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Weakness areas conducive to the intrusion of dykes by reference to the migration of the epicenters of swarms of long period earthquakes around the volcanoes Nyiragongo and Nyamulagira for the period 2002-2011

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ABSTRACT: We analyzed the seismic data collected in the database of the Goma Volcano Observatory, for the period from 2002 to 2011. Based on the location of the various swarms of Long Period Earthquakes, migration of epicenters were assessed in order to estimate the weakness areas which are the ways for dyke intrusions at Nyiragongo and Nyamulagira volcanoes, the two very active volcanoes the Western Branch of the East African Rift in the Democratic Republic of the Congo. We found that the intrusions of dykes occur in two main perpendicular weak axes: the NE-SW axis generated by tensional forces from the East African Rift actions, and the NW-SE axis generated by divergent forces from the actions of magmas of both volcanoes.

KEYWORDS: Nyiragongo Volcano, Nyamulagira Volcano, dyke intrusion, epicenter's migrations, NW-SE axis NE- SW axis.

1 INTRODUCTION

Dike intrusion is an important process during volcanic eruptions and has been intensely studied by theoretical modeling and geophysical observations. The migration of hypocenters of earthquake swarms associated with volcanic activity is considered as one of the most reliable indicator of dike propagation [1], [2], [3]. These earthquakes are considered to occur at the perimeter of the dikes where the fractures open, viscous fluid fills the crack, and the wall rock pushes in to resist the opening, leading to spatially varying state of stress around the dike [4], [5]. Migration of the tip of the dike is often recorded by the migration of hypocenters and hypocenters are aligned on a plane or line as a consequence [6].

Most previous studies have been unable to accurately determine hypocenter locations within earthquake swarms, and consequently have been unable to produce a detailed picture of dike intrusion. Precise tracking of hypocenter migration is required for an understanding of the dike intrusion process [7].

The patterns of hypocenter distribution indicate that dike intrusion generates extensional stress within a very narrow region and it makes easy to satisfy the fracture criterion of host rock around the tip of the propagating dike [8]. Therefore precisely determined hypocenters that record a systematic linear or planar alignment with a systematic migration are one of the most reliable tracers of the magma perimeter; furthermore, systematic migration of the hypocenters indicates movement of the magma. Seismic data provides a high resolution in the location of a perimeter of the magma [7]. The distribution of epicenters is the surface expression of the hypocenters located in depth, in other words, the orientation of the epicenters gives an idea of the orientation of a magmatic dike in depth.

In this paper, we show an accurate epicentral distribution of the earthquake swarms occurring at volcanoes Nyiragongo and Nyamulagira from 2002 until 2011, and propose a Pattern that explains the different migrations of epicenters which embodies the various processes of intrusions of dikes and their weakness areas forming. This area is the only most active volcanic region of the Western branch of the East African Rift, where the earthquake swarms have been intermittently recorded from the implantation of a seismic network after the latest eruption of Nyiragongo in 2002, which caused many property damages in the city of Goma.

2 Tectonic Settings And Seismic Activity Of Nyiragongo And Nyamulagira Volcanoes

2.1 Tectonic Sittings

Nyiragongo (29 ° 15 'E, 1 ° 30' S) and Nyamulagira (29°12’E, 1°24’S) remained the only two active volcanoes of the Virunga chain where raw volcanic events are beginning to Cenozoic there are about 11 Millions of years [9], [10], [11], [12]. The Virunga volcanic chain is a highly alkaline province of the western branch of the East African Rift [13], which extends over approximately 50Km in East-West direction, north of Lake Kivu, and locally crossed by the Rift. It is obvious that in this region two systems are in game: Volcanism and Tectonics [14]. Nyiragongo volcano is more characterized by fissural eruptions and some cracks from the southern flank of the volcano reaching the Lake Kivu and are in connection with the faults of the Rift [15], [16]. There were the lava flows from these southern flank cracks of the volcano which caused disasters to the city of Goma and its surroundings in 2002 after the eruption of Nyiragongo [15]. Nyiragongo possesses two main secondary volcanic cones; Baruta in the North and Shaheru in the South, as well as several cones that Reference [13] classified into three groups: (1) The Mudjoga- Bushwaga group; taking the NNE-SSE axis on the southern flank of Shaheru, (2) The Nyamushwa group taking the EW axis, and (3) The Rusayo group taking the NE-SW axis. The alignment of these different axes of cones, defines the presence and orientation of fissures [17].

Many of the eruptions from Nyamulagira volcano are fissural and come out of the flank of the volcano [18], [19]. These cracks from which Nyamulagira erupts are connected with the faults of the Rift [16]. The eruptions of Nyamulagira are made by means of dikes and fissures, which occasionally cut the 2 × 2.2 Km of the caldera, but many come mostly on the flank [16]. The orientations of the dykes are controlled by the stresses of the regional tectonic occurring in the Rift interior [20], [21]. Both local stress resulting from factors such as topography, major pressures on the surface of magmas [20], also by pre-existing faults, fractures and layers of rocks of low consolidation [22], are factors which game in the region. Fig. 1 shows that the area is completely invaded by numerous faults from the Rift, in the Virunga Volcanic field as well as in the Lake Kivu. This causes the region to beat heater of tectonic earthquakes with magnitude between 4 and 6, especially in the Lake Kivu and its surroundings.

2.2 Seismic Activity

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.
As noted above, two types of parameters play both in the region: Tectonic parameters related to the stresses generated by the movement of the East African Rift and volcanic parameters generated by stresses related to the movement of the magma. Thus the authors of References [23], [24] and [18] were based on studies made by [25, [26], [27] and classified the seismic events of the region as follows:

- The Short- period earthquakes (SP) or High Frequency earthquakes (HF), which are earthquakes with P and S waves discernible like tectonic earthquakes, with frequency higher than 5Hz. Their S-P is less than 5 seconds and are located in the Virunga volcanic field. These types of earthquakes are thought to be induced by sudden fractures of rocks, behind the stress caused by magma pressure [28], [24], [18],
- Long Period earthquakes (LP) or low frequency earthquakes, which are transition seismic signals with low P and S emerging or non-existent, with a predominance of the low frequency component between 1 and 3 Hz. These types of earthquakes are assumed to be likely due to the excitement of some fixed cavities behind a magmatic fluid migration [25], [24],

- 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.

The seismic behavior of Nyiragongo and Nyamulagira volcanoes was also studied by different authors and their results show that there is always a gradual increase in seismic activity before a volcanic eruption [29], [24], [19].

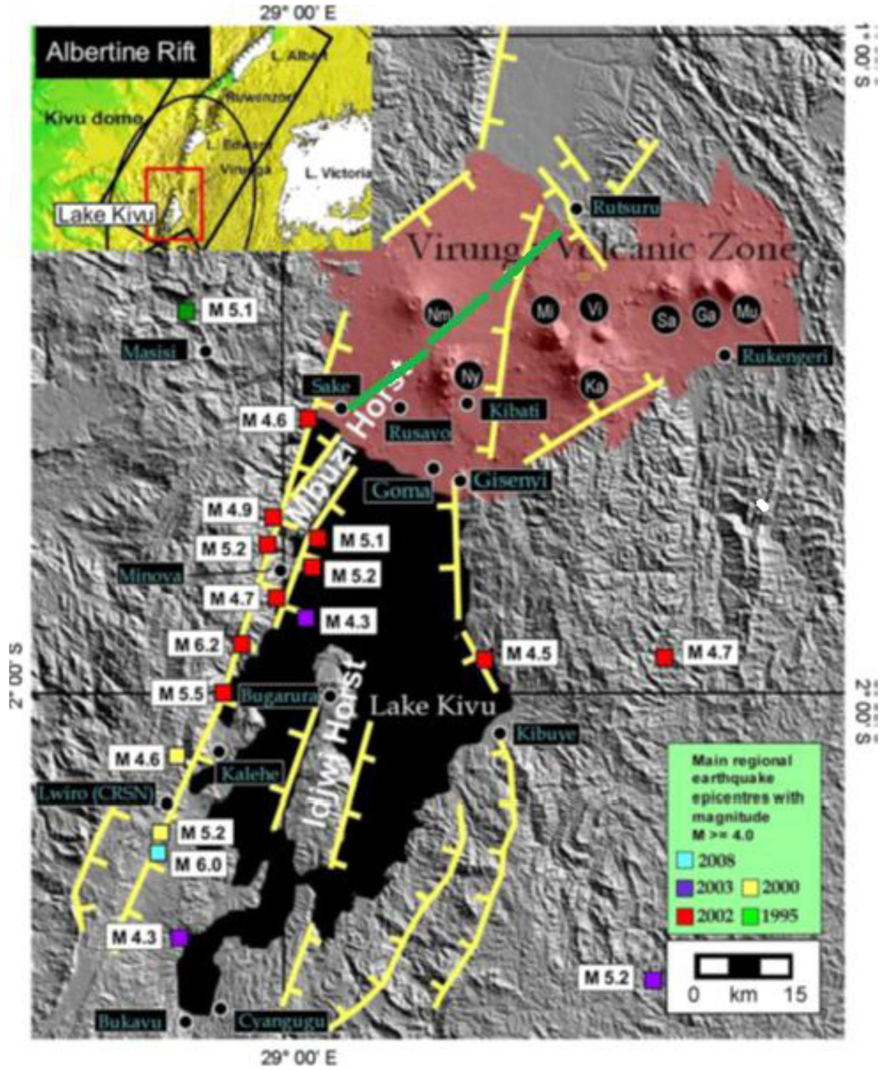

Fig. 1. Fault map of the Kivu Basin and recent large earthquake epicenters (>=Mw 4.0). It shows the eight volcanoes of the Virunga volcanic field; Nm=Nyamuragira; Ny=Nyiragongo; Mi=Mikeno; Ka=Karisimbi; Vi=Visoke; Sa=Sabinyo; Ga=Gahinga; Mu=Muhavura. Inset: The location of the Kivu Basin at the southern end of the Albertine Rift (red box), the Yellow lines represent the faults of the rift, interspersed green lines between Nyiragongo and Nyamulagira represent the general trends of the rift direction in this area. Modified after [16]

3 DATA ACQUISITION AND METHODS

3.1 DATA ACQUISITION

The seismograms used in this study were provided by the seismological network of the Goma Volcano Observatory (GVO). The true observation network began in 2002 and was composed of eight analog stations (Fig. 2) : 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 convertisser 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.

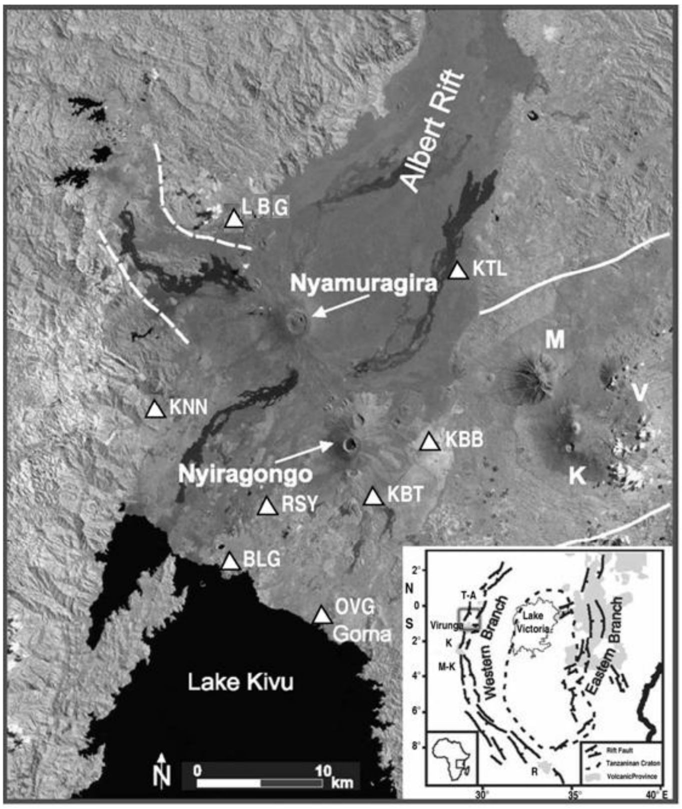

Fig. 2. Seismic network of the Goma Volcano Observatory. Seismic stations are marked by white triangles (Goma-OVG, Kunene-KNN, Rusayo-RSY, Bulengo-BLG, Kibumba-KBB, Kibati-KBT, Katale-KTL, Luboga-LBG).

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].

3.2 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. 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. A total of 55374 P and 33863 S wave arrival times were picked from ∼22320 local earthquakes recorded within the Virunga volcanic province from 2002 until 2011 operating period of the analysis. All 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 6 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 2.5 km and a standard root mean square (rms) error on the travel time residual less than 0.5 s. It was thus revealed that the maximum accuracy on focal depth is obtained for erz=5 km.

4 RESULTS

The database of the Goma volcano observatory has been looked for the period from 2002 to 2011. A total of 73 swarms were identified as well as 5 Nyamulagira volcano eruptions (25th July 2002, 8th May 2004, 27th November 2006, 2nd January 2010 and 6th November 2011). No outside eruption was observed for the Nyiragongo volcano during this period if not the intracrateriel eruption materialized by the presence of a permanent lava lake in place since its January 2002 eruption. In this paper, the period between two eruptions is considered as an eruptive cycle. Then, a total of five eruptive cycles are assessed. In the compilation of the data we plotted all the swarms of each eruptive cycle on a map in order to evaluate trends of epicenters before each eruption.

Table 1. Description of the different swarms of LP earthquakes observed in the Nyiragongo-Nyamulagira Volcanic zone for the five eruptive cycles

Eruptive Cycle	Duration of the cycle	Number of swarms	Total number of events for all the eruptive cycle	Locatable events for each eruptive cycle
1	17th January 2002 - 25th July 2002	3	873	354
2	26th July 2002 - 8th May 2004	21	8974	4576
3	9th May 2004 - 27th November 2006	17	5489	1584
4	28th November 2006 - 2nd January 2010	25	10871	3289
5	2nd January 2010 - 6th November 2011	8	1089	573
Total		73	27296	10376

Swarms which preceded the 25th July 2002 eruption, marked earthquakes early harvested after the eruption of the Nyiragongo in January 2002. They can be classified into three groups: The first group is characterized by earthquakes aligned to an oblique line, pass through the Nyiragongo, follow the NE-SW direction (see blue line in Fig. 3.a), which is the general trend of the Rift in the Nyiragongo and Nyamulagira zone. It is obvious that after the January 2002 Nyiragongo eruption, many events were aligned in the areas of the Rift faults, and more precisely on the axis of the Rusayo group of cones described above. The second group of swarms precedes directly the 25th July 2002 eruption of Nyamulagira, which released on the northern flank of the volcano. These events are concentrated in the Nyamulagira crater and more precisely in the North and Northeastern part of the crater. The third group of swarms consists of earthquakes observed in the Lake Kivu and in the northwestern areas of Nyamulagira Volcano (See fig.3.a), they are due to the Rift activity.

This seismic activity on Nyiragongo was highly observed after the January 2002 eruption. After this eruption a lava lake appeared inside the volcano and seismic activity decreased gradually. All the activity remained focused around the Nyamulagira volcano and at Nyiragongo, only very long period events are observed from 2003 until 2011.

After the eruption of the Nyiragongo in january 2002 and the July 2002 Nyamulagira, stresses due to magma movements were intense and were been combined with stresses generated by the effects of the Rift. Henceforth a zone of great weakness was been generated in the area between the two volcanoes, in the NW-SE direction and becomes the theater of volcanic earthquakes (Figure 3.b, 3.c, 3.d and 3.e).

The May 2004 eruption was preceded by 21 swarms of volcanic earthquakes, all located in this weakness zone along the NW-SE direction, forming a flat surface (See Fig. 3.b). All the events are located and concentrated in this direction. The eruption of November 2006 was preceded by 17 swarms, all located in the same direction, with the same trends along the axis NW-SE, and almost all the epicenters are in the crater of Nyamulagira and its surroundings. The eruption of January 2010 was preceded by several swarms, a total of 25 swarms, including swarms with very long duration but without leading to an eruption. On January 2, 2010 a small swarm span of roughly 16 hours occurred on the side of the S-SW of Nyamulagira at about 2 km from the summit crater. It was this swarm which conducted to the eruption. Before this eruption, swarms observed show different trends aligned in two main areas: The NE-SW axis corresponding to the general direction of the rift, in what many intrusions and dykes are associated, the January 2, 2010 eruption is no exception of this axis and the NW-SE axis along the weakened area connecting the two volcanoes, very intense seismic zone of the fields. We make sure that the combined effects of tectonics and magmatic mark the two axes creating areas of weakness between Nyamulagira and Nyiragongo volcanoes. The eruption of November 6, 2011 was preceded by a total of 8 swarms, all located in the crater of Nyamulagira and its surroundings and the most remarkable trend epicenter is in the NE-SW axis, general trend of the Rift orientation.

So synthetically, migration of epicenters shows us that two main axes are conducive to dyke intrusions in the volcanic field of Nyiragongo and Nyamulagira. (1) The NE-SW axis, corresponding to the general trend of the faults from the East African Rift and areas of weakness in this axis are generated by tectonic effects of the Rift. This axis is more remarkable for its eruptive fissures with large volumes of lava coming out, more often on the side of the volcano or at distances not exceeding 5 Km from the main crater. Areas affected by this axis are the NE and SW part of the Nyamulagira crater, which are so active and from which come most of the volumetric eruptions of Nyamulagira.

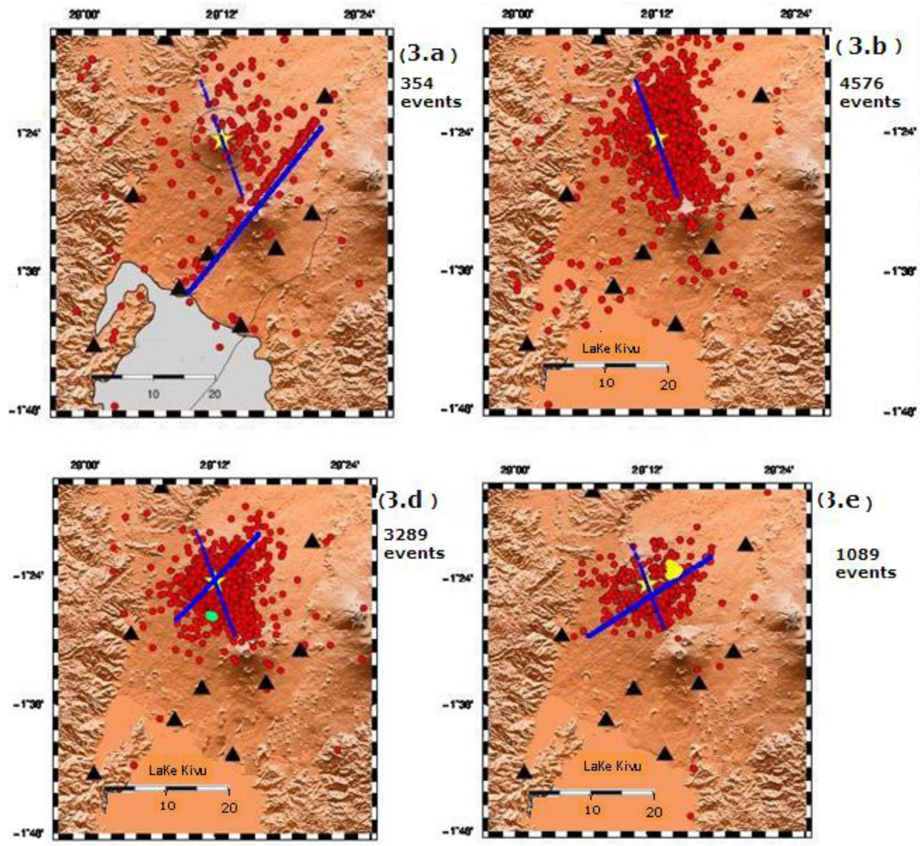

Fig. 3. Epicenter locations of the LP events for all the five eruptive cycles.(3.a) January 2002- 25th July 2002; (3.b) 26 july 2002-08 May 2004; (3.c) 9 may 2004-27 november 2006; (3.d) 28 November 2006-2 january 2010; (3.e) 2 january 2010-6 Novembre 2011. Blue lines indicate the alignment of epicenters and therefore define weakness areas in the region. Green and yellow dots on 3.d and 3.e represent respectively eruptive points of the January 2010 and November 2011 eruptions from Nyamulagira. The yellow stars indicate the crater of the volcano Nyamulagira.

(2) The NW-SE axis, corresponding to the line of stress created by magmatic activity. The highest pressures in the magma chambers of the two volcanoes create divergent stress forces which consequently have managed to form a very important area of weakness between the two volcanoes. Using Satellite imagery, reference *[32]* developed the new volcanological map of Nyamulagira volcano, and listed that from 1938 to 2010, Nyamulagira volcano erupted 26 times, with 35 points of lava outcome. From them 7 on the summit of the volcano, 5 in the south-western part of the crater , 10 in the north-east part , 4 in the north-western part and 9 in the south-eastern part . It is there foreseen that the NE-SW and NW-SE axis are the best places of dyke intrusion following the areas of weakness they mark. The pattern developed in this paper is explained by the following mechanism: The Rift exercises extension forces in the region and of course between the two volcanoes in NE-SW direction, the flow of active magma in the rooms of the two volcanoes exerts also stresses in all sides of their surrounding environments. Thus, the combination of these two forces has created a very large fracture of more units of meters which connects the two volcanoes.

5 Discussion

5.1 The Weakness Areas From The Combined Rift And Volcanic Stresses

Generally, the state of tectonic stress in the crust of the Western Branch of the East African Rift, determined from earthquake slip vectors, has the least principal stress (σt3) directed horizontally and perpendicular to the Rift and the greatest principal stress (σt1) oriented vertically *[33]*. Reference [*33]* found E-W tension in the Lake Kivu basin, and oddly, a reverse faulting-type stress field with the intermediate principle stress axis (σt2) oriented NW-SE in the Virunga Volcanic Region. If we take this to be representative of the crust beneath Nyamuragira and Nyiragongo at the present time, then any faults underlying the major fissure systems ought to have different amounts of normal and oblique motion across them depending on their orientation relative to that of σt3, the least principal horizontal stress. Thus the roughly sigmoidal pattern of fissures/faults formed by the southwest fissures, the Nyamuragira-Nyiragongo fissures, and the northeast fissures means that from the sense of oblique-slip predicted on them, the plate motion-induced regional stress field will create zones of enhanced localized extension just north of Nyamuragira caldera.

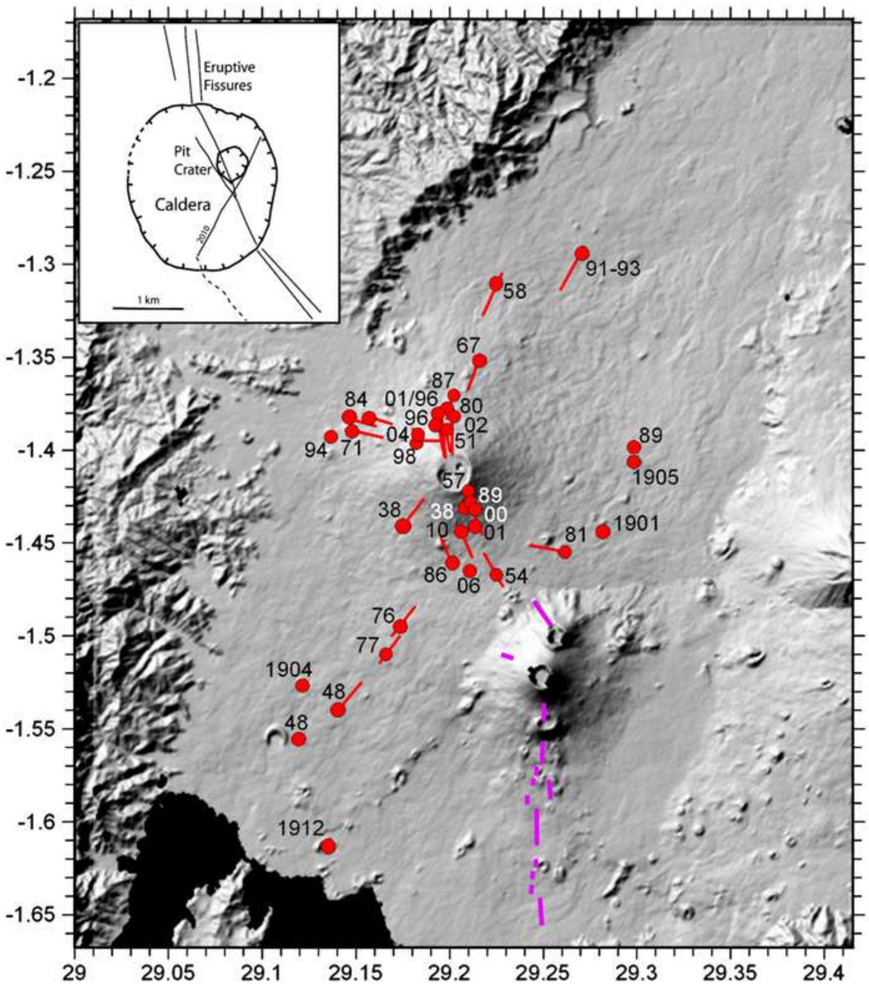

Fig. 4. Map showing the orientation of the historical eruptive fissures (red lines) of Nyamuragira, where known, and vent locations (red circles) of the historical flank eruptions, labelled with dates, on a shaded relief DEM. Base level is ~1500 m above sea level at Lake Kivu, lower left. The fissure systems of the 1977 and 2002 eruptions of Nyiragongo are shown in purple. Inset is a sketch map of the summit caldera of Nyamuragira and the main fissure systems. Figure from [21]

Reference [29], suggested that a major crack ≈ 5 km long and 1 m thickness come in the southern part of Nyiragongo in the direction S10 ° E, and the epicentral area of tectonic earthquakes are aligned to this fault from the top of Nyiragongo pass through the Lake Kivu in the direction S25 ° W, until the Idjwi Island. This direction does not coincide with those of surface cracks but have links with the Rift faults. He suggested again that the seismic activity along the axis of the rift becomes active after the eruption of Nyiragongo. This temporary spatial relationship between tectonic seismicity and eruptions strongly suggest the existence of a mutual connection between volcanic activity and Rift episodes. The slightly elongate caldera (2.3×2.0 km; NNW×ENE principal dimensions) at the summit of Nyamuragira indicates the presence of a shallow (less than 10 km depth), magma reservoir at some time in its recent history. The stress field surrounding such a reservoir, if axisymmetric, would have its intermediate principal stress ($\sigma v2$) radial and its least principal stress tangential ($\sigma v3$) which would tend to produce a system of radial fissures during flank eruptions.

The stress fields can be associated with a tectonic rifting environment and a central volcano within it as at Nyamuragira and nyiragongo. The distribution of eruptive fissures and the measurements of co-eruptive strain at Nyamuragira and Nyiragongo do not up port the concept of a single, simple source of magma at a shallow depth beneath the calderas that generates its own axisymmetric stress field guiding dyke emplacement. Thus such a stress field is either of another form or very much weaker than the tectonic field. However, there is evidence that eruptions fed by dykes parallel to the Rift tend to have longer durations than those fed by dykes oriented across the Rift. This can be explained qualitatively using the tectonic stress field alone. The magmatic overpressure within the Rift-parallel dyke must be greater than the least principal stress ($\sigma t3$) in order to remain open during the eruption, whilst in the case of the Rift perpendicular dyke the magma pressure must exceed the larger value of the intermediate principal stress ($\sigma t2$) [21]. For a given available volume and overpressure of magma the Rift-parallel eruption will continue longer than the Rift-perpendicular one [21].

5.2 Dyke Emplacements

The geodetic observations done by reference [21] suggest that the eruptions fed by dykes parallel to the East African Rift Valley are eruptions with long durations (and larger volumes) than those fed by dykes with other orientations. Reference [34] tried to make a modeling of InSAR displacements related with the January 2002 eruption of Nyiragongo volcano, and determined that the main part of deformation signal observed by InSAR, south and east of Nyiragongo between 14 january and 13 february 2002, can be explained by the combined effects of a 2 Km high sub vertical dike feeding the observed eruptive fissure, and a 15 Km long West dipping normal fault extending from the foot of Nyiragongo to the Northern part of the Lake Kivu.

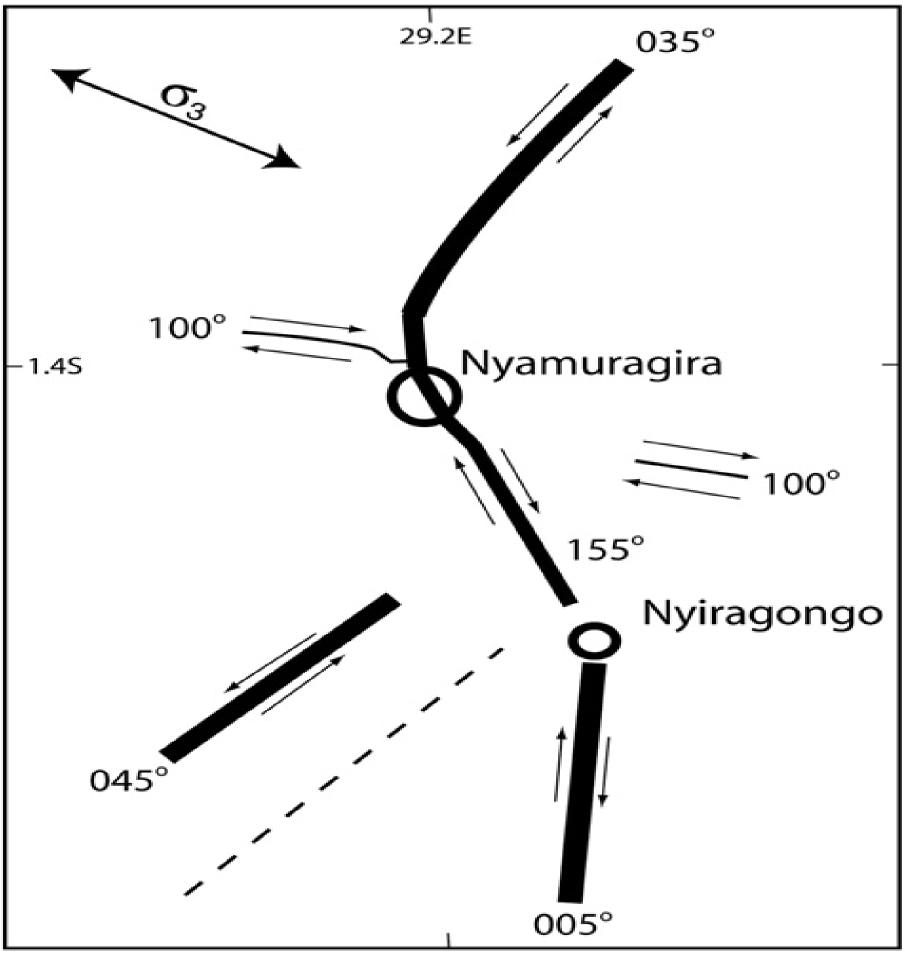

Fig. 5. Schematic map of the eruptive rift system of Nyamuragira and Nyiragongo as bold lines with the orientation at the most distal point. The width of the lines is proportional to their orientation perpendicular to least principal stress direction of the regional tectonic field, σt3 oriented 110°. The pairs of arrows show the sense of lateral motion across each dyke system due to the regional field. For clarity vertical components of displacement are not shown. The dashed line shows the approximate boundary between the two volcanoes. Figure from reference [21]

The dike is submitted to a low overpressure, consistent with the rift tension [34]. This fault is in the continuation of the known horst structures of the Idjiwi Island. It could also correspond to the interface between sedimentary layers tilted by the half rift graben opening. In their model, they explain about three weakness zones at Nyiragongo Volcano: The first links the two volcanoes, the second come from the south foot of Nyiragongo and continues until reaching beyond the city of Goma, the third come from the South-west of the foot of Nyiragongo and continuous until reaching lake Kivu. Reference [16] tried also to determine Co-eruptive and inter eruptive surface deformation measured by satellite radar interferometry at Nyamuragira volcano and found that during 7 of the 8 eruptions in their studying period, deformation was measured that is consistent with the emplacement of shallow near-vertical dykes feeding the eruptive fissures and associated with a NW-trending fissure zone that traverses the summit caldera. Between eruptions the caldera and the summit part of this fissure zone subsided gradually (b3–5 cm/year) [16]. Dyke orientations are controlled by regional tectonic stress accommodation within the rift zones. During intrusions at Nyamulagira, seismicity is limited only to the intruded portion of the rift and hypocenters are distributed between the surface and up to 10 km depth [16]. Generally, these hypocenters migrate geographically with the orientation of the dike, and after migration ceases earthquakes continue to occur for days along the inferred dike length with higher concentrations in the middle and tip of the dikes. Such patterns are always observed during intrusions in basaltic volcanoes, where they have been interpreted to be the result of the volumetric deformation caused by intrusion of magma into the solid medium [35], [36]. Thermal stress may also contribute to high seismicity levels after dike intrusions [37], therefore, the timing of occurrence of the high level seismicity relative to the dike intrusion periods may show the presence of lower crustal magma source(s) possibly connected with the shallower mid segment feeder zone [37].

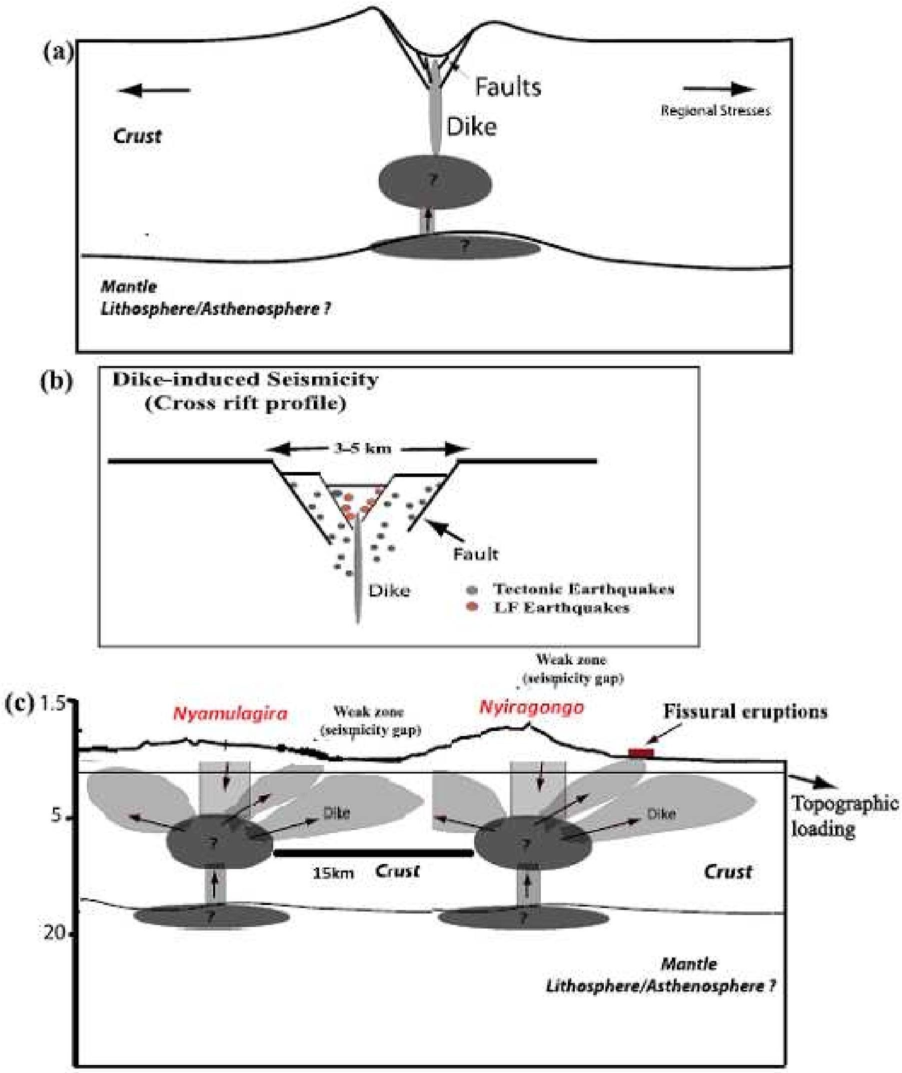

Fig. 6. Cartoon model integrating the dike-induced seismicity patterns and geodetic constraints on the probable magma source zone. (a) Across rift profile showing the midcrustal to subcrustal chambers, dikes, and faults activated by the multiple intrusions. (b) Zoomed in cross rift profile showing distribution of low-frequency and tectonic earthquakes, and the 3–5 km zone of faults with surface offsets of up to 3 m. Red dots indicate low-frequency earthquakes that are generated by the interaction between graben forming the faults and the dikes. The black dots represent distributions of tectonic earthquakes. (c) Along-axis topography relative to the dikes, subcrustal magma chambers, and possible upper mantle reservoirs. The two volcanoes are 15 Km distant only but they have different behaviors and thus different sources. Figure modified after [38]

6 CONCLUSION

The epicenters distribution in the Nyiragongo and Nyamulagira region was studied in detail with data obtained from seismic network of the Goma Volcano Observatory. A general conclusion shows that the epicenters are located on two main axes that are conducive to intrusion of dykes. Geodetic results show the same results with the seismological ones. The NE-SW axis with the direction of the rift and the NW-SE axis with the main crack connecting the two volcanoes are the weakness areas found. It has been suggested that the NE-SW axis is generated by tension forces that occur by tectonic activities within the Rift system, and NW-SE axis is generated by divergent forces caused by the movement magma resulting of strong pressure prevailing in the magma chambers. A long ≈ 5 Km fault come from the southern foot of Nyiragongo, extend the Lake Kivu and reach the Idjwi Iceland. This fault is in connection with the Rift system and controls the southern eruptions of Nyiragongo.

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REFERENCES

[1] Brandsdottir, B., and Einarsson P., "Seismic activity associated with the September 1977 deflation of the Krafla Central volcano in northeastern Iceland", Journal of Volcanology and Geothermal Research, Vol. 6, pp. 197– 212, 1979.

[2] Einarsson, P. and B. Brandsdottir, "Seismological evidence for lateral magma intrusion during the July 1978 deflation of the Klafla volcano in NE-Iceland", Journal of Geophysics, Vol. 47, pp. 160– 165, 1980.

[3] Karpin, T.L. and Turber, C.H.,"The relationship between earthquake swarms and magma transport: Kilauea volcano, Hawaii", Pure applied Geophysics, Vol. 125, pp. 971–991, 1987.

[4] Rubin, A. M., and D. D. Pollard, "Dike-induced faulting in rift zones of Iceland and Afar", Journal of Geology, Vol. 16, pp. 413–417, 1988.

[5] Ukawa, M., and H. Tsukahara, "Earthquake swarms and dike intrusions off the east coast of Izu Peninsula, central Japan", Tectonophysics, Vol. 253, pp. 285–303, 1996

[6] Rubin, A.M., Gillard, D. and Got, J.L., "A reinterpretation of seismicity associated with the January 1983 dike intrusion at Kilauea volcano, Hawaii", Journal of Geophysical Research, Vol. 103, pp. 10 003–10 015, 1998

[7] Yuichi Morita, Shigeru Nakao and Yoshinari Hayashi, " A quantitative approach to the dike intrusion process inferred from a joint analysis of geodetic and seismological data for the 1998 earthquake swarm off the east coast of Izu Peninsula, central Japan", Journal of Geophysical Research, Vol. 111, pp. B06208, 2006. Doi: 10.1029/2005JB003860.

[8] Rubin, A. M., and D. Gillard, "Dike-induced earthquakes: Theoretical Considerations", Journal of Geophysical Research, Vol. 103, pp. 10017– 10030, 1998

[9] Kampunzu, A.B., Bonhomme, M.G. and Kanika, M., "Geochronology of volcanic rocksand evolution of the Cenozoic Western Branch of the East African Rift System", Journal of African Earth Science Vol. 26 no 3, pp. 441-461, 1998

[10] Furman, T., D. and Graham, D., "Erosion of lithospheric mantle beneath the East African Rift system: geochemical evidence from the Kivu volcanic province", Lithosphere, Vol. 48, pp. 237-262, 1999

[11] Furman, T.,"Geochemistry of the East African Rift basalts: An overview". Journal of African Earth Sciences Vol. 48, pp. 147-160, 2007

[12] Elisabet Marie Head, "Investigation into the degassing and eruption mechanisms of Nyamulagira volcano, Democratic Republic of the Congo". Michigan Technological University, Dissertation Thesis, 2012.

[13] Demant, A., Lestrade, P., Lubala, R.T., Kampunzu, A.B., and Durieux, J., "Volcanological and petrological evolution of Nyiragongo volcano, Virunga volcanic field, Zaire", Bulletin of Volcanology, Vol. 56, no 1, pp. 47-61, 1994

[14] Cynthia Ebinger and Tanya Furman, "Geodynamical Setting of the Virunga Volcanic Province East Africa", acta vulcanologica Vol. 14, pp. 1-2, 2002

[15] Komorowski, J.-C., Tedesco, D., Kasereka, M., Allard, P., Papale, P., Vaselli, O., Durieux, J., Baxter, P., Halbwachs, M., Akumbi, M., Baluku, B., Briole, P., Ciraba, M., Dupin, J.C., Etoy, O., Garcin, D., Hamaguchi, H., Houlie, N., Kavotha, K.S., Lemarchand, A., Lockwood, J., Lukaya, N., Mavonga, T.G., De Michele, M., Mpore, S., Mukambilwa, K., Munyololo, F., Newhall, C., Ruch, J., Yalire, M., Wafula, M., "The January 2002 flank eruption of Nyiragongo volcano (Democratic Republic of Congo): chronology, evidence for a tectonic rift trigger, and impact of lava flows on the city of Goma", Acta Vulcanologica Vol. 15, pp. 27–42, 2003

[16] Andy Toombs and Geoff Wadge, "Co-eruptive and inter-eruptive surface deformation measured by satellite radar interferometry at Nyamuragira volcano, D.R. Congo, 1996 to 2010", Journal of Volcanology and Geothermal Research, Vol. 245–246, pp. 98–122, 2012. doi:10.1016/j.jvolgeores.2012.07.005

[17] Demant, A., Lestrade, P., Lubala, R.T., Kampunzu, A.B. and Durieux, J., "Volcanological and petrological evolution of Nyiragongo volcano, Virunga volcanic field, Zaire", Bulletin of Volcanology, Vol. 56 no 1, pp. 47-61, 1994

[18] Mavonga, T., Kavotha, K.S., Lukaya, N., Etoy, O., Mifundu, W., Bizimungu, R.K., and Durieux, J., "Some aspects of seismicity prior to the 27 November 2006 eruption of Nyamuragira volcano and its implication for volcano monitoring and risk mitigation in the Virunga area, Western Rift Valley of Africa", Journal of African Earth Sciences, Vol. 58, pp. 829–832, 2010

[19] Rusangiza B.K., Mavonga T., Lesage P., Kavotha K.S., Wafula M., Lukaya N., and Ciza A., “About Swarms of Long - Period Earthquakes at Volcano Nyamulagira of the Virunga Region, Western Rift Valley of Africa (D.R. Congo)”, Geographica Pannonica, Vol. 16, no 1, pp. 10-17, 2012

[20] Acocella, V. and Neri, M., “Dike propagation in volcanic edifices: overview and possible developments” Tectonophysics, Vol. 471, pp. 67–77, 2009

[21] G. Wadge and Burt, ”Stress field control of eruption dynamics at a rift volcano: Nyamuragira, D.R.Congo”, Journal of Volcanology and Geothermal Research, Vol. 207, pp. 1–15, 2011

[22] Gudmundsson, A. and Loetveit, I.F., ”Dyke emplacement in a layered and faulted rift zone”, Journal of Volcanology and Geothermal Research, Vol. 144, pp. 311–328, 2005

[23] Lukaya, N., Ciraba, M., Mavonga, T. and Wafula, M., “Main pattern of waveforms observed in the Virunga volcanic zone, Western Rift Valley of Africa”, Tectonophysics Vol. 209, pp. 261–265, 1992

[24] Mavonga, T., Kavotha, K.S., Lukaya, N., Etoy, O. and Durieux, J., “Seismic activity prior to the May 8, 2004 eruption of volcano Nyamuragira, Western Rift Valley of Africa”, Journal of Volcanology and Geothermal Research, Vol. 158, pp. 355–360, 2006

[25] Fehler, M. and Chouet, B., “Operation of a digital seismic network on Mount St Helens volcano and observations of long-period seismic events that originate under the volcano” Geophysical Research Letters, Vol. 9, pp. 1017–1020, 1982

[26] Tanaka, K., “Seismicity and Focal mechanism of the volcanic earthquakes in Virunga volcanic region” In: Hamaguchi, H. (Ed.), “Volcanoes Nyiragongo and Nyamuragira. Geophysical Aspects”, Tohoku University, Sendai, Japan, 1983

[27] McNutt, S.R.,” Volcanic Tremor”, Encyclopedia of Earth System Sciences 4, Academic Press, 1992

[28] Ohnaka, M. and Mogi, K., 1982, “Frequency characteristics of acoustic emission in rocks under uniaxial compression and its relation to the fracturing process to failure”, Journal of Geophysical Research, Vol. 87, pp. 3873–3884, 1982

[29] Hiroyuki Hamaguchi, Ndontoni Zana, Kazuo Tanaka, Minoru Kasahara, Masaaki Mishina, Sadato Ueki, Katsongo Sawa-Sawa and Kenji Tachirana, “Observations of Volcanic Earthquakes and Tremors at Volcanoes Nyiragongo and Nyamuragira in the Western Rift Valley of Africa.”, Tohoku Geophysical Journal (Sci. Rep. Tohoku Univ., Ser. 5), Vol. 29, No. 1, pp. 41-56, 1982.

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

[31] N.M. Pagliuca, L. Badiali, M. Cattaneo, H. Ciraba, A. Delladio, M. Demartin, A. Garcia, A. Lisi, F. Lukaya, A. Marchetti, G. Monachesi, G. Mavonga, T. Sgroi and D. Tedesco, “Preliminary results from seismic monitoring at Nyiragongo Volcano (Democratic Republic of Congo) through telemetered seismic network, Goma Volcanological Observatory” Bollettino di Geofisica Teorica ed Applicata, Vol. 50, n° 2, pp. 117-127, 2009

[32] Smets, B., Wauthier, C. and d'Oreye, N., “A new map of the lava flow field of Nyamulagira from satellite imagery”, Journal of African Earth Sciences, Vol. 58, pp. 778–786, 2010

[33] Tanaka, K., “Seismicity and Focal mechanism of the volcanic earthquakes in Virunga volcanic region”. In: Hamaguchi, H. (Ed.), “Volcanoes Nyiragongo and Nyamuragira. Geophysical Aspects”, Tohoku University, Sendai, Japan, 1983

[34] Wauthier, C., Cayol, V., Kervyn, F. and d'Oreye, N., “Modeling of InSAR displacements related with the January 2002 eruption of Nyiragongo volcano”, Cahier du Centre Européen de Géodynamique et de Séismologie Vol. 29, pp. 115–128, 2010

[35] Traversa, P., and J. Grasso, “Brittle creep damage as the seismic signature of dyke propagations within basaltic volcanoes,” Bulletin of the Seismological Society of America, Vol. 99, pp. 2035–2043, 2009 doi: 10.1785/0120080275.

[36] Traversa, P., V. Pinel, and J. R. Grasso,” A constant influx model for dike propagation: Implications for magma reservoir dynamics”, Journal of Geophysical Research, Vol. 115, pp. B01201, 2010, doi: 10.1029/2009JB006559.

[37] Coté, D. M., K. Kulpinski, C. J. Ebinger, D. Keir, and A. Ayele, “Testing models of dike intrusion during rifting episodes: The role of heating in triggering earthquakes in Afar”, Eos Trans. AGU, 9(52), Fall Meet. Suppl., Abstract T31B–1820, 2009

[38] Manahloh Belachew, C. Ebinger,1 D. Coté, D. Keir, J. V. Rowland, J. O. S. Hammond and A. Ayele, “Comparison of dike intrusions in an incipient seafloor-spreading segment in Afar, Ethiopia: Seismicity perspectives”, Journal of African Earth Sciences, Vol. 116, pp. B06405, 2011 , doi:10.1029/2010JB007908