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Abstract

Swarms of Long Period earthquakes generated by the Nyamuragira volcano for the period from January 2000 to November 2006 before 21 January 2000, 5 February 2001, 25 July 2002, 8 May 2004 and 27 November 2006 Nyamuragira eruptions have been analyzed. Interest is focused on the frequency distribution of these earthquakes and on the variation of the m-value of observed earthquake swarms. It is found that m-values which generally vary between 0.9 and 1.6, and shifts towards larger values of 1.7 to 3.23 two to four months prior to eruptions of the volcano.

Keywords: Swarms, earthquakes, volcano, Nyamuragira, Virunga

Introduction

The Nyamuragira Volcano is situated in the Western Rift Valley of Africa, Virunga Province, at the northern edge of Lake Kivu. It covers an area of 800 km² (Pouclet and Villeneuve, 1971). The volcano Nyamuragira is characterized by frequent Hawaiian-type eruptions and highly potassic lavas (Hayashi et al., 1992; Tuluka et al., 2006). An active lava lake has persisted in its central crater from 1921 to 1938. Most eruptions, with the exception of the summit eruption of 1938, occur on the flanks of the volcano. This Volcano is also of interest due to its frequent, and potentially devastating fissural eruptions of highly fluidized lavas (Tedesco et al., 2007). In fact, Volcano Nyamuragira is among the most active volcanoes in the world as indicated, since 1901, by a sequence of 30 flanks eruptions (Pouclet, 1975; Smets et al, 2010, Kavotha et al., 2010).

The most recent flank eruptions occurred on January 27, 2000; February 5, 2001; July 25, 2002; May 8, 2004 and November 27, 2006.

At volcano Nyamuragira, seismic swarm composed mainly of long-period earthquakes precede by 2-4 months these flank eruptions (Zana et al., 1989; Tuluka, 2006).

However, not all earthquake swarms are followed by eruptions. Therefore, it is of great interest to draw characteristics of the swarms that are followed by eruptions in order to distinguish them from the swarms that are not followed by lava outbursts. This study deals with this aspect.

Data and method of analysis

The seismograms used in this study were provided by the Katale Station which is part of the Goma Volcano Observatory (GVO) seismic network. In fact, the GVO seismic network has been gradually improved, and it currently comprises stations at Katale (KTL), Luboga (LBG), Kunene (KNN), Rusayo (RSY), Kibumba (KBB), Bulengo (BLG) and Goma. (Figure 1).

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These Stations are each equipped with a short-period Kinemetrics vertical SS-1 ranger Seismometer (To=1sec) connected to a PS-2 portable seismic recorder instrument, three component short-period Lennartz(LE-3D/5s) seismometers and Nanometrics Trillium 40 broadband seismometer at KNN and KBB stations. Signals from the Kinemetrics seismometer are amplified and filtered in the amplifier module. The amplifier module has controls for amplifier gain and filter setting.

In this study, on the basis of waveform pattern, long-period earthquakes are defined as transient signals having weak P and emergent or no S phases with predominant frequency content between 1 and 3Hz (Mavonga et al., 2006). Long-period (LP) earthquakes are though to be caused by fluid pressurization and by shear failure, tensile fail or nonlinear flow processes at very shallow depths (McNutt, 2000).The LP are probably due to the excitation of some fixed cavity under the volcano and/or the migration of magmatic fluid consisting of hot water and/or magma (Fehler and Chouet, 1982; Nishimura et al., 2002; Tuluka et al., 2010) (Figure 2).

The records (swarms) of one of these stations (Katale station) were analysed for the period from January 2000 to November 2006 and 44 swarms of long-period earthquakes were identified.

The Katale Station data have been chosen out of the seven stations taking part in the Goma Seismic network because this station is the nearest from the crater of volcano Nyamuragira and during the period from 2000 to 2006, the period when we made this study, the data used in it have only been recorded by Katale station without interuption as has been observed in almost the other stations comprising the seismic network.

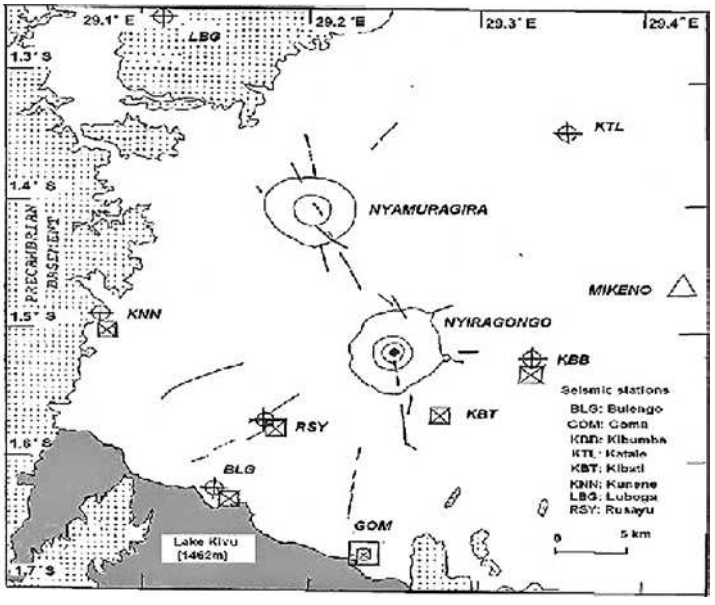

Figure 1: Map showing the eight seismographic stations surrounding the Nyiragongo and Nyamuragira Volcanoes.
- Circle with cross indicates the analog stations;
- Square with cross indicates digital stations
- Double square and cross indicates the location of Goma volcano Observatory.

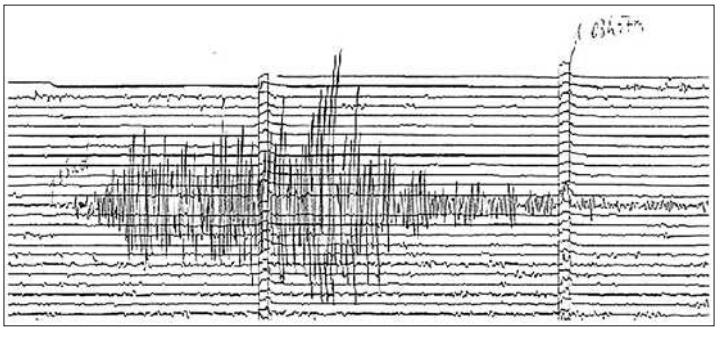

Figure 2. Typical long-period event recorded at Katale Station (October 16, 2004).

Table 1. *Distribution of maximum earthquake amplitude during the September 19-20, 2006 swarm recorded at the Katale station*

Amplitude(mm)/ Time interval (Hours)	0 – 2 [mm]	2 – 4 [mm]	4 – 6 [mm]	6 – 8 [mm]	8-10 [mm]	10-12 [mm]	12-14 [mm]	14-16 [mm]	16-18 [mm]	18-20 [mm]	+20 [mm]	TOTAL
04 – 06 [H]	5	4	4	1	2					2	1	19
06 – 08 [H]	2	13	4		1	2						22
08 – 10 [H]	4	9	5	2	3	1	2	1	2		1	30
10 – 12 [H]	5	12	5	2				1	1	1	1	28
12 – 14 [H]	11	5	2	1	2	2		1			4	28
14 – 16 [H]	6	7	1	1	1				1	2		19
16 – 18 [H]	1	4	1	1							1	8
18 – 20 [H]	11	5	3	1	1							21
20 – 22 [H]	17	5	1	1			1				1	26
22 – 00 [H]	11	1	3	1								16
00 – 02 [H]	7	2	1	2		1	1				2	16
02 –04 [H]	7	5	1							1		14
TOTAL	87	72	31	13	10	6	4	3	4	6	11	247

Table 2. *Distribution of maximum earthquake amplitude during the June 16, 2006 swarms recorded at the Katale station*

Amplitude[mm]/ Time interval (Hours]	0 – 2 [mm]	2 -4 [mm]	4 – 6 [mm]	6 – 8 mm]	8-10 [mm]	10-12 [mm]	12-14 [mm]	14-16 [mm]	16-18 [mm]	18-20 [mm]	+20 [mm]	TOTAL
09 - 11 [H]	10	9	4	1				1	3		1	29
11 - 13 [H]	10	8	2	1		1		1			3	26
13 - 15 [H]	13	19	8	1	3	1				2	5	52
15 - 17 [H]	20	17	6	1	2	1	1	2	1		3	54
17 - 19 [H]	11	18	6	8	1	2	2			1	2	51
19 - 21 [H]	11	11	6	1	3		1		1		3	37
21 - 23 [H]	10	10	3	1	1						2	27
23 - 01 [H]	13	10	3			1	1			1	1	30
01 - 03 [H]	9	6	2	1	1		1				2	22
TOTAL	107	108	40	15	11	6	6	4	5	4	22	328

All those records were reported to the same gain of 48db. We focussed our interest to swarms generated by Volcano Nyamuragira by analysing the amplitude distribution of the recorded earthquakes.

The duration of the swarms was divided into 2 hours- intervals. Also, earthquakes were grouped according to their maximum trace amplitude (in millimeter) into 11 classes: 0-2mm; 2-4mm; 4-6mm; 6-8mm; 8-10mm; 10-12mm; 12-14mm; 14-16mm;16-18mm;18-20mm and 20-22mm as indicated in the table 1 and table 2 taken as examples of the 44 swarms.

We considered 2006 and two examples were taken randomly to compile the two tables simply because it is the year where the last Nyamuragira eruption was observed during this study.

As noticed, the classification of the time interval in the two tables differs. It depends on the time of the beginning of a swarm. Thus, in the table 1, the swarm started on September 19th, 2006 at 4Am and took end the following day (September 20th) at 4Am; whereas, in the table 2, it started at 9Am and took end at 3Am of the following day.

We used the Ishimoto and Iida relation (1939) who indicated that the number N of earthquakes whose amplitudes lie between A and A+dA vary as:

$$N(A)\,dA = k\,A^{-m}\,dA \qquad (1)$$

Where A and N are the maximum amplitude and frequency, k and m are numerical constants.

k depends on the number of events, the recording station considered and the component used.

Suzuki (1953, 1954, 1958, 1959) found that this formula was not influenced by the transmission of seismic waves and the seismometer used for observations.

Taking the logarithm of the equation (1), we obtain:

$$logN\,(A) = logk - mlogA \qquad (2)$$

With: N = Number of earthquakes recorded with amplitude A;

A = Amplitude of seismogram.

This relation has enabled us to determine the different values of « m » and with these values we have distinguished the different categories of swarms that are followed by eruptions and the swarms that are not followed by lava outbursts.

Standard error $\boldsymbol{D}$ is calculated by:

$$\boldsymbol{D} = \frac{\sigma}{\sqrt{\sum(\log A_i)^2 - \frac{1}{n}\quad\left[\sum(\log A_i)^2\right]}} \qquad (3)$$

Where:

$$\boldsymbol{\sigma}^2 = \frac{1}{n\text{-}1}\sum(\log N_i - \log k + m\log A_i)^2$$

$$= \frac{1}{n\text{-}1}\left\{\sum(\log N_i)^2 + m^2\sum(\log A_i)^2 + \right.$$

$$+ 2m\sum(\log A_i)(\log N_i) - \mathrm{m}(\log K)\sum(\log A_i) -$$

$$\left. - (\log K)\sum(\log N_i)\right\} \qquad (4)$$

If the total number of earthquakes is N, and they are subdivided into n bins according to their amplitude, the constant k is calculated by:

$$logk = \frac{\sum \log N_i + m\sum \log A_i)^2}{n} \qquad (5)$$

With all these formulas (2, 3, 4 and 5), we calculated the different values of "m" as those shown in the Table 3.

Results and discussion

We processed 44 seismic swarms consisting of 12720 micro earthquakes. As evidenced by Figure3A, several earthquake swarms characterized the period prior to the eruption of volcano Nyamuragira in 2004. This characteristic was com-

Table 3. *The 44 swarms prior each eruption of Nyamuragira Volcano*

#Swarm	Start date	Stop date	N	m
1▲	Jan.13,2000	Jan.14,2000	389	1,9386 ± 0,110
2●	Jan.16,2001	Jan.16,2001	205	1,7694 ± 0,104
3●	Jan.21,2001	Jan.21,2001	384	1,7498 ± 0,097
4	Jan.18,2002	Jan.19,2002	242	1,2363 ± 0,061
5	Jan.19,2002	Jan.20,2002	297	1,5804 ± 0,086
6	Jan.20,2002	Jan.21,2002	239	1,2779 ± 0,065
7	Jan.24,2002	Jan.25,2002	245	1,332 ± 0,075
8 ◄	May 24,2002	May 24,2002	125	1,9638 ± 0,098
9 ◄	May 25,2002	May 25,2002	117	1,9026 ± 0,108
10 ◄	July 10,2002	July 10,2002	108	1,9437 ± 0,112
11	Jul.30,2003	Jul.30,2003	386	1,3335 ± 0,073
12	Nov.27,2003	Nov.27,2003	113	0,4298 ± 0,024
13	Dec.08,2003	Dec.08,2003	174	0,9375 ± 0,045
14♥	Jan.15,2004	Jan.16,2004	229	1,7052 ± 0,150
15♥	Jan.17,2004	Jan.18,2004	389	1,8448 ± 0,105
16♥	Mar.09,2004	Mar.09,2004	172	1,948 ± 0,109
17♥	Mar.10,2004	Mar.11,2004	551	2,4653 ± 0,141
18♥	Apr.21,2004	Apr.21,2004	308	2,854 ± 0,256
19♥	May.04,2004	Mar.05,2004	354	2,7927 ± 0,223
20	Sep.24,2004	Sep.25,2004	128	1,0891 ± 0,062
21	Sep.30,2004	Sep.30,2004	248	1,3377 ± 0,065
22	Oct.16,2004	Oct.16,2004	284	1,2325 ± 0,071
23	Oct.17,2004	Oct.18,2004	172	0,9039 ± 0,47
24	Dec.24,2004	Dec.24,2004	511	1,4913 ± 0,014
25	Jan.11,2005	Jan.12,2005	102	1,5052 ± 0,132
26	Apr.12,2005	Apr.13,2005	151	1,4234 ± 0,081
27	May 04,2005	May 05,2005	117	1,3877 ± 0,083
28	Oct.27,2005	Oct.28,2005	163	1,0325 ± 0,058
29	Jan.7,2006	Jan.7,2006	67	1,3437 ± 0,075
30	Feb.15,2006	Feb.15,2006	233	1,3482 ± 0,076
31	Feb.28,2006	Feb.28,2006	122	0,9841 ± 0,106
32	Mar.20,2006	Mar.20,2006	185	1,6103 ± 0,214
33	Mar.31,2006	Mar.31,2006	103	1,5051 ± 0,131
34	Apr.01,2006	Apr.01,2006	129	0,9023 ± 0,051
35	Apr.08,2006	Apr.08,2006	110	1,4324 ± 0,018
36	May 05,2006	May 05,2006	295	1,1766 ± 0,058
37	Jun.16,2006	Jun.17,2006	328	1,2803 ± 0,02
38 ♣	Aug.02,2006	Aug.03,2006	218	2,8547 ± 0,139
39 ♣	Aug.23,2006	Aug.24,2006	75	2,7927 ± 0,223
40 ♣	Sep.19,2006	Sep.20,2006	247	3,2362 ± 0,94
41 ♣	Nov.25,2006	Nov.26,2006	398	1,9617 ± 0,109
42	Dec.05,2006	Dec.05,2006	120	0,9754 ± 0,74
43	Dec.10,2006	Dec.10,2006	146	1,4319 ± 0,053
44	Dec.24,2006	Dec.24,2006	261	1,5720 ± 0,120

Legend:

▲ *Swarm observed two weeks prior to the January 27, 2000 Nyamuragira eruption;*

● *Swarms observed two months prior to the February 05, 2001 Nyamuragira eruption;*

◄ *Swarms observed two months prior to the July 25, 2002 Nyamuragira eruption;*

♥ *Swarms observed four months prior to the May 08, 2004 Nyamuragira eruption;*

♣ *Swarms observed three months prior to the November 20, 2006 Nyamuragira eruption.*

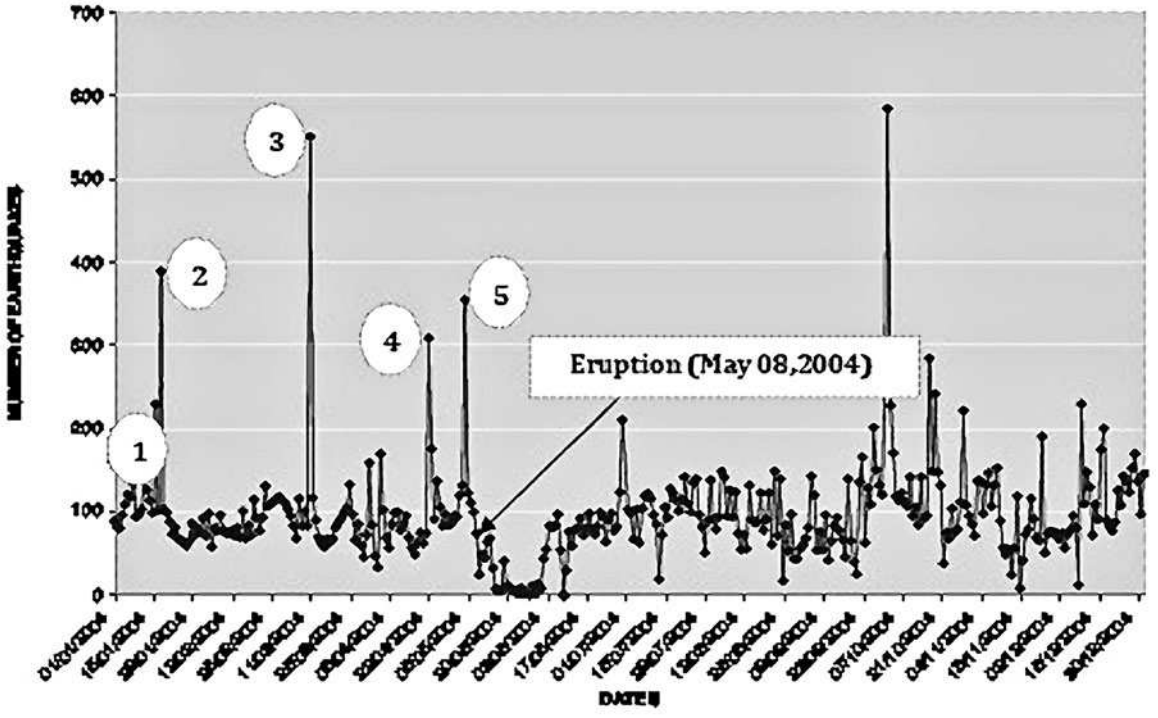

Figure 3A. Graph showing the daily occurrence of long-period earthquakes, prior to the May 8, 2004 eruption of Volcano Nyamuragira. The five squares respectively indicate different swarms of earthquakes recorded prior to Nyamuragira eruption of 8 May 2004 (♥):
1. The January 15, 2004 Swarm: 229 earthquakes;
2. The January 17, 2004 Swarm: 389 earthquakes;
3. The March 10, 2004 swarm: 551 earthquakes;
4. The April 21, 2004 swarm: 308 earthquakes;
5. The May 4, 2004 swarm: 354 earthquakes.

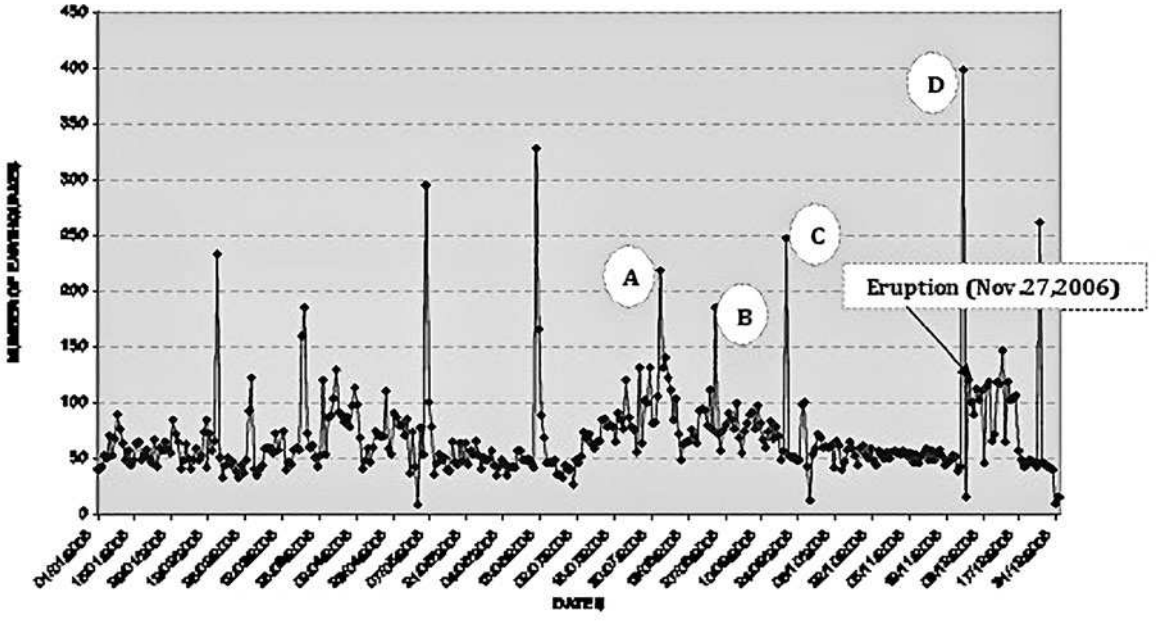

Figure 3B. Graph showing the daily occurrence of long-period earthquakes, prior to the November 27, 2006 eruption of Volcano Nyamuragira. The four letters respectively indicate different swarms of earthquakes recorded prior to Nyamuragira eruption of 27 November 2006 as indicated in the table 3 (♣):
A: Swarm of August 02, 2006: 218 earthquakes;
B: Swarm of August 23, 2006: 185 earthquakes;
C: Swarm of September 19, 2006: 247 earthquakes;
D: Swarm of November 25, 2006: 398 earthquakes.

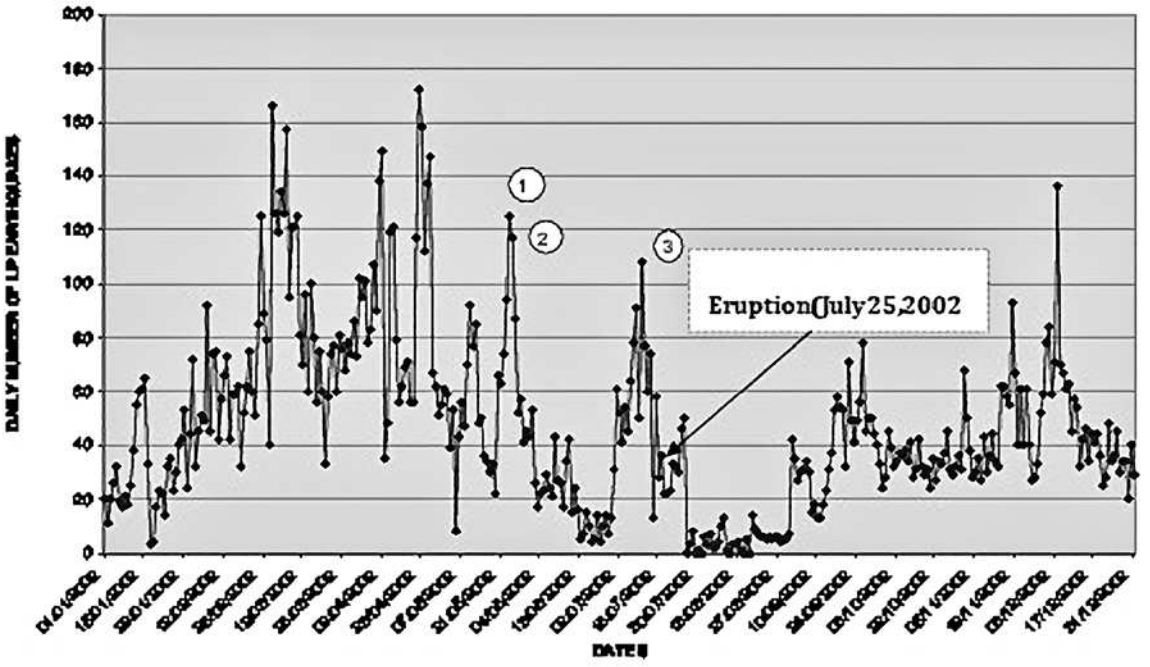

Figure 3C. Graph showing the daily occurrence of long-period earthquakes, prior to the July 27, 2002 eruption of Volcano Nyamuragira. The three squares respectively indicate different swarms of earthquakes recorded prior to Nyamuragira eruption of 27 July 2002 (table 3 :◄):
1. Swarm of May 24, 2002: 125 earthquakes;
2. Swarm of May 25, 2002: 117 earthquakes;
3. Swarm of July 07, 2002: 108 earthquakes.

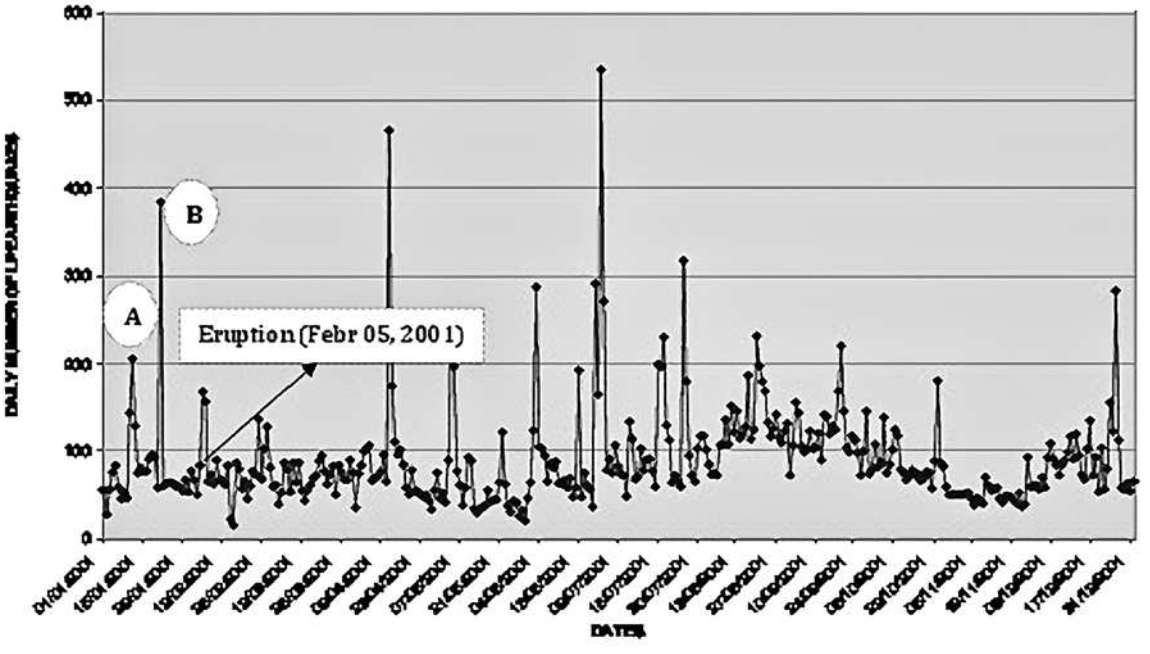

Figure 3D. Graph showing the long-period earthquake, prior to the 05 February 2001 eruption of Volcano Nyamuragira. In this graph it is indicate the swarm composed mainly of long-period earthquakes recorded at Katale station, a few weeks before the 05 February 2001 eruption:
A: Swarm of January 16, 2001: 205 earthquakes;
B: Swarm of January 21, 2001: 384 earthquakes.

mon to the five successive eruptions that occurred from 2000 to 2006 at this volcano (2000; 2001; 2002; 2004 and 2006).

According to Wafula et al. (2009), Mavonga et al. (2010) and Kavotha et al. (2010), these eruptions were characterized by precursory and post-eruption intense swarms of long-period earthquakes just in the time intervals of the seismicity increases as it is shown in each figure.

Clearly, the seismicity that precedes each eruption increases appreciably three to four months before the eruption. It is also clear in those figures that the number of long-period earthquakes increases when the volcanic eruption draws near.

However, some swarms of long period earthquakes have been observed before an eruption, but were not considered as precursors of the eruption. Indeed, by calculating their m-value, we find that they are not classified as swarms precursors. This is the case of the swarms of June 16, 2006 as well as from 05 May 2006 (Figure 3B).

The most significant result in this analysis (Table 3) was that, the m-value was ranged from 0.9 to 3.23 with an interesting feature as follows:

1. For the 44 swarms, those that were not accompanied by an eruption, m-values were ranged from 0.9 to 1.6.
2. Particularly, the seismic swarms that just preceded the Nyamuragira eruptions (three or four months before an eruption) showed higher m-values ranging from 1.7 to 3.23

Conclusion

In this work we have taken into account the daily frequency of long-period earthquakes. The major purpose of this analysis was to study the characteristics of swarms of long-period earthquakes observed at the Volcano Nyamuragira before, during and after the eruption.

Through the analysis of 44 earthquakes swarms and the comparison of their m-values, we noticed that the frequency of the volcanic earthquakes generally increases when the volcanic eruption draws near. Figures3 (A-B-C-D) shows the history of the earthquake swarms for the period from 2000 to 2006: clearly, we notice that the Seismicity of volcano Nyamuragira significantly increases several months or weeks before the eruption. This seismicity decreases gradually towards the end of eruption.

The study of these earthquakes presents a particular interest in the prediction of the volcanic eruptions at volcano Nyamuragira.

Using the seismic data recorded at Katale station during the six years period from 2000 to 2006, we tried to characterize the volcanic earthquake swarms according to their m-values.

It was shown that the magnitude-frequency-relation(Gutenberg-Richter/ishimoto-Lida relation) of swarms that forerun volcanic eruptions show higher m-values from 1.7 to 3.23 while other swarms are of lower m-values (0.9 – 1.6).

It should also be noticed that a large number of volcanic earthquakes is recorded a few months or a few hours before the eruption. However, this seismic activity decreases rapidly and is followed by eruption tremors.

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