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The Nyamulagira Volcano, a Sub Structure of that of Nyiragongo Volcano (Analysis using Seismic Species)

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ABSTRACT

Following the processing of data from earthquakes in the area from 2016 to 2021, the researchers discovered the following: The model developed specifically the scale designed for characterization of the areas surrounding Nyamulagira (29.0°E-29.5°E; 1.2°S-1.5°S) and Nyiragongo (29.0°E-29.5°E; 1.45°S-1.75°S), is valid, logical, and reasonable, as are the assumptions made. The concept of "volume density" of earthquakes or seismic energy was introduced in the the application of these hypotheses, along with other parameters, has allowed the craters of these two volcanoes to be located in accordance with field observations: the crater of Nyamulagira volcano is located at [29.15°E; 1.35° S] and the crater of Nyiragongo volcano is located at [29.25°E; 1.50° S].

Structures of Nyamulagira and Nyiragongo are strikingly similar, indicating that Nyamulagira is a subset of Nyiragongo, with the latter showing particularly striking similarities in its Western crater. Structures of Nyamulagira and Nyiragongo are strikingly similar, indicating that Nyamulagira is a subset of Nyiragongo, with the latter exhibiting particularly striking similarities in its Western crater.

The similarity rate between the two is 75%, based on structural factors shared by Nyiragongo and Nyamulagira. Nyiragongo has a 25% singularity. Justified by its extremely complex shape (stratovolcano with a crater made up of three platforms,). With a few exceptions, there is a correlation between minimum volume density of energy and maximum volume density of the number of earthquakes at the same location for both Nyamulagira and Nyiragongo, and the characterization around the craters according to quadrants notes that the degree of heterogeneity is 100% for Nyamulagira, as opposed to 75% for Nyiragongo, with high activity on the left (West).

Findings indicate that the magma reservoirs of the volcanoes are predominantly spherical for Nyamulagira and cylindrical for Nyiragongo. As a result, the geological characteristics in the area have been highlighted by this model; the geological implications of this model can be used for geological prospecting.

These results, and others above, show that the structure of the Nyamulagira Volcano is a substructure of (included in) the Nyiragongo.

It would be necessary to confirm the hypotheses suggested earlier. Besides, this necessitates the expansion or continuation of research into other areas with volcanic-seismic activity. We note that the model effectively compares various structures with seismo-volcanic activity.

1. INTRODUCTION

The East African Rift System is described as a continental extension of the global system of lithospheric fractures that run across the Atlantic and Indian Oceans and into the eastern half of the African continent via the Gulf of Aden and the Red Sea (Mukange, 2016; Boden et al. 1988; Bantidi, 2014a).

This fracture system has two branches, specifically: - The eastern branch, which originates in the Afar triangle and travels across Ethiopia and Kenya to the northern Tanzanian divergence (Figure 1; Mukange, 2013).

The western branch is made up of a network of fractures that span the Great Lakes daisy chain, from Lake Albert (617 m) to Lake Edward (912 m), Lake Kivu (1462 m), Lake Tanganyika (780 m), Lake Rukwa (782 m), Lake Malawi (460 m), and south to Mount Beira in Mozambique and south-west to Lake Kariba, Zimbabwe . This branch thus encompasses the majority of the Eastern provinces of the DRC between latitudes 4°N and 8°S.

The East African Rifts are more than 6,000 km long and 40–60 km broad, extending from the Red Sea to the Zambezi. The Aswan Lineament is where the two branches separate, and Lake Malawi is where they converge (Figure 1).The "Congolese craton," or the entire Congolese basin, is affected by the typical intra-plate cracks that are part of the DRC's seismic activity.

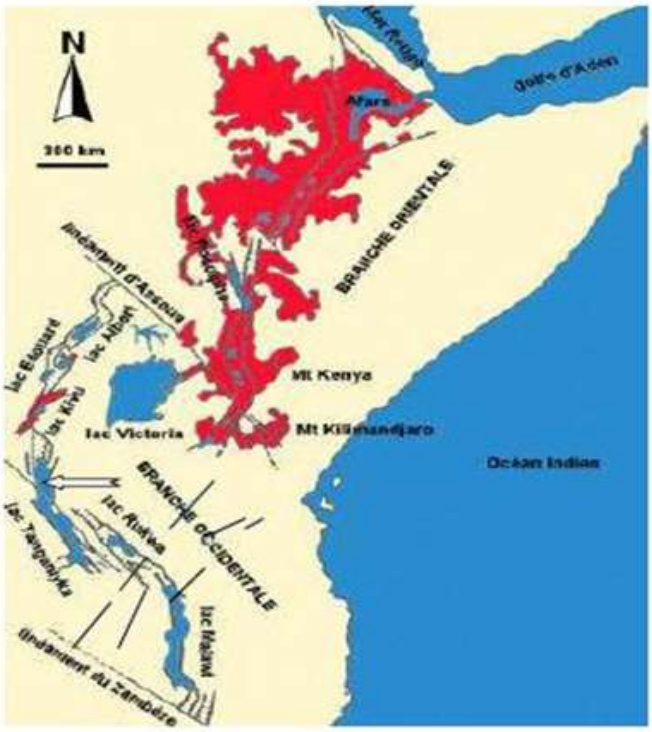

Fig.1: Système des Rifts Est – Africains[1] (modifié).
- Ligne pleines: failles principales.
- Couleur bleue: lac, mer et océan.
- Couleur rouge: volcanisme.

Figure 1 : Major faults in the East African Rift System are represented as solid lines, with the oceans being blue and the volcanoes being red.

The Congolese Rift has three main volcanic provinces: Toro-Ankole Province in the north, Virunga Province (Nyiragongo, Nyamulagira volcanoes) in the center, and South Kivu Province in the south. Basin boundary faults are typically normal, and the volcanic provinces (Figure 2) are located in the inter-basin zones (Wafula and al, , 2009).

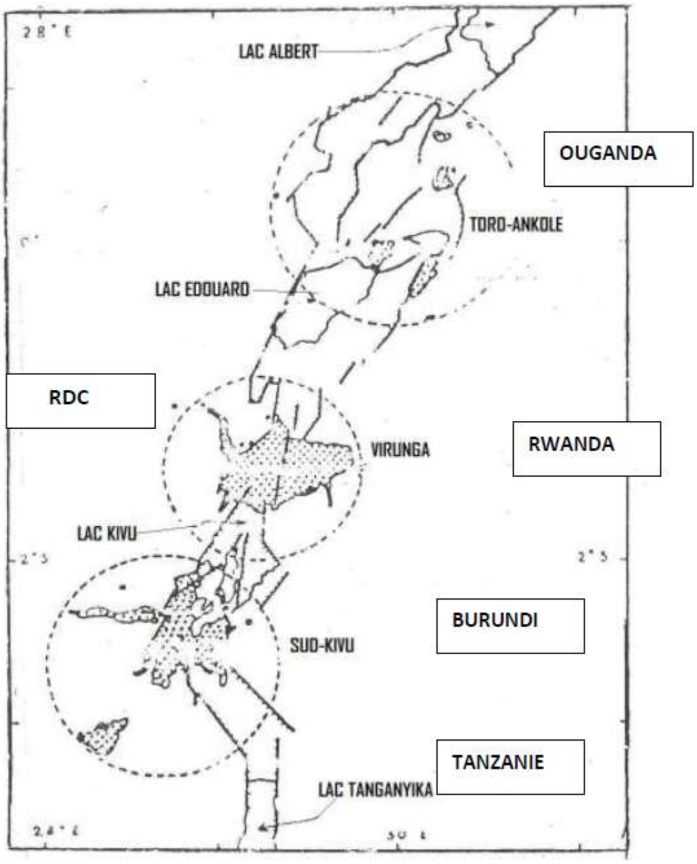

Figure 2 : The volcanic region of the Virungas is located in the exterme North of Lake Kivu.

Eight volcanoes make up this area, which is separated into three groups known as volcanic provinces. The eastern group, which includes the Muhavura, is comprised of these volcanoes (4127 m),

The eastern group consists of Nyiragongo (3470 m) and Nyamulagira, while the middle group consists of Visoke (3911 m), Karisimbi (4506 m), and Mikeno (4437 m). The western group consists of Muhavura (4127 m), Gahinga (3474 m), and Sabinyo (3647 m) (3056 m).

Except for the brief eruption of Mugogo on August 1, 1957, the volcanoes in the first two subgroups are dormant at the moment. Mugogo, which is 11 kilometers to the north of Visoke and sits at a height of 2350 meters, is regarded as a satellite cone of the latter (Visoke).

The western group of volcanoes, particularly Nyamulagira with its frequent eruptions (on average every two years), and Nyiragongo with its permanent lava lake in the center crater, are among the most active in the world today (Wafula, 1999,2011; Zana,1977)

Additionally, it should be noted that Nyiragongo is regarded as one of the most dangerous volcanoes on Earth due to its proximity to the city of Goma (15 km from the crater, with an estimated population of over one million) and the superfluidity of its lava, which can flow at speeds of up to 40 km/h (Wafula, thesis).

In the same area of the Rift Valley cracks, both volcanoes are situated (Figure 3).

Despite the fact that Nyiragongo and Nyamulagira volcanoes are just 13 km apart (figure 3) Both the chemical composition of their lavas and the way in which they erupt show remarkable differences.

Basalts, which are abundant in alkaline elements and have a high concentration of potassium, make up the volcanic rocks of these two volcanoes and are the reason why lavas are so fluid.

These two volcanoes' volcanic activity is of the Hawaiian variety, characterized by an effusive and passive emission of lava that has a low viscosity (100–1000 poise) and a very high temperature (1000°C).

There are three other similar volcanoes in the world: Erta Alee in Ethiopia, Mount Erebus in the Arctic, and Kilauea in the Pacific. Similar to the Redoubt volcano in Alaska, the Virunga region's seismograms are classified as type A (4-10 Hz), type B (1-4 Hz), and type C (peak at 2.6 and 8 Hz) based on frequency.

Along with tremors (1-2 Hz), earthquakes are recorded (Wafula, 2009. Nyiragongo's final eruption occurred on May 22, 2021, while Nyamulagira's last eruption occurred on April 18, 2018.

The seismic structure near the Nyiragongo and Nyamulagira volcanoes has been categorically described in recent papers (Mukange, 2023a-b).

In short, the current work compares the two structures to identify their similarities and differences.

2. DATA ANALYSIS AND METHOD

2.1. Data analysis

The Volcanological Observatory of Goma (VOG) collected the basic data for the Nyiragongo and Nyamulagira volcanoes throughout the time period 2016–2021 in the region between 29.00°E and 29.50°E longitude and 1.20°S and 1.75°S latitude (Figure 3).

Prior surveys were conducted on the volcanoes Nyamulagira (29.0°E-29.5°E; 1.2°S-1.5°S) and Nyiragongo (29.0°E-29.5°E; 1.45°S-1.75°S), separately (Mukange, 2023a-b).

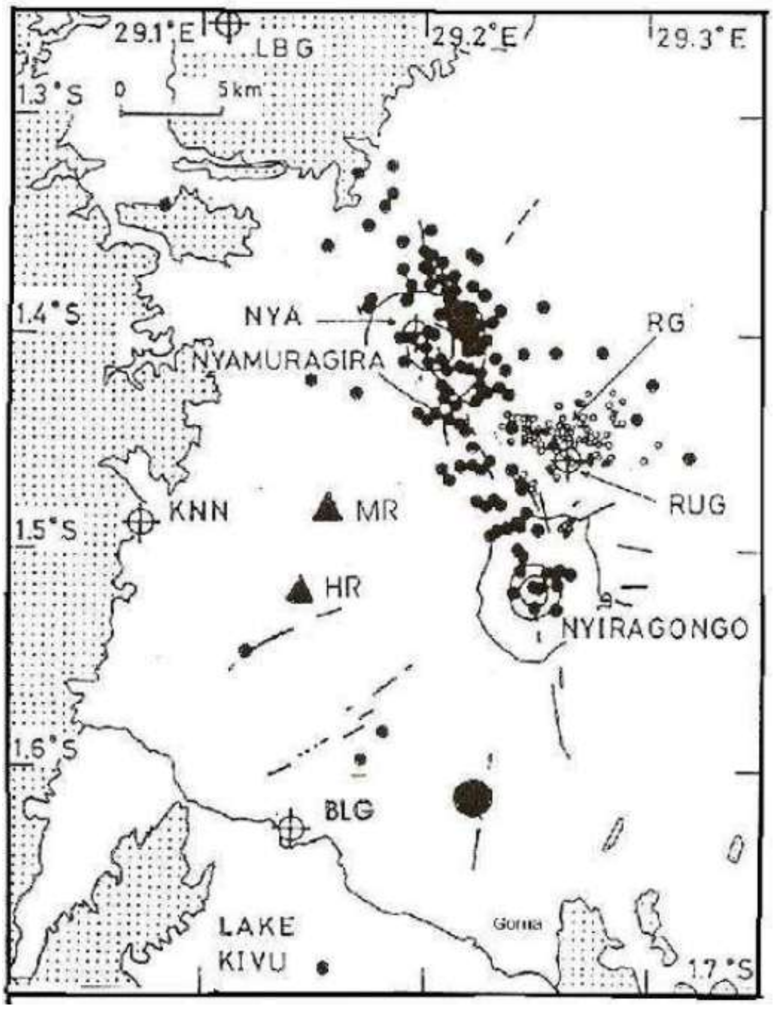

Figure 3 shows seismic activity and geological structure following the eruption of the Nyamulagira volcano in 1981.

- Tiny solid circle: Earthquake of Type (A).
- Tiny open circle: Earthquake with low frequency.
- The solid triangle indicates the volcano's eruptive sites of 1976, MR: Murara cone, and HR: Harakandi cone.
- The sizable solid circle indicates the 20 November 1990 earthquake, which had a magnitude of 4.5.
- RG: The 1981 Nyamulagira volcanic cone (Rugarambiro).
- RUG: Temporary Seismographic Station Rugarambiro

More than 1,300 volcanoes serve as a marker for the planet's underlying activity. They are generally all engaged.

One of the most active volcanoes in Africa is Nyamulagira, which is located in the Democratic Republic of the Congo (DRC). It is a volcano in the Great Rift Valley's western branch and a part of the Virunga Mountains. The internal activity of the globe is marked by more than 1,300 volcanoes. A majority of them are engaged.

One of Africa's most active volcanoes is Nyamulagira in the Democratic Republic of the Congo (DRC). It is a volcano on the western branch of the Great Rift Valley and a part of the Virunga Mountains. The Nyamulagira volcano is surrounded by the towns of Burungu in the northwest, Nyiragongo in the south-southeast, Lake Kivu in the south by 25 kilometers, and Sake in the southwest. The Nyamulagira volcano rises to a height of 3058 meters, and its peak caldera measures 2.3 kilometers in length and two kilometers in width.

In contrast to its close neighbor, the Nyiragongo volcano, the Nyamulagira volcano's slopes, which are typical of shield volcanoes, are not particularly steep and give the volcano a volume of 500 km3. These slopes are broken up by fissures and scoria cones, and 1500 km2 of basaltic lava flows with a high potassium content cover them. These lava flows are exceptionally long and extensive, sometimes extending for up to 30 kilometers.

On the south-eastern flank of the caldera, a strikingly enormous fissure runs in the direction of (NNW-SSE).

The Nyamulagira volcano is thought to be weakest along this fissure. So, of the Nyamulagira and Nyiragongo volcano fields, it is the most active zone. The magma chamber's accumulation of magma is what causes the earthquakes that are caused by the Nyamulagira volcano.

Numerous micro-earthquakes (tremors) caused by ruptures in compacted rock or the degassing of magma are captured by seismographs.

A sign that Nyamulagira is about to awaken and that an eruption is about to occur is the progressive rise of the hypocentres (related to the rise of magma).

As a shield volcano, Nyamulagira produces polygenic lava because it possesses hot and fluid magmas that enable a two-phase conviction that keeps the chimney from shutting by solidifying the material.

The Nyamulagira volcano has the ability to emit tens of millions of cubic meters of lava in a single eruption in the form of flows that can travel more than 20 kilometers from the source of emission, notably by obliterating everything in their path. The wind can carry the volcanic products released, such as slag, volcanic ash, Pelee's hair, etc., over considerable distances, burning and contaminating meadows, farms, and river waters.

Three volcanoes make up the Nyiragongo volcano complex, which is aligned in a north-south direction: Baruta (3,100 m) in the north, Nyiragongo main cone (29, 25°E, 1.50°S, 3,470 m) in the middle, and Shaheru (2,800 m) in the south (Figure 4).

The shape of Nyiragongo is comparable to that of a stratovolcano, which is a volcano with an undulating shape and a layered structure caused by the accumulation of volcanic elements making up the cone (Simkin et al., 1981).

Because of the lake that was discovered in 1928, the Nyiragongo volcano is well recognized (Tazieff, 1977; Hamaguchi et al., 1982).

The three platforms that made up the Nyiragongo crater up until 1977 were as follows: the top platform was 180 meters away, the second was 180 meters below it, and the third was 60 meters below.

Since the level of this lava lake was continually changing, by December 5, 1976, it had reached the first platform's critical level (Pouclet, 1973, Tazieff, 1977).

Seismic anomalies that are fairly spectacular frequently occur before the volcanic eruptions of Nyiragongo and Nyamulagira.Finding anomalies can help us find signs of impending eruptive activity by revealing features.

Additionally, because both volcanoes are part of a very active tectonic system, the local seismic activity has a significant effect on how they behave. The eruptive activity and its impact go hand in hand.

Furthermore, the eruptive activity of one volcano may have an impact on the activity of another volcano.

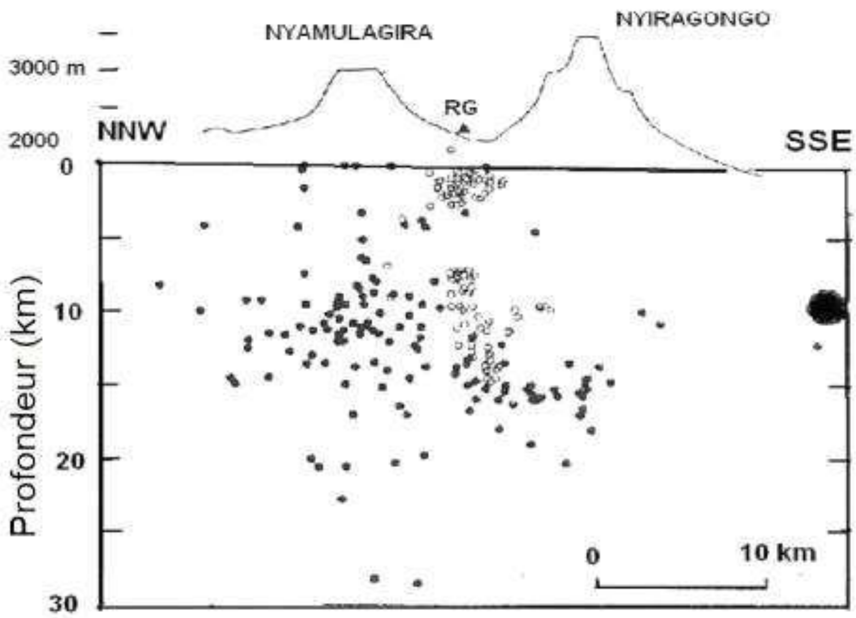

Figure 4: Depth distribution (North-South) of the volcanic earthquakes in Figure (3).

Even though the volcanoes Nyiragongo and Nyamulagira are just 13 km apart (Fig. 4-5), their lava's chemical composition and eruption mechanisms differ noticeably (Wafula).

Figure 5: View from the West of Nyiragongo (left) and Nyamulagira (right) volcanoes.

The eruptions of the Nyamulagira volcano are a real disaster for the Virunga National Park, with the loss of many animals and the destruction of large areas.
The plume of smoke and dust emitted during each eruption can rise into the atmosphere to the base of the stratosphere, hindering air navigation and causing damage to aircraft if they are not warned to avoid the area affected by this volcanic cloud.

Since 1980, the Nyamulagira volcano has erupted on average every two years. Since the beginning of the last century, the Nyamulagira volcano has erupted more than 30 times on its flanks with lava flows

2.2. Méthod of analysis

2.2.1. Presentation of previous results

As the foundation for any characterization, previous research on the two volcanoes has produced the following seismic species (Table 1-2 and Figures 6-10). I strongly suggest reading the previously stated works in order to properly comprehend this study (see references).

Table 1 : lists the color code, seismic species, and seismic level for each sub-zone in the Nyamulagira region.

Sub-areas	Seismic species	Seismic level $ou\ (b_j)$	Colour code
A1	IIIbc	7	Light red
A2	Ibc	4	yellow
A3	Ibc	4	yellow
A4	Iab	1	Pink
A5	Iab	1	Pink
B1	IIIbb	6	Orange
B2	Ibc	4	Yellow
B3	IIIbc	7	Light red

Table 2: Code des couleurs, espèce sismique et niveau sismique associés à chaque sous-zone pour la région du Nyiragongo.

Sub-areas	Seismic species	Seismic level $(a_i)\ ou\ (b_j)$	Colour code
A1	IIIbb	6	orange
A2	Ibc	4	Yellow
A3	Ibc	4	Yellow
A4	Ibb	3	Light green
A5	Iac	2	Light blue
B1	Ibc	4	Yellow
B2	Iab	1	Pink
B3	IIIbc	7	Light red

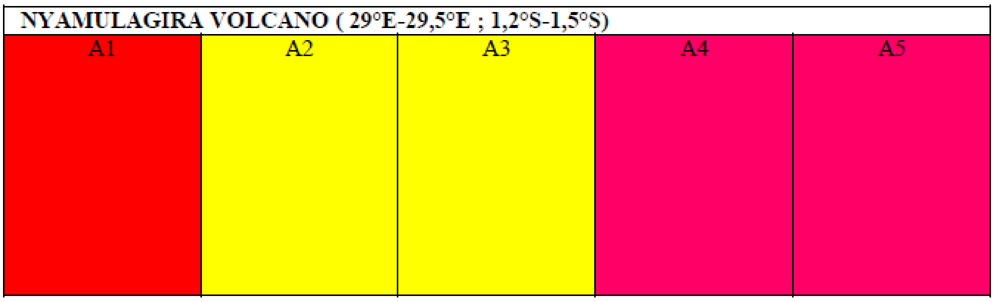

Figure 6: Seismic zoning map, vertical subdivision of the Nyamulagira area.

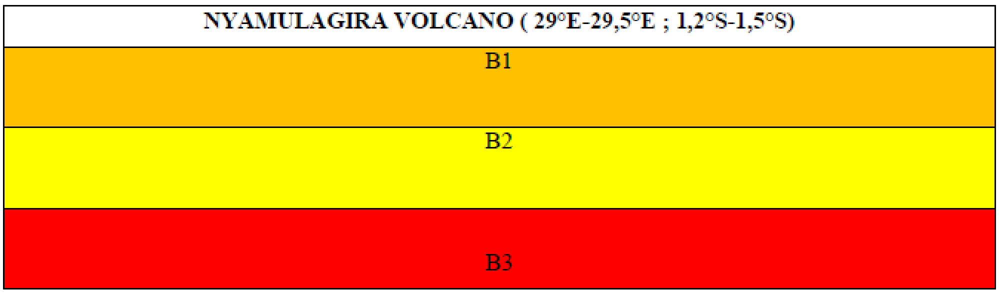

Figure 7: Seismic zoning map, horizontal subdivision of the Nyamulagira area.

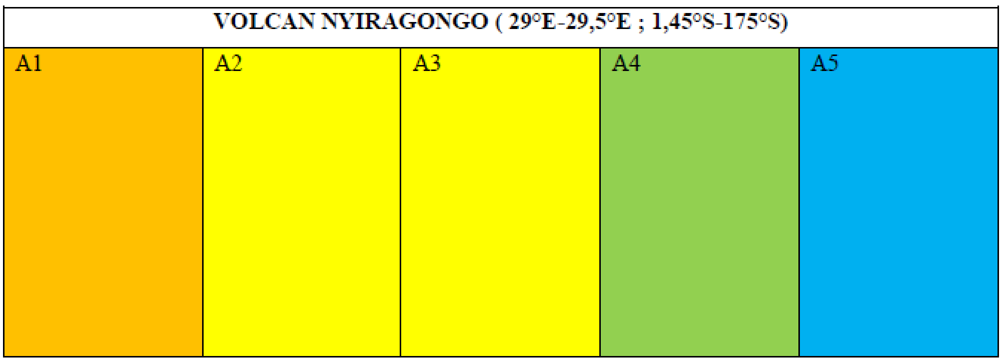

Figure 8 : Seismic zoning map, vertical subdivision of the Nyiragongo area.

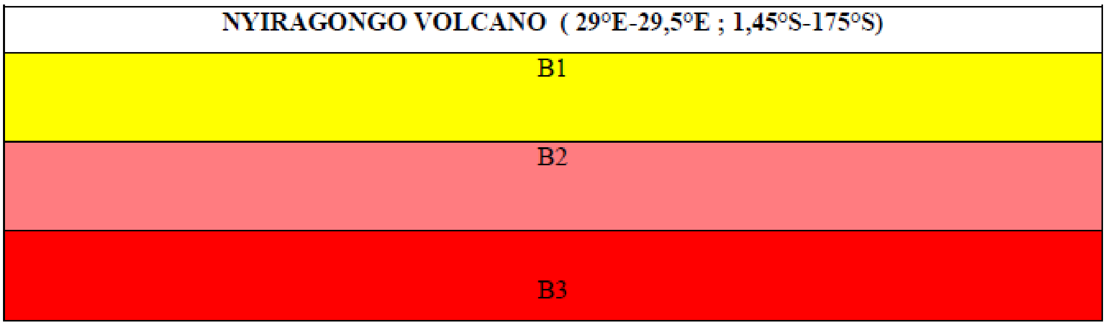

Figure 9 : Seismic zoning map, horizontal subdivision of the Nyiragongo area.

Table 3 : degree of heterogeneity of the Nyamulagira volcano sub-areas

Sub-areas	Degree of heterogeneity	Degree of heterogeneity in %
A_i	3/5	60 %
B_j	3/3	100 %
Average		80%

Table 4 : Overall degree of heterogeneity of the Nyiragongo volcano sub-zones

Sub-areas	Degree of heterogeneity	Degree of heterogeneity in %
A_i	4/5	80 %
B_j	3/3	100 %
Average		90%

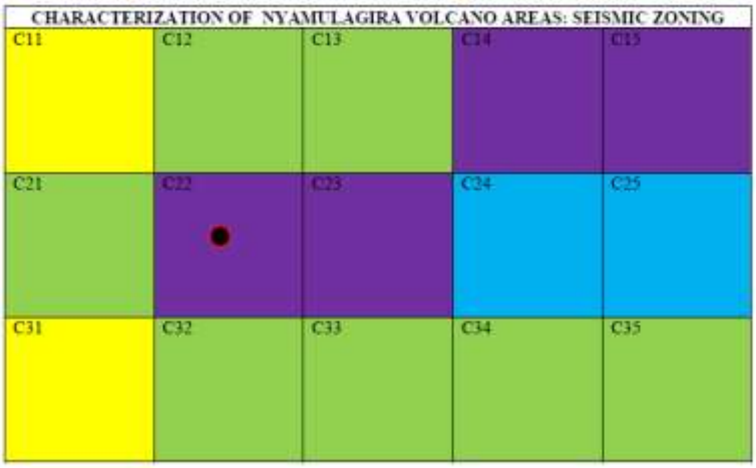

Figure 10a : caractérisation de l'activité sismique : carte de zonage sismique de la zone Nyamulagira

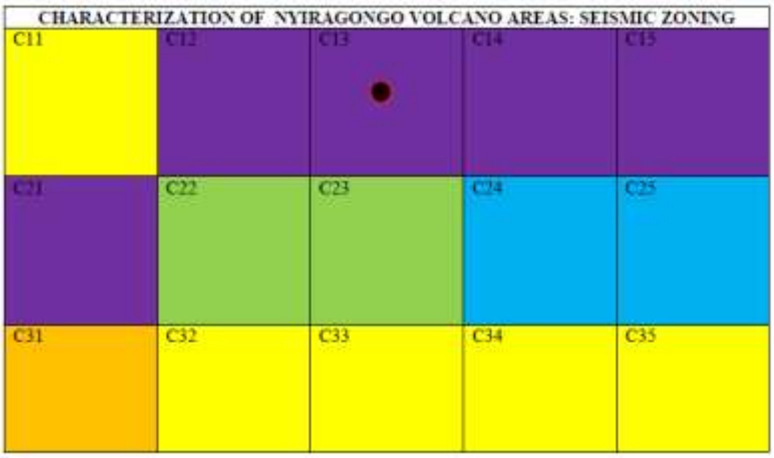

Figure 10b : characterisation of seismic activity: seismic zoning map of Nyiragongo area

2.2.2. Standardization of seismic levels , modulus and of colour code

It is essential to standardize these parameters because the work was done independently with various seismic levels (Table 1-2), making it difficult to compare the results (Tables 5-6).

Table 5 : seismic species, seismic levels and related colors of two areas being investigated

NYIRAGONGO				NYAMULAGIRA			
SUB-AREA	**SEISMIC SPECIES**	**SEISMIC LEVEL**	**COLOUR CODE**	**SUB-AREA**	**SEISMIC SPECIES**	**SEISMIC LEVEL**	**COLOUR CODE**
A1	IIIbb	6	Orange	**A1**	IIIbc	7	Light red
A2	Ibc	4	Vert	**A2**	Ibc	4	Green
A3	Ibc	4	Vert	**A3**	Ibc	4	Green
A4	Ibb	3	Violet	**A4**	Iab	1	Pink
A5	Iac	2	Bleu clair	**A5**	Iab	1	Pink
B1	Ibc	4	Vert	**B1**	IIIbb	6	Orange
B2	Iab	1	Rose	**B2**	Ibc	4	Green
B3	IIIbc	7	Rouge clair	**B3**	IIIbc	7	light red
D1	Ibb	3	Violet	**D1**	IIIbc	7	Light red
D2	IIIbb	6	Orange	**D2**	IIIbb	6	Orange
D3	Ibc	4	Vert	**D3**	Iab	1	Pink
D4	Ibc	4	Vert	**D4**	Ibc	4	Green

NB : For details of sub-areas D1, D2, D3 and D4, see figures (24-25).

Table 6 : Modulus, quantum seismic levels and grid-area colours (Cij) of the two areas being investigated.

NYIRAGONGO				NYAMULAGIRA			
GRID-AREA Cij	**MODULUS**	**QUANTUM LEVEL**	**COLOUR**	**GRID-AREA Cij**	**MODULUS**	**QUANTUM LEVEL**	**COLOUR**
C11	9	5	YELLOW	**C11**	9	5	YELLOW
C12	7	4	GREEN	**C12**	7	4	GREEN
C13	8	4	GREEN	**C13**	7	4	GREEN
C14	7	4	GREEN	**C14**	6	3	PURPLE
C15	6	3	PURPLE	**C15**	6	3	PURPLE
C21	7	4	GREEN	**C21**	8	4	GREEN
C22	4	2	LIGHT BLUE	**C22**	6	3	PURPLE
C23	5	3	PURPLE	**C23**	6	3	PURPLE
C24	3	2	LIGHT BLUE	**C24**	4	2	LIGHT BLUE
C25	2	1	PINK	**C25**	4	2	LIGHT BLUE
C31	11	6	ORANGE	**C31**	10	5	YELLOW
C32	9	5	YELLOW	**C32**	8	4	GREEN
C33	10	5	YELLOW	**C33**	8	4	GREEN
C34	9	5	YELLOW	**C34**	7	4	GREEN
C35	8	4	GREEN	**C35**	7	4	GREEN

The results in the two tables above, particularly with regard to the quantum level, can be achieved by using the table below. We assign a quantum level and a color to each modulus slice.

Tableau 7 : Quantisation des modules et ode des couleurs y associée

Module interval (M)	Quantum level	Colour code
0<M≤2	1	PINK
2<M≤4	2	LIGHT BLUE
4<M≤6	3	PURPLE
6<M≤8	4	GREEN
8<M≤10	5	YELLOW
10<M≤12	6	ORANGE

Thus, the unification of the results through the use of table (6) transforms figures (10) into figures (11 and 13) with their corresponding structures in figures (12 and 14).

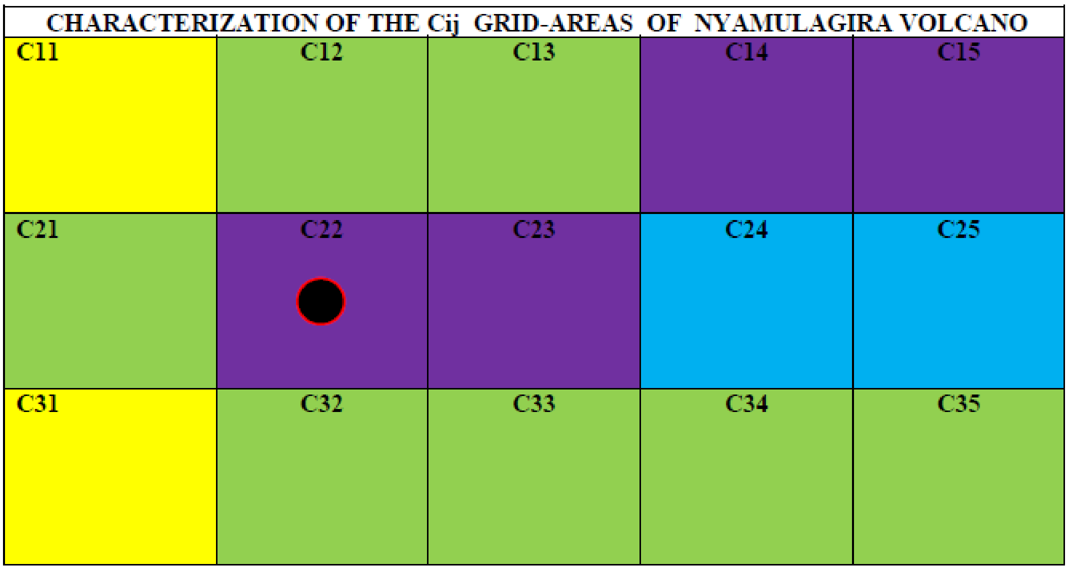

Figure 11 : Seismic zoning map of Nyiragongo area after standardisation

Below is the corresponding geo-seismic signature

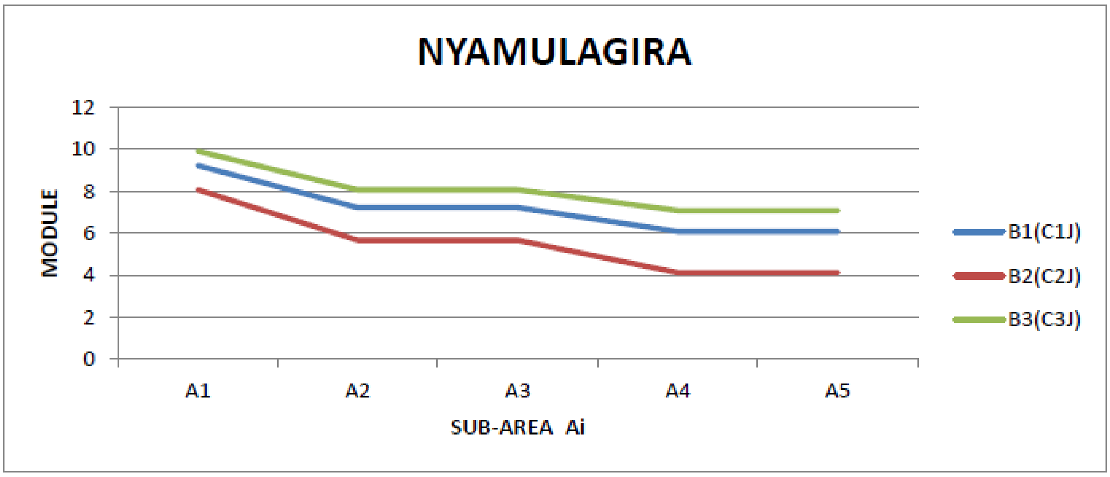

Figure 12 : Seismic structure curve of Nyamulagira area

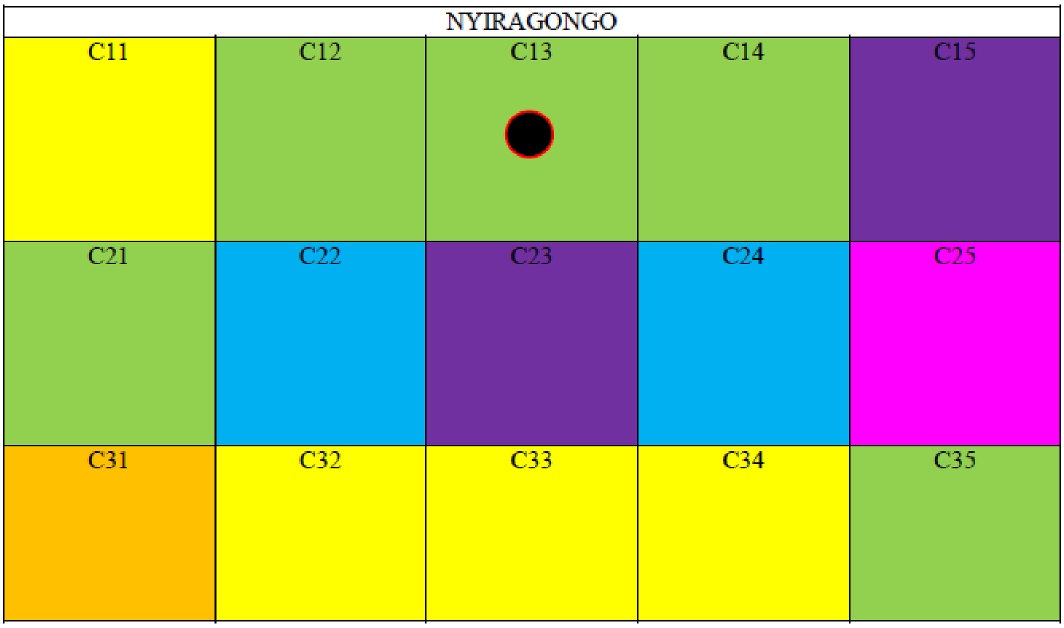

Figure 13 : Seismic zoning map of Nyiragongo area after standardization

Below is the corresponding geo-seismic signature.

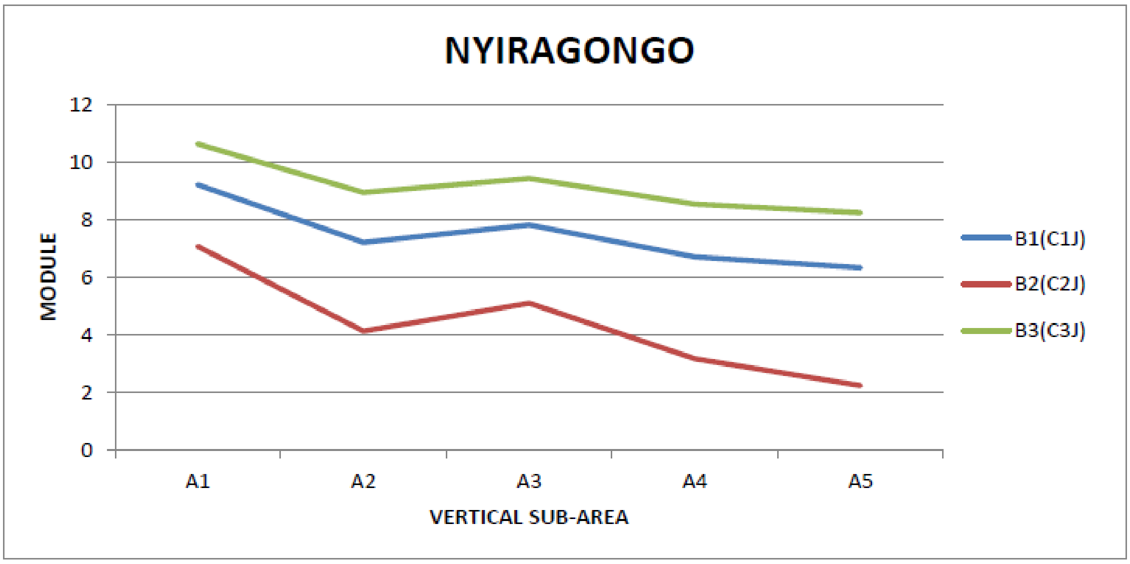

Figure 14 : Seismic structure curve of Nyiragongo area

3.2. Discussion of results

Results from Nyamulagira and Nyiragongo areas will be compared by using a variety of parameters that were gathered in each area and are described above. These include :

3.2.1. About seismic species

The results of the table(5) are shown in the Venn diagrams below.

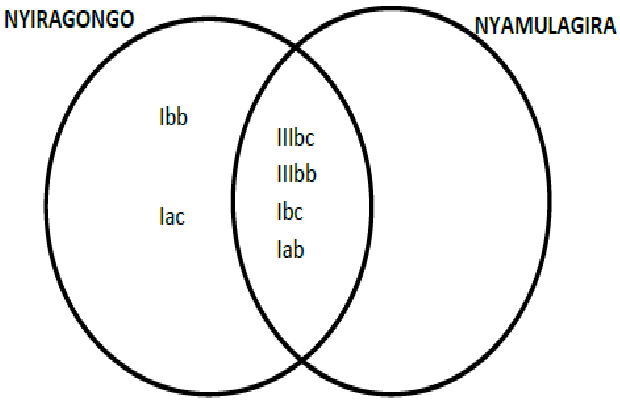

Figure 15a : Venn diagram showing a comparison of seismic species.

It appears that all species of Nyamulagira are included in the Nyiragongo. The latter has only two species (Iac and Ibb).These two species, which are unique to Nyiragongo, were discovered in vertical sub-areas A5 and A4, respectively (Table 5). So, in comparison to Nyamulagira, we may argue that these places behave in a particular way. This peculiarity is also shown in figures (12) and 14, where there is an excessively large gap between curves B2 and B3 (see point 3.2.3). Thus, it appears that Nyamulagira is a 67% similar subset of Nyiragongo (four out of six species are common)

According to the structure factors (in seismic species indices), the above figure becomes

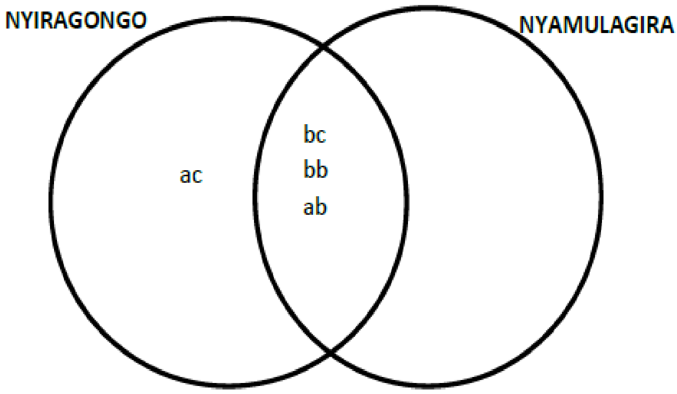

Figure 15b : A Venn diagram is used to compare the structural factors of seismic species.

In terms of structural factors, it appears that only the (ac) factor distinguishes the two volcanic areas; thus, the similarity is 75%. 25% of Nyiragongo's peculiarity is justified by its extremely complex shape (stratovolcano with a crater made up of three platforms, ...)

3.2.2. On the zoning maps and quantum level of the areas – grids.

On the zoning maps and quantum level of the grid areas. The zoning maps and related quantum level curves (Figures) reveal :

- A grouping of grid-zones (Cij), based on colours, into four groups for the Nyamulagira zone (Table 8).

Table 8 : Color statistics for Nyamulagira (module)

N°	COLOUR	AREAS-GRIDS	CONTRIBUTION(%)
1	PURPLE	C14, C15, C22, C23	4/15 (27%)
2	BLUE	C24,C25	2/15 (13,3%)
3	GREEN	C12,C13,C21,C32,C33,C34,C35	7/15 (47%)
4	YELLOW	C11,C31	2/15 (13,3%)

- A grouping of grid areas (Cij), based on colours, into six groups for the Nyiragongo zone (Table 9).

Table 9 : Color statistics for Nyiragongo (module)

N°	COLOUR	AREAS-GRIDS	CONTRIBUTION(%)
1	PURPLE	C23,C15	2/15 (13,3%)
2	BLUE	C22,C24	2/15 (13,3%)
3	GREEN	C12,C13,C14,C21,C35	5/15 (33,3%)
4	YELLOW	C11,C32,C33,C34	4/15 (27%)
5	PINK	C25	1/15 (6,7%)
6	ORANGE	C31	1/15 (6,7%)

- The table results (8-9) are depicted in the figure below.

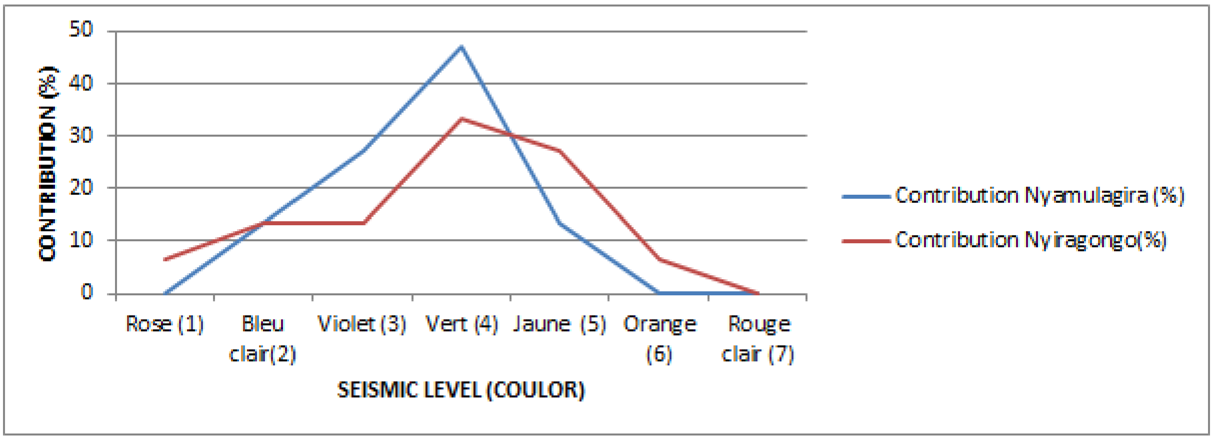

Figure 16: A comparison of the color weights of the Nyamulagira and Nyiragongo areas.

The two curves in Figure (16) show that:

- Except for the purple color, the two structures are nearly identical (same shape).
- The Nyiragongo structure is stronger or more abundant than the Nyamulagira structure because its curve is wider on the x-axis representing the color spectrum.
- The proportion of blue color is the same in both areas (intersection point at 13%).
- The proportion of blue color is the same in both areas (intersection point at 13%), and there are green and purple singularities; interestingly, these are the locations of the Nyiragongo and Nyamulagira craters, respectively.
- What these two curves have in common is that they all have a green peak. They all have a bell shape with a point of symmetry on the abscissa, which is green. As a result, all of the green areas (Figures 11 and 13) for Nyiragongo and Nyamulagira have the same structure. Let us now look at the quantum level curves derived from the table (6):

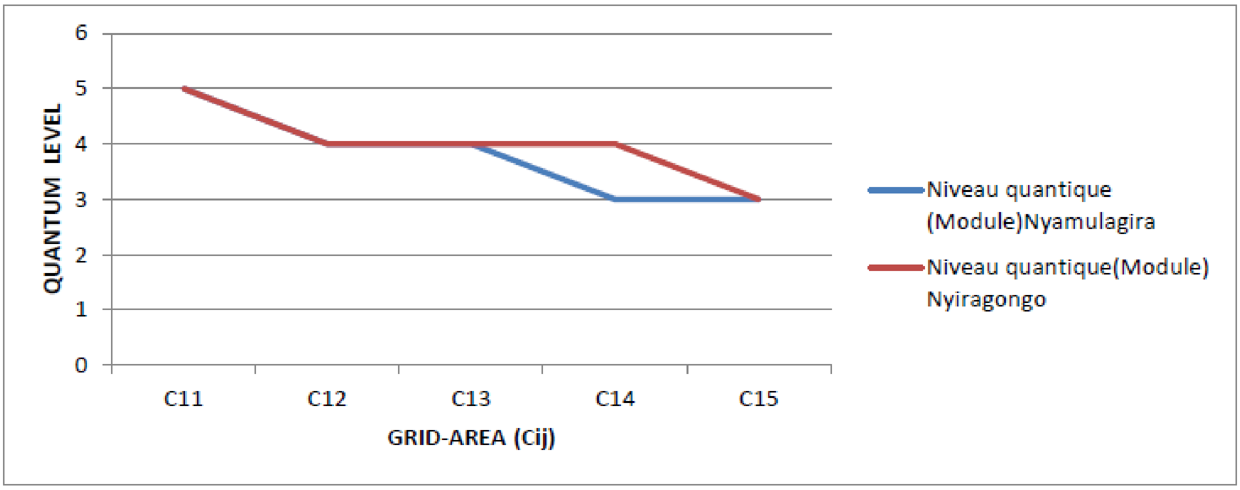

Figure 17: Quantum level of Nyamulagira and Nyiragongo areas on the first line (B1i)

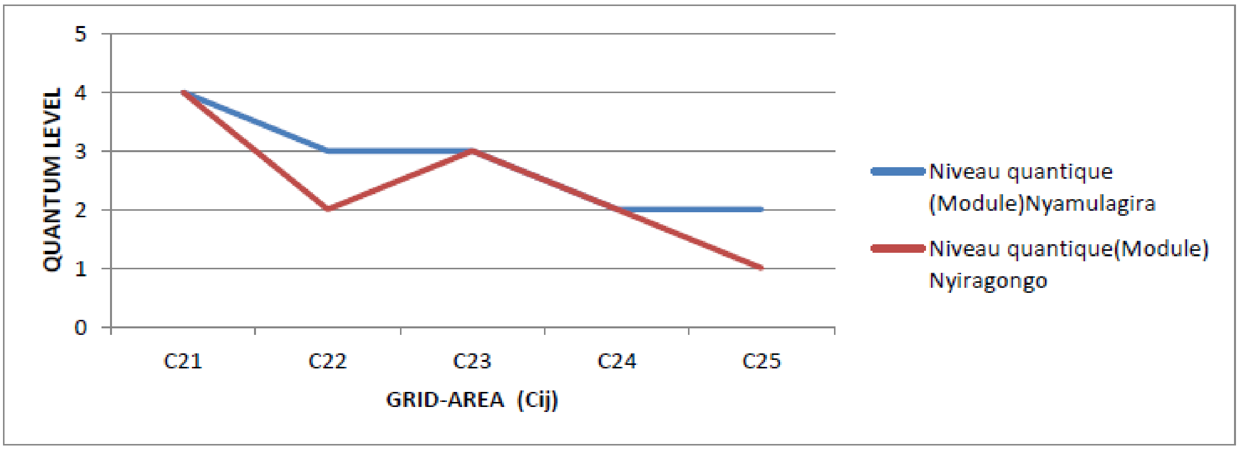

Figure 18 : Quantum level of Nyamulagira and Nyiragongo areas on the second line (B2i)

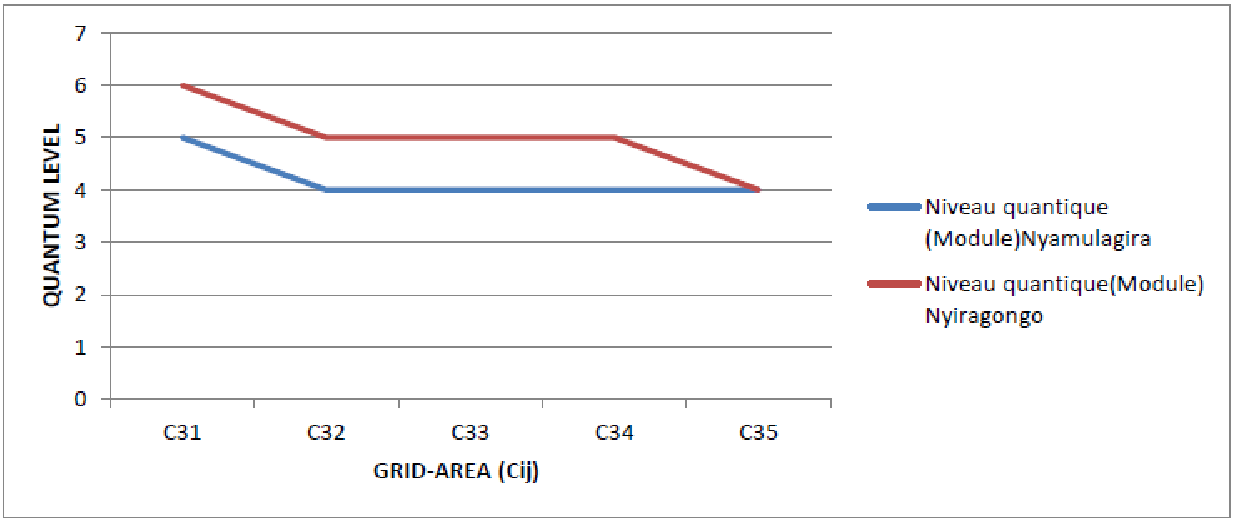

Figure 19 : Quantum level of Nyamulagira and Nyiragongo areas on the third line (B3i)

The observation of these curves shows that :

- The first lines (Figure 17,11 and 13) of Nyiragongo and Nyamulagira are 80% identical,
- The second lines (Figure 18, 11 and 13) of the Nyiragongo and Nyamulagira are identical at 60%,
- The third lines (Figure 19, 11 and 13) of Nyiragongo and Nyamulagira are 20% identical and have similar shapes at 80%, and become identical (same value) at the end (at C35),
- The third line of Nyiragongo is 80% identical to the first line of Nyamulagira (Figure 11 and 13). The strong resemblance is due to the fact

that these two areas are located between two craters (Figure 33).

- The first line of Nyiragongo is 100% similar to the third line of Nyiragongo (Figure 11 and 13).

Finally, the degree of heterogeneity is 70% and 88% for Nyamulagira and Nyiragongo respectively.

3.2.3. Structural curves

Let us analyse the following structural curves.

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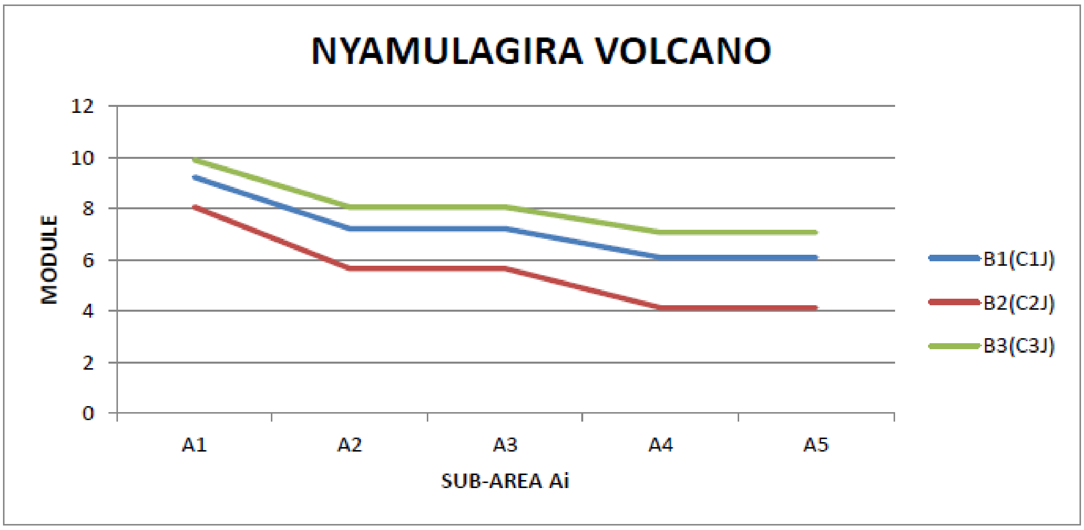

Figure 20 : Seismic structure curve of Nyamulagira area

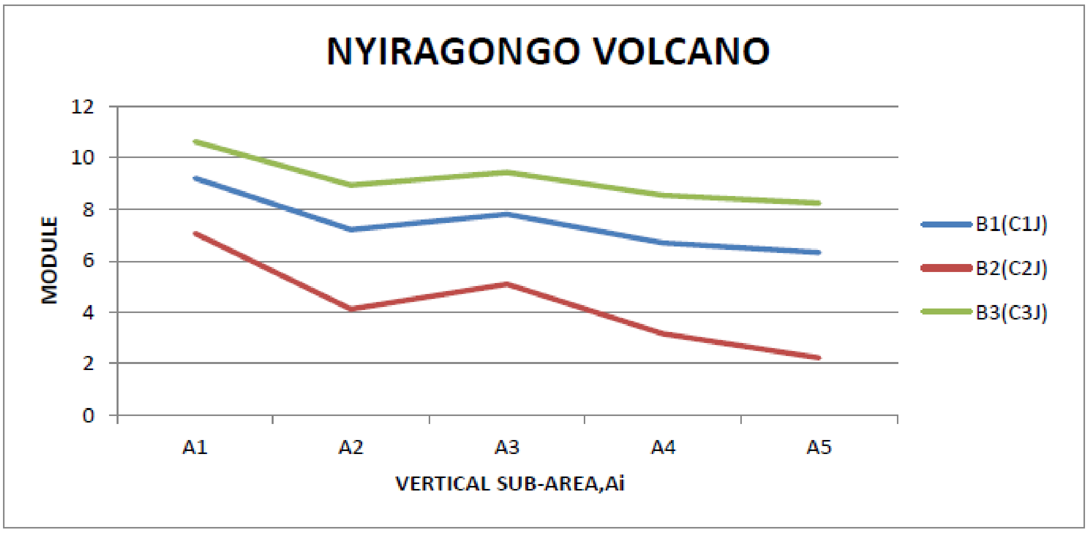

Figure 21 : Seismic structure curve of Nyiragongo area

The observation of these geo-seismic signatures shows that :

- The gap between curves B2 and B3 becomes twice as large at A4 and A5 for both Nyamulagira (Figure 20) and Nyiragongo (Figure 21): twice as large as at A1, A2, and A3 for the same curves (B2 and B3). Craters are more likely to be found at the latter locations (A1, A2 or A3).
- The curves generally descend from west (A1) to east (A2) (A5).

- The structure of both Nyiragongo and Nyamulagira decreases from top to bottom (B1) from top to bottom (B3).

3.2.4. Curves linking maximum depths to sub-areas Ai and Bj

Let's compare the following curves:

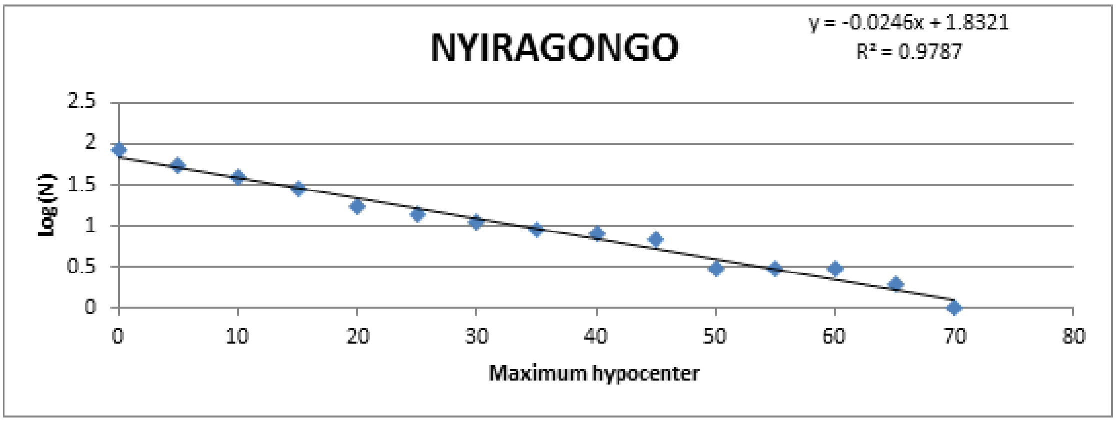

Figure 22 : Modelling the soil structure around Nyiragongo

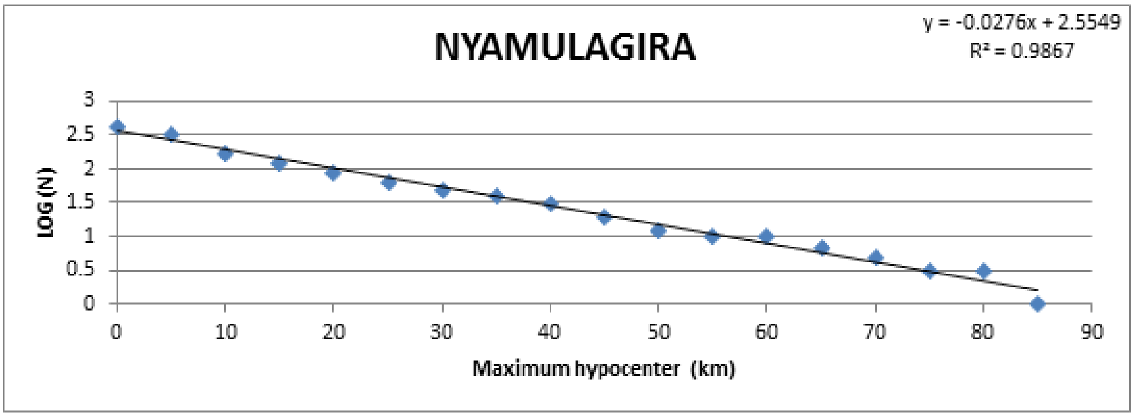

Figure 23 : Modelling the soil structure around Nyamulagira

Observation of these curves shows that they are almost similar; indeed, the angular coefficients of their lines, characterising the ground structure, are almost equal.

The figure above models the behaviour of the maximum hypocentres recorded at each vertical sub-area(Ai) for the two volcanoes, moving from west to East.

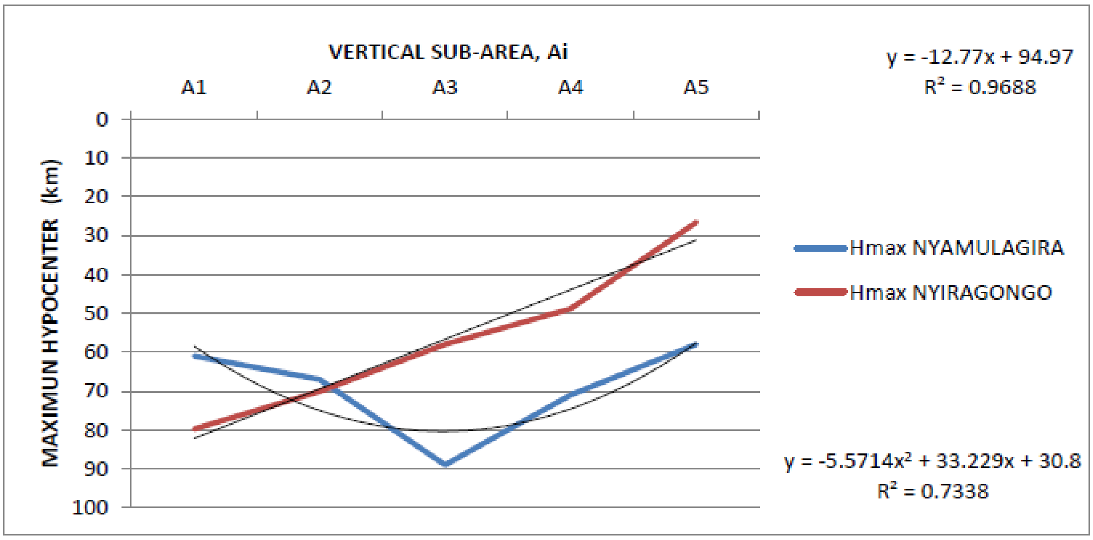

Figure 24 : Soil structure curve of Nyiragongo and Nyamulagira zones following the Ai

We can see from this figure that :

- From A1 to A3, the two lines move in the opposite direction:
- Nyiragongo has a positive slope, while the other has a decreasing slope, with the following details:

- At A1, Nyamulagira's hypocentre is lower than Nyiragongo's; at A2, there is equality; A2 is the zone of intersection between the two volcanoes.
- At A3, the hypocentre of Nyamulagira becomes greater than that of Nyiragongo.
- From A3 to A5, the two lines are nearly parallel with a positive slope, with Nyamulagira's hypocentres deeper than Nyiragongo's.
- From A1 to A5, the model in Nyiragongo has a linear shape with a positive slope, whereas Nyamulagira has a parabolic curve with an upward slope (two straight lines, one decreasing and the other decreasing),
- The A2 and A3 zones are thus of special interest to us.

Consider the distribution of maximum hypocentres in each horizontal zone (Bj), from North to South (Bj).

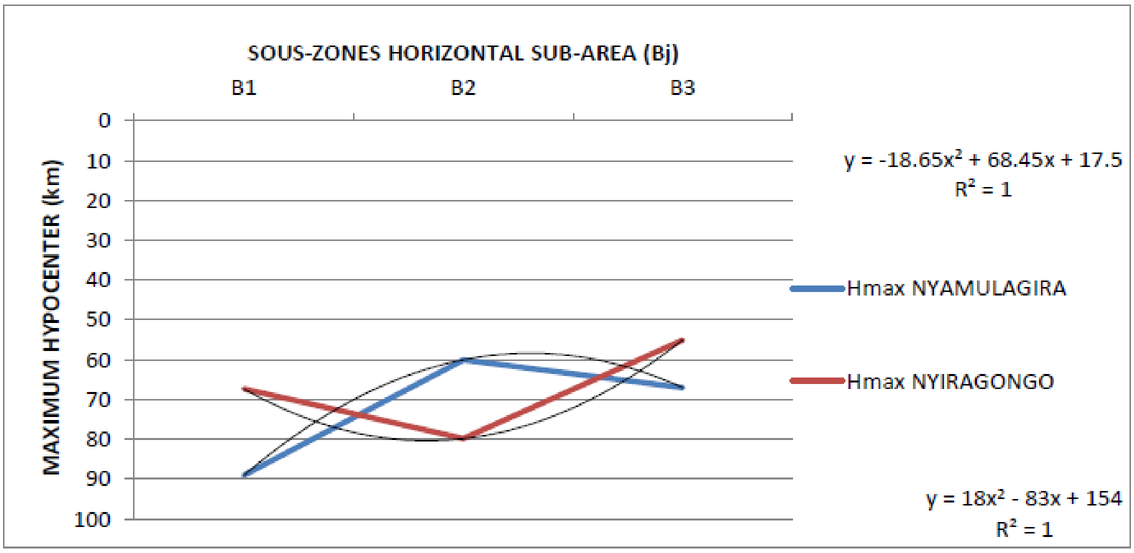

Figure 25 : Soil structure curve of Nyiragongo and Nyamulagira areas according to Bj

The figure above reveals the following:

- The two parabolic curves are symmetrical, with :
at B1, the hypocentre of Nyamulagira is higher than that of Nyiragongo
at B2, the reverse is true, the hypocentre of Nyamulagira becomes lower than that of Nyiragongo,
At B3, we return to the initial situation, as at B1,

- B2 is therefore of interest as a singular point: the symmetrical line to the two curves passes through B2.

The comparison of curves (Figures 24-25) shows that:

- The Nyiragongo area studied from North to South (Bj) has a similar structure to that of Nyamulagira, studied from West to East (Ai),

- These two structures act inversely to the Nyamulagira structure studied along the Bj (horizontally).

The following curve shows the distribution of the maximum hypocentres from the North (Nyamulagira) to the South (Nyiragongo).

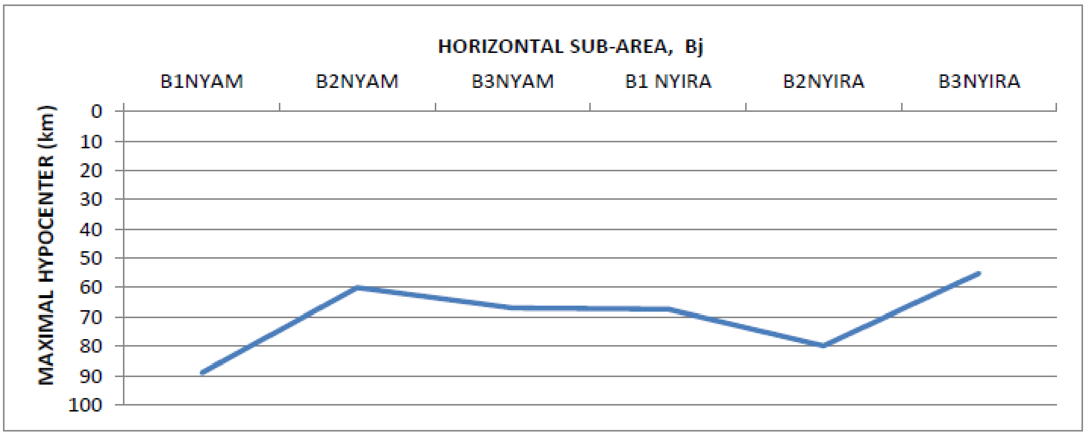

Figure 26 : Soil structure curve of the Nyamulagira (North) and Nyiragongo (South) zones according to Bj, from North to South.

The two curves below depict the shape of the magma reservoir.

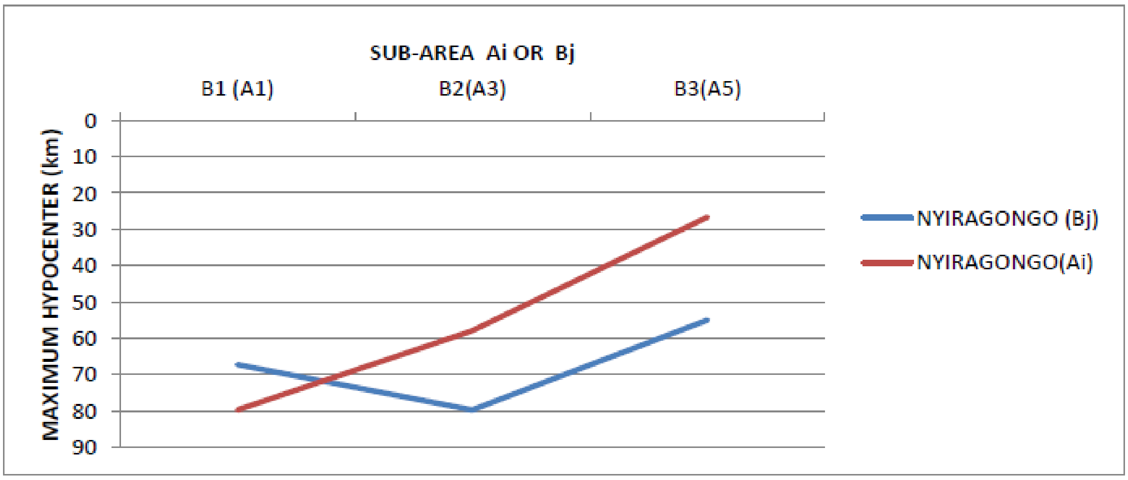

Figure 27 : Soil structure curves of the Nyiragongo area according to Bj and Ai.

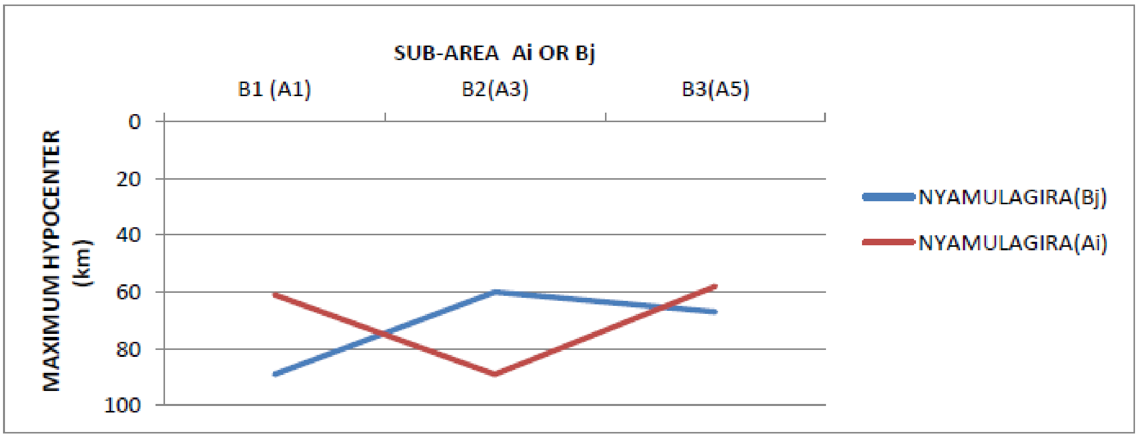

Figure 28a : Soil structure curves of the Nyamulagira area according to Bj and Ai.

After observation, we should note the following:

- Knowing that the shape of the Nyamulagira volcano reservoirs is predominantly cylindrical (quote), the curves in figure (28b), would henceforth represent this shape,
- Knowing that the shape of the Nyiragongo volcano reservoirs is predominantly spherical (quote), the curves in figure (28a) would now represent this shape.
- Ultimately, we say that the shape of the curves would give an indication of the shape of the magma reservoir; this is one of the geological implications.

The curve below gives statistics on the distribution of hypocentres by depth bands for each volcanic area.

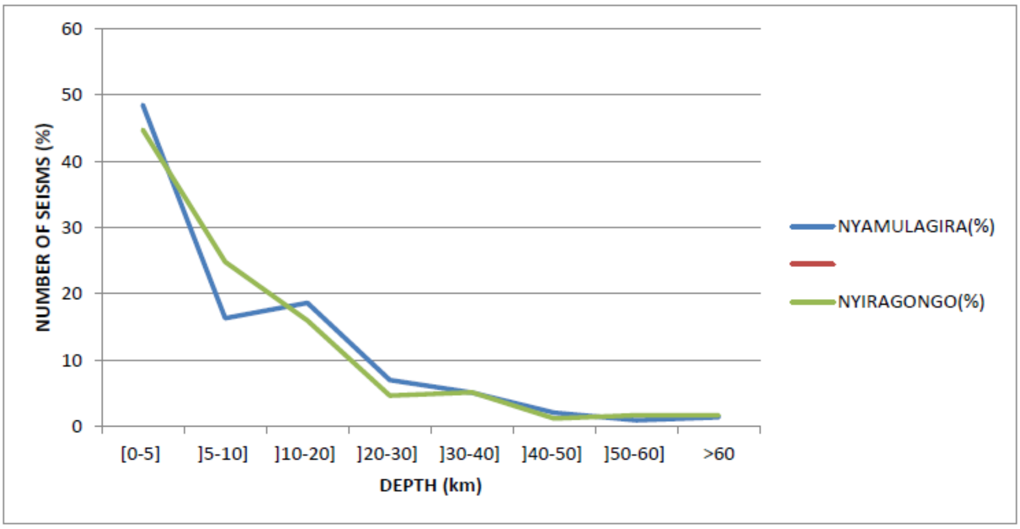

Figure 28b : Hypocentre distribution based on depth band

These curves show: - A Nyamulagira anomaly at depths [5-10] and [10-20],
- A Nyiragongo anomaly at depths [20-30] and [30-40],
- A perfect coincidence of two curves ranging from [30-40] at Moho to beyond,
- The anomalies observed in these locations are almost certainly the result of significant volcanic activity, which would indicate the location of the magma reservoir at depth; another geological implication.

3.2.5. From seismic energy, earthquake frequency, and d-value

The distribution of the number of earthquakes, seismic energy released, and soil structure constant (d-value) for each sub-area is depicted in Figures 29 and 30.

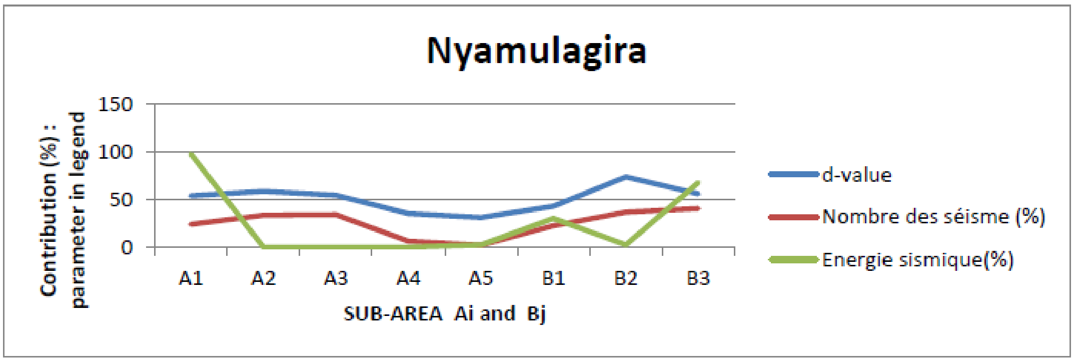

Figure 29 : Distribution of energy, number of earthquakes and d-value over the Ai and Bj sub-areas of Nyamulagira area

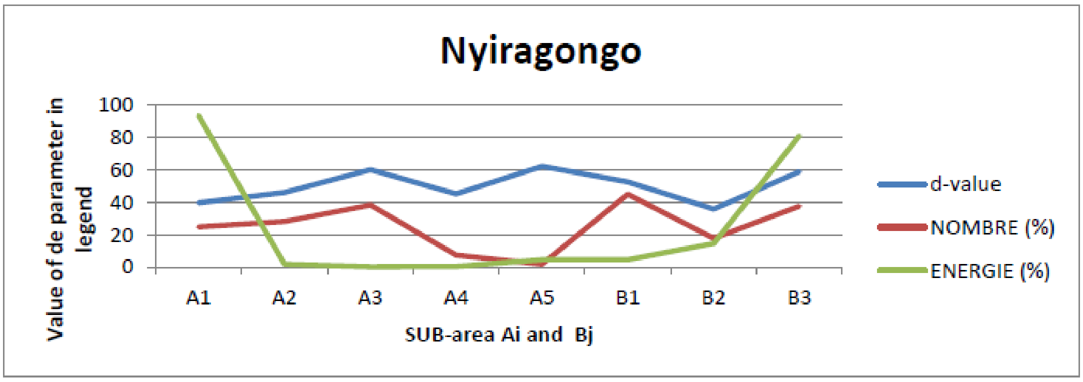

Figure 30 : Energy distribution, number of earthquakes, and d-value over the Ai and Bj sub-zones of the Nyiragongo area

NB: the d-value has been multiplied by 2000.

These two figures show: - a strong correlation between the curve of the number of earthquakes (%) and the d-value (which characterises the soil structure).

We conclude and confirm that seismic activity is influenced by soil structure. That, on a global scale, the structure constant curve evolves inversely to the energy curve. Figures (31 and 32) express previous realities by introducing the concept of the "volume density" parameter.

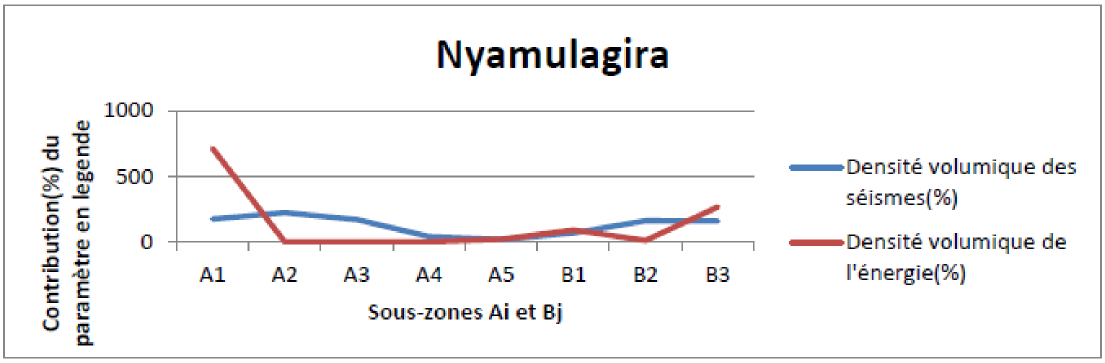

Figure 31 : Distribution of d-value and volume densities of energy and number of earthquakes in sub-areas Ai and Bj, Nyamulagira area

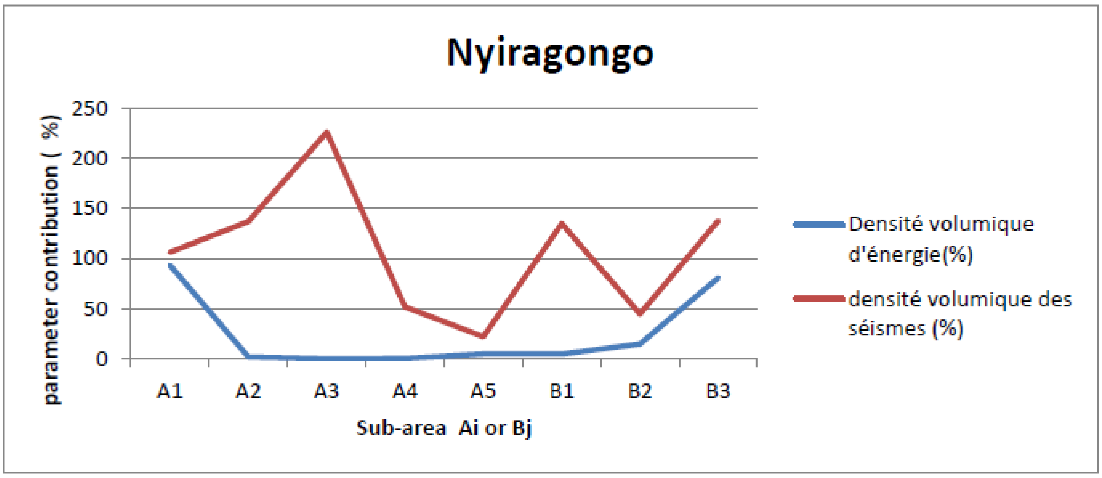

Figure 32: Distribution of d-value and volume densities of energy and number of earthquakes in sub-areas Ai and Bj, Nyiragongo area

These two curves show the following:

- With a few nuances, there is a correlation between the minimum of the high energy density and the maximum of the number of earthquakes at the same location for both Nyamulagira and Nyiragongo and vice versa.
- The assumptions made at the outset are validated at sub-areas A2 and B2 for Nyamulagira and A3 and B1 for Nyiragongo, the most likely location of craters.

It is concluded that it is preferable for the characterisation of seismicity to be described in terms of volume density rather than in terms of number of earthquakes or energy. The notion of volume is therefore important in this study.

3.2.6. Craters location and distance among them

The location of the crater is based on the assumptions that the crater is located where :

- The volume density of the number of earthquakes is abnormally high,
- the volume density of the seismic energy of tectonic or volcano-tectonic earthquakes is very low.

Based on these assumptions, other discriminating elements mentioned above and the exploitation of the results of figures (24-25), it turns out that the crater is located at zone C22≡ (B2, A2) ≡ [29.15°E; 1.35° S] for the Nyamulagira volcano and at zone C13≡ (B1, A3) ≡ [29.25°E; 1.50° S] for the Nyiragongo volcano (Figure 33). Red solid circles indicate their locations of Nyamulagira (above) and Nyiragongo (below) craters

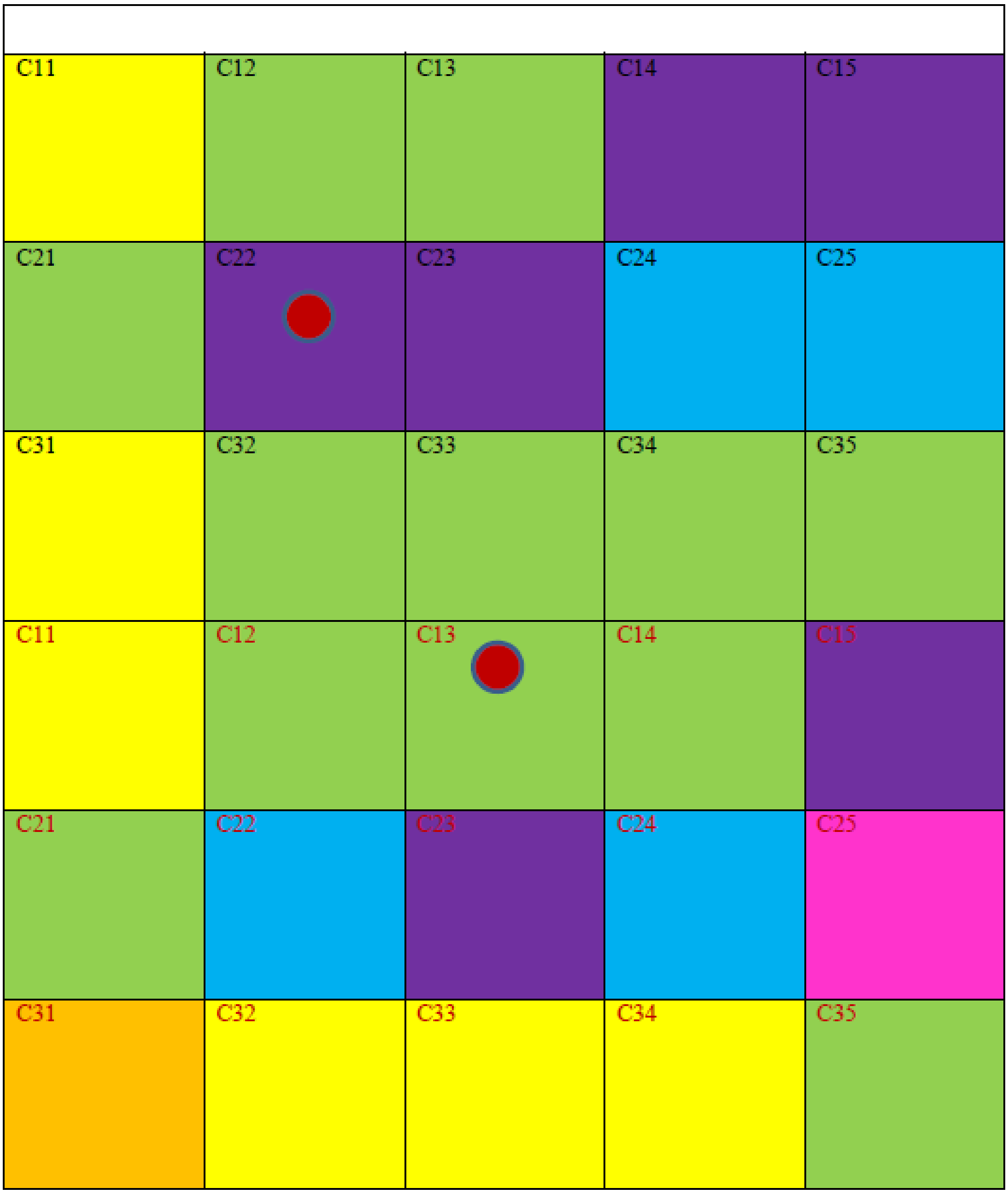

Figure 33 : Location of Nyamulagira (red bubble, above) and Nyiragongo (solid red bubble, below) craters

Cij grid areas in black correspond to the Nyamulagira volcano area and Nyiragongo in red. It is clear that (Figure 33):

- the two columns A2 (C12 ,C22,32,C12 and C22)and A3(C13 ,C23,33,C13 and C23) where the craters of the volcano Nyamulagira and Nyiragongo respectively are located are 100% identical,
- Adding (C22 and C32) to A2 and (C12 and C22) to A3, the similarity rate reduces to 83%.
- The distance between the two craters is about 15 km, which is consistent with field observations.

3.2.7. Characterisation around craters

We are interested in characterising the seismicity of the volcanoes around craters (solid red circle in the following figures): We subdivide the area into four quadrants, called Di , by drawing two straight lines, one vertical and one horizontal, pass through the crater point. This model was used to characterize these zones.

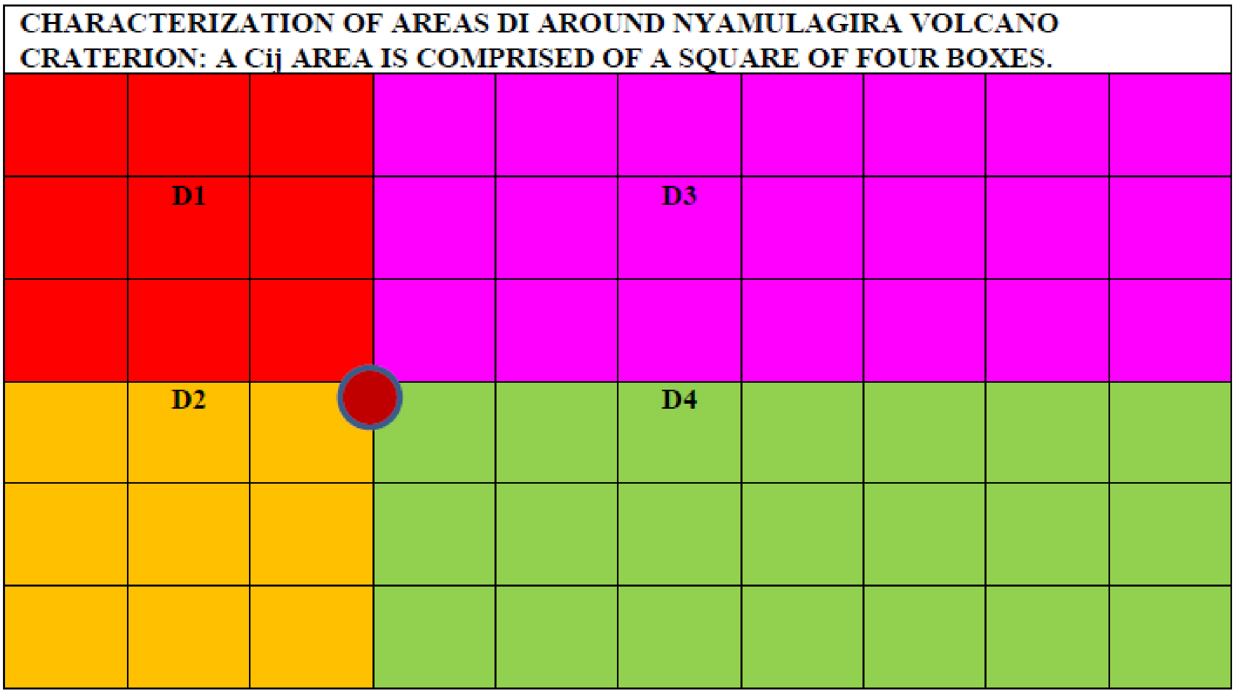

Figure 34 : Characterization around Nyamulagira crater is extremely fine.

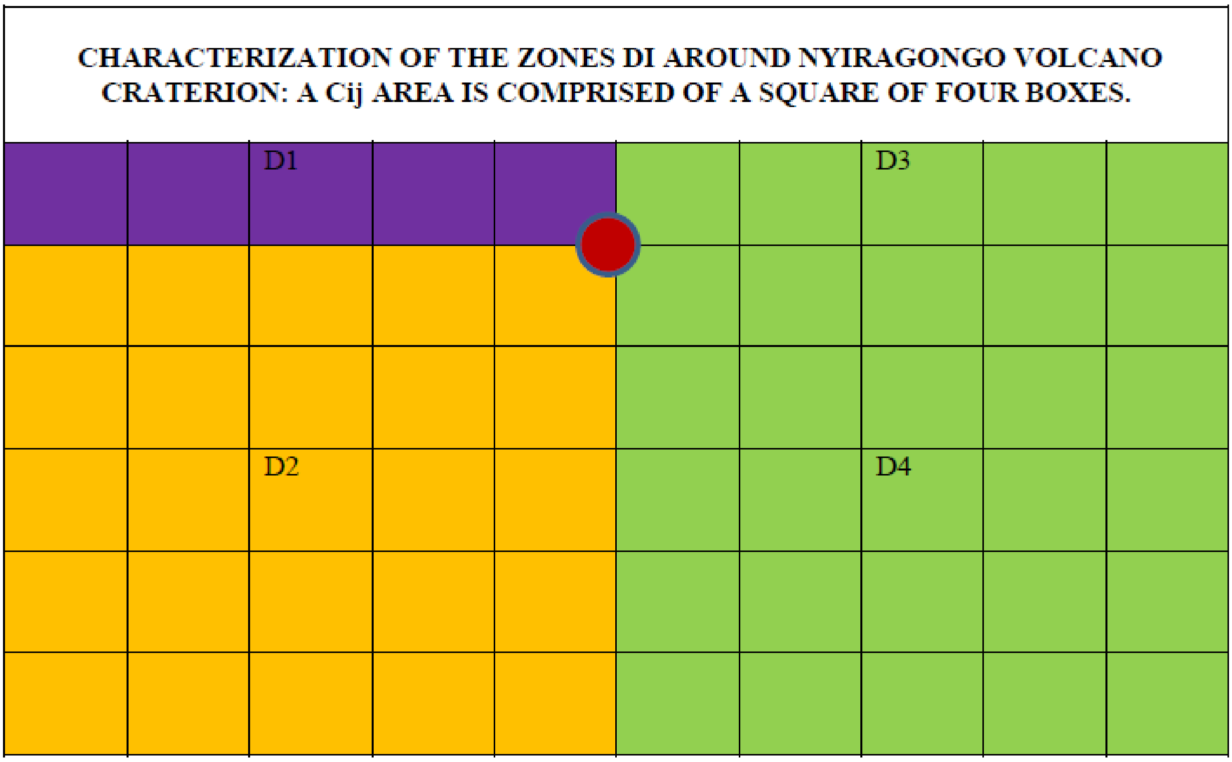

Figure 35 : Characterisation around the Nyiragongo crater is extremely fine.

These figures highlight the following observations:

3.2.7.1. About Nyamulagira volcano

The investigation is carried out in three stages:-

We notice four color groups:

The northwest red cluster (D1) is distinguished by extremely high activity.The orange grouping in the southwest (D2) is active. The green cluster in the south-east (D4) is active, while the pink cluster in the north-east (D3) is inactive.

- In terms of quadrants, we observe: high activity to the left (West) of the crater (D1 and D2), medium activity to the right (East) of the crater (D3 and D4), and low activity to the center (D4) of the crater (D3 and D4)

Nothing can be said about North-South activity.

- We can see from the diagonals passing through the crater that:

The North-West-South-East diagonal (D1-D4): the North-West has low activity, while the South-East has medium activity.

The North-East (D3-D2) and South-West diagonals are moderately active, whereas the South-West is extremely active. As a result, the seismic activity structure is symmetric, with a degree of heterogeneity of 100%. (four groups of colours in four quadrants: each quadrant has a colour).

3.2.7.2. On top of Nyiragongo volcano

The analysis is carried out in three steps, as before: - There are three color categories:

- The orange grouping (D2), with high seismicity, is located in a large south-western area.
- The medium activity green grouping in the east (D3 and D4),
- The purple assemblage (D1),

In terms of quadrants, we note :

- High activity on the left (west) side of the crater (D1 and D2),
- Low activity to the right (east) of the crater (D3 and D4),
- Nothing can be said in terms of activity between the North and the South

According to the diagonals passing through the crater, we observe the following:

- The North-West, South-East diagonal (D1-D4): the North-West has high activity, while the South-East has medium activity,
- The North-East-South-West diagonal (D3-D2): The North-East is low activity, while the South-West is high activity. This is the opposite of what is observed for Nyamulagira.
- We therefore observe a quasi-symmetry of the seismic activity structure and a degree of heterogeneity of 75% (three groups of colours on four quadrants: each quadrant has a colour)

3.2.7.3. Comparison between the two volcanoes

The comparison between the two structures is done in two ways and is well visualized using Vein diagrams.

The statistics on the colors of the structures in Figures 10a-b: we will do this in terms of the North, South, East and West zones of the structures. The C2j zones (J=1, 2.3) separate the North from the South, while the Ci3 zones (i=1, 2.3) separate the East from the West of the structure.

The structures (Figure 10 ab or Figure 33) are clearly presented in the diagrams below

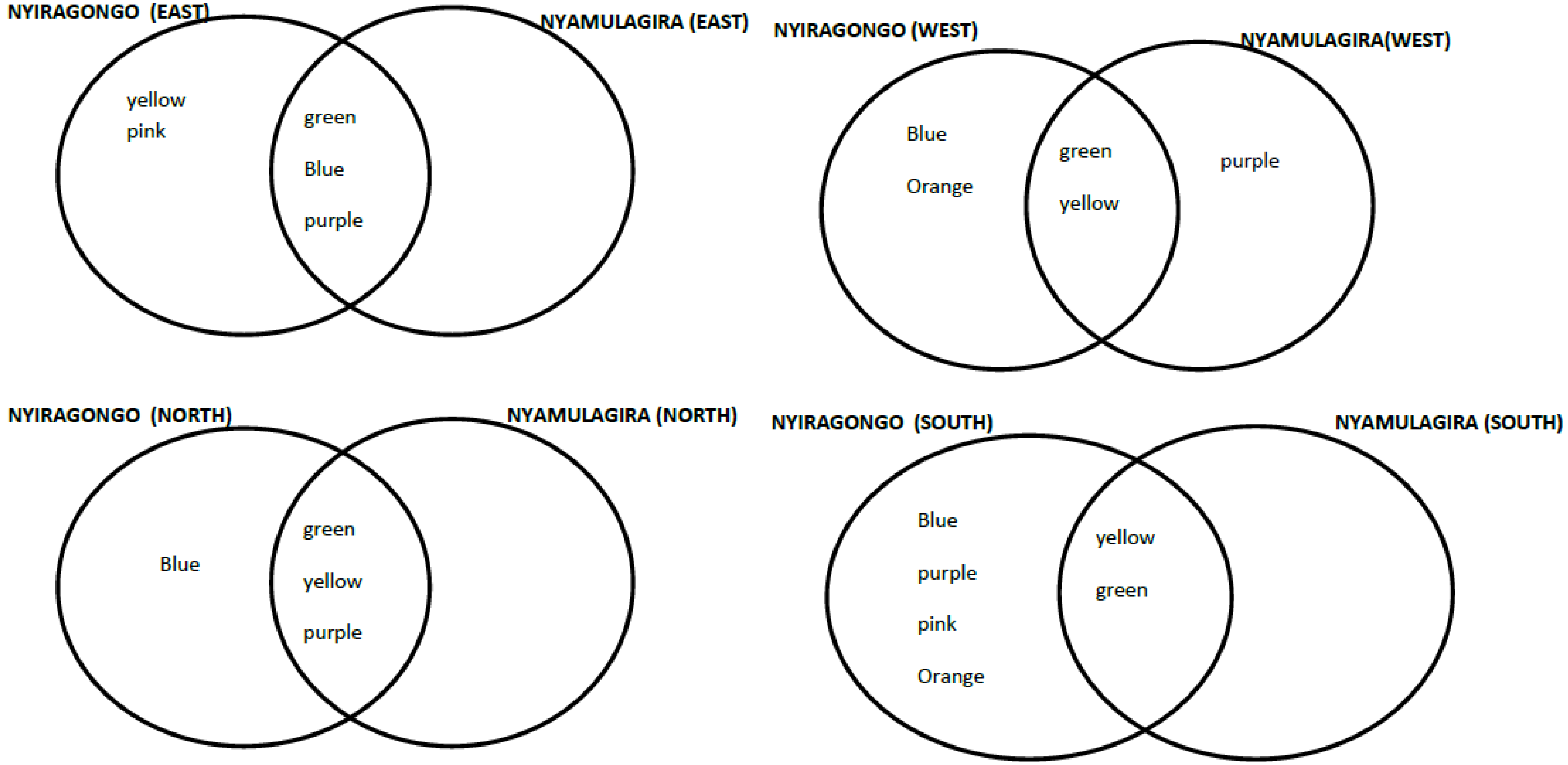

Figure 36: Qualitative comparison of the Nyiragongo and Nyamulagira structures through Vein diagrams; symmetrical subdivision

Statistically, these results are contained in the table

The statistics on the colors of the structures in Figures 10a-b: we will do it in terms of the North, South, East and West zones of the structures, but on the basis of the quadrants (Figures 34 and 35): the C2j zones (J= 1, 2,3) separate the North from the South, while the zones Ci3 (i=1,2,3) separate the East from the West of the structure. The structures (Figure 34 and 35) are clearly presented in the diagrams below.

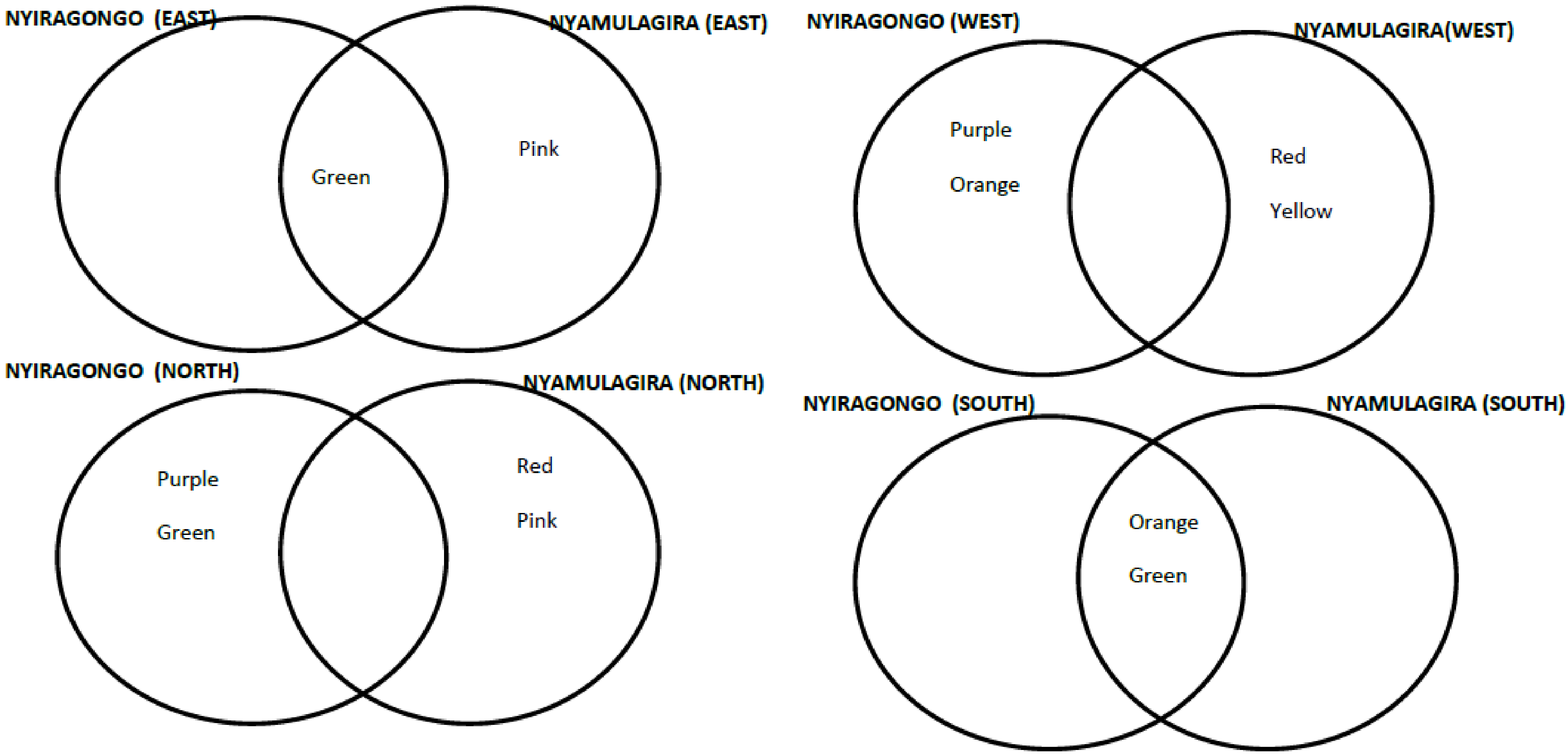

Figure 37: Qualitative comparison of Nyiragongo and Nyamulagira structures through Vein diagrams; subdivision into quadrants

Statistically, these results are contained in the table

Table 10: Statistics relating to figure (36), East-West subdivision

SUBDIVISION/COMPARISON	COMMON COLORS (%)	COLORS EXCLUSIVE TO NYIRAGONGO (%)	EXCLUSIVE COLORS IN NYAMULAGIRA (%)
EAST	60	40	0
WEST	40	40	20

Table 11: Statistics relating to figure (36), North-South subdivision

SUBDIVISION/COMPARISON	COMMON COLORS (%)	COLORS EXCLUSIVE TO NYIRAGONGO (%)	EXCLUSIVE COLORS IN NYAMULAGIRA (%)
NORTH	75	25	0
SOUTH	33	67	0

Table 12: Statistics relating to figure (37), East-West subdivision

SUBDIVISION/COMPARISON	COMMON COLORS (%)	COLORS EXCLUSIVE TO NYIRAGONGO (%)	EXCLUSIVE COLORS IN NYAMULAGIRA (%)
EAST	50	0	50
WEST	0	50	50

Table 13: Statistics relating to figure (37), North-South subdivision

SUBDIVISION/COMPARISON	COMMON COLORS (%)	COLORS EXCLUSIVE TO NYIRAGONGO (%)	EXCLUSIVE COLORS IN NYAMULAGIRA (%)
NORTH	0	50	50
SOUTH	100	0	0

The results from the tables above are transformed into the following curves.

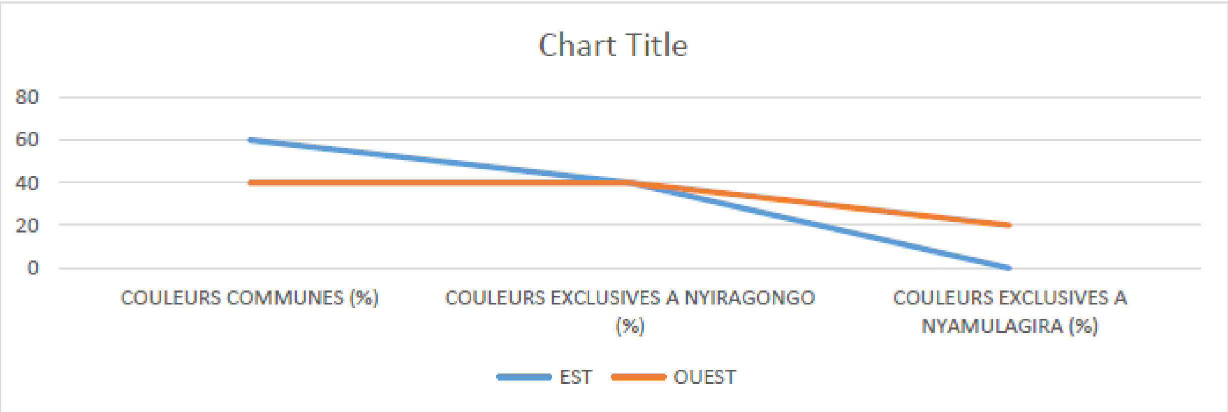

Figure 38 a: East-West fine structure of Nyiragongo and Nyamulagira volcanic zones; Table 10

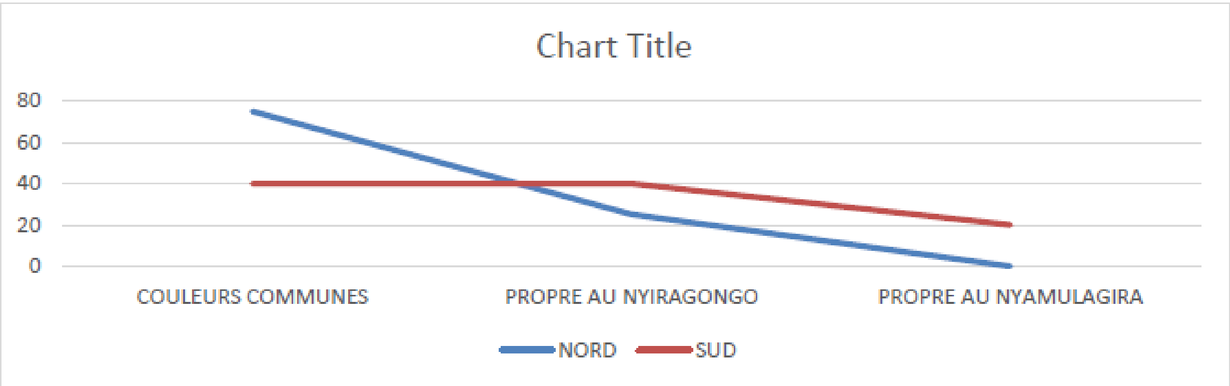

Figure 38 b: North-South fine structure of Nyiragongo and Nyamulagira volcanic zones; Table 11

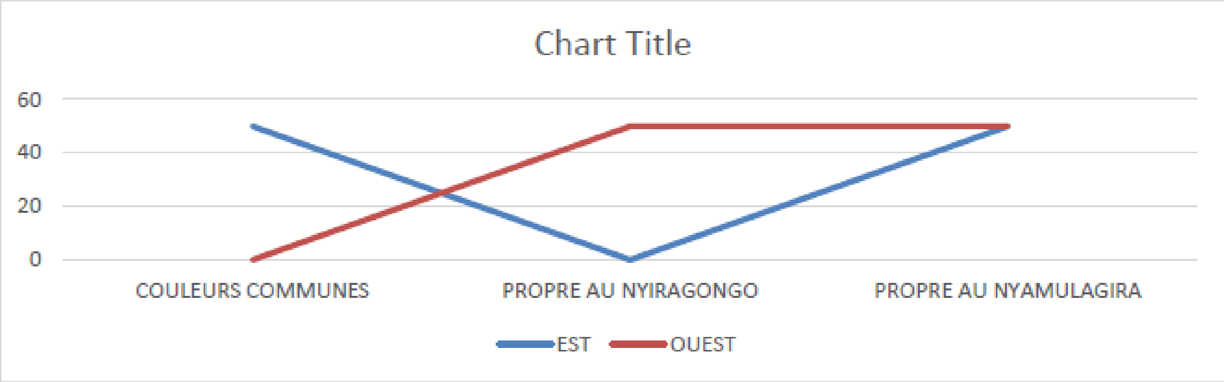

Figure 39a: East-West hyperfine structure of Nyiragongo and Nyamulagira volcanic zones; Table 12

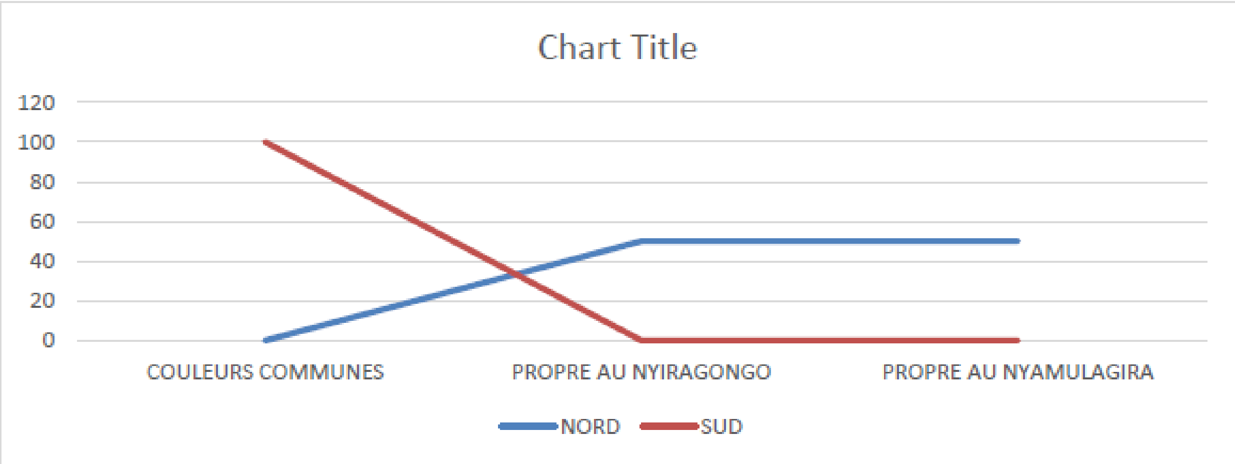

Figure 39b: North-South hyperfine structure of Nyiragongo and Nyamulagira volcanic zones; Table 13

Observing the shape of these curves reveals the following:

- From the fine structure (Figure 38 ab), we observe that:
  - ❖ The lines diverge first, to converge later;
  - ❖ Their intersection is located at the point of abscissa “colors exclusive to Nyiragongo” and ordinate “40%”
- From the hyperfine structure (Figure 39a-b), we observe that:
  - ❖ The lines diverge first, to converge later;
  - ❖ Unlike the previous case, the stopping point (maximum divergence) corresponds to the point of abscissa “colors exclusive to Nyiragongo” and ordinate “40%”
- From these two structures, two groups of curves emerge classified according to concavity:
  - ❖ The following lines have a concavity facing upwards: EAST and WEST of the fine structure (Figure 38a), South of the fine structure (Figure 38b), West of the hyperfine structure (Figure 39a) and North of the hyperfine structure (Figure 39b),
  - ❖ The following lines have a concavity facing downwards: North of the fine structure (Figure 38b), South of the hyperfine structure (Figure 39b), and East of the hyperfine structure (Figure 39b),

The above results are useful in particular for monitoring the geodynamics of a seismic zone; it is enough to repeat the same calculations in this area, and evaluate the deviation or deformation of the curves, a reflection of the geodynamics of the region.

These results, and others above, show that the structure of the Nyamulagira Volcano is a substructure of (included in) the Nyiragongo. This trend has been observed by other studies (Ongendangenda T., 2020; Kamathe K., 2018) the main elements of which appear in the table above.

Table 14: Structural and petrographic comparison between the two volcanoes

VOLCANO	Structure	Magma reservoir location	Composition of lavas (Petrography)	Isotope ratio			
				$\frac{87_{Sr}}{86_{Sr}}$	$\frac{143_{Nd}}{144_{Nd}}$	$\frac{87_{Sr}}{88_{Sr}}$	$\frac{206_{Pb}}{204_{Pb}}$
NYIRAGONGO	Strato-volcano	25-35km (Deep)	Feldspaths and Melilitis	Weak	Very high	High	Very high
NYAMULAGIRA	Shield Volcano	3-7km (superficial)	Feldspaths	High	Very weak	Weak	weak

4. GENERAL CONCLUSION AND PERSPECTIVES

The findings of this study revealed that: - The model developed, particularly the scale designed for characterizing the areas surrounding the volcanoes Nyamulagira (29.0°E-29.5°E; 1.2°S-1.5°S) and Nyiragongo (29.0°E-29.5°E; 1.45°S-175°S), is valid, logical, and reasonable.

The introduction of the concept of earthquake "bulk density" or seismic energy in the design of the characterisation scale played an important role, - The assumptions made for the location of the craters of these two volcanoes are also valid.

Both assumptions can be summed up as follows:

"The crater of a volcano, at least in our case, is located where the volume density of the number of earthquakes is maximum, while the volume density of the seismic energy released by tectonic earthquakes is minimum."

The application of this hypothesis, together with other parameters, allowed us to locate the craters of these two volcanoes, in accordance with field observations:

- The crater of the Nyamulagira volcano is located at [29.15°E; 1.35°S] and at [29.25°E; 1.50°S] for Nyiragongo. The two craters are about 15 kilometers apart. These findings corroborate the field observations.
- The structures of Nyamulagira and Nyiragongo share many similarities, with some differences in the Nyiragongo area, particularly in its western part.
- The model allowed us to quantify the rate of heterogeneity of each structure and calculate (compare) the rate of similarity between the two; depending on the case, this rate is 67%, 75%, or 40%.

As a result, this model has highlighted the geological features in the region; the geological implications of this model can be used for geological prospecting.

Indeed, the application of the characterisation scale and hypothesis in the study of the areas surrounding Nyamulagira and Nyiragongo yielded the following results:

- Iab, Ibc, IIIbb, and IIIbc are the seismic species discovered for Nyamulagira.
- The species of Nyiragongo are Iab, Iac, Ibb, Ibc, IIIbb, and IIIbc.
- Nyiragongo appears to include all of the Nyamulagira species.
- The latter has two distinct species (Iac and Ibb) at (29.3°E-29.5°E).
- The region's structure factors (ab, ac, bb, and bc) were identified, with one (ac) being unique to Nyiragongo.
- As a result, the similarity rate between the two is 67%.
- In terms of structural factors, this rate is 75%.
- The 25% singularity of Nyiragongo is justified by its extremely complex shape (stratovolcano with a crater consisting of three platforms, ...).
- Several peculiarities or anomalies have been observed at (29.3°E-295°E).
- The zoning maps made it possible to calculate the degree of heterogeneity, which is 70% and 88% for Nyiragongo and Nyamulagira, respectively. The structural curves revealed that the structures of areas deteriorated from west to East and North to South.

The observation of these curves relating to the statistics of the hypocentres as a function of the number of earthquakes, i.e. the ground structure, reveals that the two structures are similar; indeed, the angular coefficients of their lines, characterizing the ground structure, are nearly equal.

The curves of the hypocentre distribution statistics show an anomaly at depths [5-10] and [10-20] for Nyamulagira, depths [20-30] and [30-40] for Nyiragongo, and a perfect coincidence of two curves from depth to depth.

The anomalies observed at these locations are most likely the result of significant volcanic activity. A comparison of these curves shows that the Nyiragongo area studied from north to south has a similar structure to that of Nyamulagira studied from west to east.

These two structures operate in the opposite direction of Nyamulagira, which is studied from north to south.

After observing the above curves, it appears that the shape of the Nyamulagira volcano reservoir is predominantly spherical, whereas that of the Nyiragongo volcano reservoir is predominantly cylindrical in accordance with the literature, The study on the volume density of seismic energy, the number of earthquakes and the d-value shows a good correlation between the curve of the number of earthquakes (%) and the d-value (which characterises the structure of the ground). It is concluded and confirmed that the seismic activity depends on the soil structure.

There is a correlation between the minimum volume density of energy and the maximum volume density of earthquakes at the same location for both Nyamulagira and Nyiragongo, with a few exceptions.

The characterisation of seismicity should be described in terms of volume density rather than number of earthquakes or energy. As a result, the concept of volume is important in this study.

These results, and others above, show that the structure of the Nyamulagira Volcano is a substructure of (included in) the Nyiragongo.

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