the city of Goma, is interesting, and at the same time alarming, on the basis of recent works of Tedesco *et al.* (2007a, 2007b). After studying the different characteristics related to the 2002 eruptive event of Nyiragongo Volcano, the authors hypothesize that possible future eruptive scenarios may start close to, or even within, the city of Goma. The same authors also propose a relationship between the January 2002 eruption of Nyiragongo and a previous, or coincident, significant rifting event in the Nyiragongo–Lake Kivu area. The cluster close to the city of Goma can be also related to the subsidence affecting the northern portion of Lake Kivu [between 35 and 70 cm; Tedesco *et al.* (2007b)] and support the hypothesis that rifting is not confined to the volcano but affects a much larger area. If so, rifting might therefore become the dominant style of future eruptions at Nyiragongo, together with the presence of an active lava lake within the main crater. This incredibly activity increases the seismic and the volcanic hazard in the Nyiragongo–Lake Kivu area.

5. Conclusions

The telemetered seismic network of GVO has been operating in the Virunga Volcanic Province and signals have been recorded continuously for four years. Data have been continuously shared between the GVO and the INGV. Waveforms and spectral analysis show how the network, despite the constraining geometry, is able to correctly record both high and low frequency events. This activity has been associated with a variety of processes occurring in this active volcanic area, including Nyiamulagira and Nyiragongo volcanoes.

Shallow quakes, less than 5 km deep, that occur under the volcano and beneath the city of Goma can evidence (i) of a plumbing system not only related to the central part of two active Nyuamulagira and Nyiragongo volcanoes, but extends south, towards the city of Goma and Lake Kivu or (ii) of an independent magmatic system located close or just beneath the city of Goma, as recently proposed by Tedesco *et al.* (2007b). To correctly figure out this issue and to have a better model is of the utmost importance in order to constrain the volcanic hazard of the area and mitigate possible future catastrophic events.

Therefore, an increasing number of seismic stations is necessary to better forecast the eruptive behaviour of Nyiragongo Volcano and to better assess the local volcanic hazard. Furthermore, future studies should be integrated with the deployment in the field of portable arrays duting periodic campaign useful to understand the local shallow seismicity occurring beneath or in the vicinity of the city of Goma and Lake Kivu.

Encouraged by those interesting results of this preliminary study, our next step will be the analysis of the four years available in the data set to better constrain the hypocentral depth of earthquakes and calculate the seismic velocity model for the crustal structure beneath the volcano.

We also need to develop routine tools to distinguish Nyiragongo from Nyamuragira seismicity, while the local GVO needs a long term perspective in order to ensure a continuous and correct evaluation of the activity of the two volcanoes, the city of Goma and the Lake Kivu area.

Acknowledgments. The authors sincerely thank all members of the Goma Volcano Observatory and Lwiro Seismographic Station for their continuous efforts to maintain seismographic stations. Stefano Vinci helped us drawing the figures with earthquake locations. The authors thank the referees for their helpful suggestions concerning the presentation of this paper.

REFERENCES

Chouet B.; 1996: *Long-period volcano seismicity: its source and use in eruption forecasting.* Nature, **380**, 309–316.

Chouet B.; 2003: *Volcano seismology*. Pure and Applied Geophysics, **160**, 739-788.

ISC (International Seismological Centre); 2008: *On-line Bulletin.* http://www.isc.ac.uk, Internatl. Seis. Cent., Thatcham, United Kingdom.

Lahr J.C.; 1989: *HYPOELLIPSE/Version 2.0: a computer program for determining local earthquake hypocentral parameters, magnitude, and first motion pattern.* U. S. Geol. Surv. Open File Rep., **95,** 89-116.

Mavonga T., Kavotha S.K., Lukaya F., Etoy O. and Durieux J.; 2006: *Seismic activity prior to the May 8, 2004 eruption of volcano Nyamuragira, Western Rift Valley of Africa.* Journal of Volcanology and Geothermal Research, **158**, 355–360.

McNutt S.R.; 2005: *Volcanic seismology.* Annual Review of Earth and Planetary Sciences, **33**, 461-491.

Platz T., Foley S.F. and André L.; 2004: *Low-pressure fractionation of the Nyiragongo volcanic rocks, Virunga Province, D.R. Congo.* Journal of Volcanology and Geothermal Research, **136**, 269-295.

Salvaterra L., Pintore S. and Badiali L.; 2007: La rete sismologica basata su stazioni Gaia. Rapporti Tecnici INGV, **68**, 1-26.

Simkin T., Siebert L., McClelland L., Bridge D., Newhall C. and Latter J.H.; 1981: Volcanoes of the World. Hutchinson Ross, Pa. Usa, 233 pp.

Tazieff H.; 1979: *Nyiragongo: the forbidden volcano*. Barron's Educational Series, 288 pp.

Tedesco D., Badiali L., Boschi E., Papale P., Tassi F., Vaselli O., Kasereka C., Durieux J., Denatale G., Amato A., Cattaneo M., Ciraba H., Chirico G., Delladio A., Demartin M., Favalli G., Franceschi D., Lauciani V., Mavonga G., Monachesi G., Pagliuca N.M., Sorrentino D. and Yalire, M.; 2007a: *Cooperation on Congo volcanic and environmental risks.* Eos, Transactions, American Geophysical Union, **88**, 177, 181.

Tedesco D., Vaselli O., Papale P., Carn S.A., Voltaggio M., Sawyer G.M., Durieux J., Kasereka M. and Tassi F., 2007b: *January 2002 volcano-tectonic eruption of Nyiragongo volcano, Democratic Republic of Congo.* Journal of Geophysical Research, Vol. 112, B09202, doi:10.1029/2006JB004762.

von Götzen G.A.; 1895: *Durch Afrika von Ost nach West*. D. Reimer, Berlin, 416 pp.

Vunganai M., Hlatywayo D.J., Chapola L.S., Kebede F., Atakan K., Lombe D.K., Turyomurugyendo G. and Tugume F.D.; 1999: *Seismic hazard assessment in eastern and Southern Africa; the Global Seismic Hazard Assessment Program (GSHAP) 1992-1999.* Annali di Geofisica, **42**, 1067-1083.

Zana N., Tanaka K. and Kasahara M.; 1992: *Main geophysical features related to the Virunga zone, Western Rift, and their volcanological implications.* Tectonophysics, **209**, 255–257.

Corresponding author: Nicola Mauro Pagliuca
Istituto Nazionale di Geofisica e Vulcanologia
Via di Vigna Murata 605, 00143 Roma (Italy)
phone: +39 06 51860459; fax: +39 06 5041181; e-mail: pagliuca@ingv.it