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Degradation of the Urban Environment of the City of Bukavu: Geological and Geomorphological Factors

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Abstract

The degradation in Bukavu, a million-inhabitant city in the central East of DR Congo, is a reality. This is linked to natural factors of the environment (geology, climate, geomorphology, plant cover and their combination) coupled with anthropogenic action. This paper is focused on the influence of geology and geomorphology on land instability in Bukavu, as well as the environmental and socio-economic impacts of the phenomenon. Geological methods, observation, photography, social survey, remote sensing and cartography were used. Indeed, Bukavu is distinguished by a rugged relief which is characterized by stages of different altitudes connected by steep escarpments and cut by the waterways, tributaries of Lake Kivu and the Ruzizi River, the shoreline of the lake with its gulfs and bays, hills, marshes and valleys with steep slopes and deep gorges.

Subject Areas

Environment

Keywords

Bukavu, Urban Environment, Environmental Degradation, Tectonics, Slope

1. Introduction

Environmental degradation has increased in the city of Bukavu over the past two decades: houses and entire neighborhoods, such as the Fund district, have disappeared and others are endangered. The inventory of geological issues includes lithology, tectonics and earthquake issues. It is accompanied by the inventory of geomorphological problems (relief). This work constitutes a useful database for researchers who will be interested in this question of degradation of the urban environment of Bukavu and its surroundings, as well as for those who will seek to rehabilitate already degraded sites. In Bukavu, the formations are mainly volcanic which show little compositional evolution on the same level. Thus, several studies (Snell [1], Fraustchi [2], Vileneuve [3], and Mweze [4]) of these rocks have sufficiently exploited the vertical evolution thanks to the various natural cuts, soundings and to other outcrops which seemed to present clear tendencies on the lithology of Bukavu. We will retain the following opinions:

Snell [1] based on data from soil reconnaissance surveys for the construction of the Ruzizi I hydroelectric power station, recognizes trachyte surmounted by a basalt with intercalation between the 2 tuffs or volcano-sedimentary sometimes with lenticular aspects. For this author, it is the trachyte that rests on Precambrian sandstone which outcrops on the side of Rwanda.

Fraustchi [2] observed at Panzi the following succession from bottom to top: lower basalt, pyroclastic or volcano-sedimentary breccias, trachyte, pyroclastic volcanic breccias (Panzi layers) and at the top the upper basalt.

Vileneuve [3] in Mandwe from bottom to top reports: lacustrine sediments, volcano-sedimentary, basalt I, pyroclastic basaltic breccias.

Mweze [4] made observations in the Kasha quarry, also called the Buholo quarry, located west of Bukavu and on the border of the Ciriri and Buholo sub-localities. The schematic cross-section of this quarry shows that they outcrop 4 important levels. From bottom to top, we recognize a basaltic formation, which presents an alteration in coarse balls of decimetric size. It is a dark gray rock in which we observe the phenocrysts of pyroxene, olivine and sometimes feldspars. The structure is porphyritic microlithic. A period of calm would have followed the setting up of these lavas during which they underwent an alteration on the superficial part which was transformed into paleosol whose top is reddened (brick red color) and on this one rests the next layer;

A trachytic formation that is light gray when fresh and creamy white when weathered. This rock contains elongated feldspar phenocrysts of a millimeter to centimeter size. It also contains black ferromagnesian phenocrysts. The structure is trachytic;

Laminated volcanic-sedimentary deposits of yellowish color, sometimes gray and finely bedded in places. These deposits contain various elements dominated by clasts of the substrate (trachytes and basalts) coated in a clay-sandstone paste. These elements are angular and show little transport. These deposits are also observed on the Cimpunda levels in the North and would be the equivalent of those described by [5] under the name "Panzi layers";

At the top, we have a basalt formation rich in olivine; we also observe pyroxene. The rock is dark gray to black in color. It is compact and dense when fresh. Its structure is porphyritic microlithic. A basalt dyke more than one-meter-thick and trending N-S cuts the lower basalt and trachyte.

The detailed petrographic and chemical studies by [6] on all the rocks of the upper Ruzizi, an area between Nyangezi in the south and Bukavu in the north, made it possible to highlight 2 series of lava: an alkaline series and a tholeiitic series. The macroscopic study was completed by a chemical study to determine the chemical composition of the volcanic rocks of the West African Rift.

In the alkaline series, by fractional differentiation, the lava evolved as follows: Ankaratrites (parent magma?)—basanites and olivine basalts—hawaites—mugearites—benmoreites—trachytes—phonolites.

The second series of tholeiitic basalts are independent of this filiation underline the authors who have proposed the following complete log from bottom to top: ankaratrites, basanites and olivine basalts, hawaites, mugearites, benmoreites, phonolitic trachytes and phonolites, tholeiitic with olivine.

2. Material and Methods

The city of Bukavu, capital of the Province of South Kivu, is located on a fracture point of the earth's crust at the southern end of Lake Kivu and between the parallels 2˚27'31" and 2˚33'17.8" south and the meridians 28˚48'3.75" and 28˚53'37" east. Its area is 60 km^2 according to Mweze [7] and Sadiki *et al.* [8]; it is subdivided into three communes, namely: the commune of Ibanda (with 12.3 km^2), which includes 3 districts (Ndendere, Nyalukemba and Panzi), the commune of Kadutu (with 10.1 km^2) with 7 districts (Cimpunda, Kajangu, Kasali, Mosala, Nkafu, Nyakaliba and Nyamugo) and the commune of Bagira (37.6 km^2) with 3 districts (Kasha, Lumumba and Nyakavogo) (**Figure 1**).

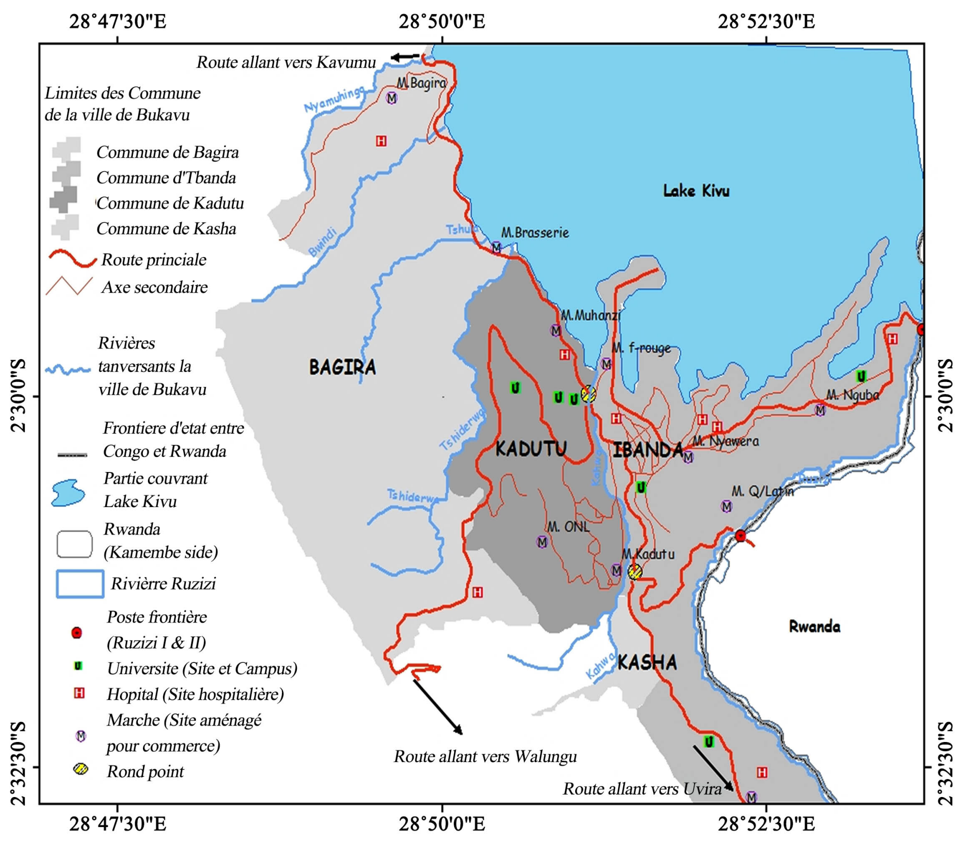

Figure 1. Study area.

Many methods and tools exist to study field history [9]. The methods used in this work combine field survey, analysis of satellite images (Google Earth imagery, etc.) and aerial photographs. To obtain certain occupancy maps, Landsat TM8 images of the area of interest had to be downloaded to Earth Explorer. The images were then processed in ArcGis software. GPS and camera were used. All this is to understand the localization of the analyzed phenomena. The LEITZ polarizing microscope was also used for the petrographic study of thin sections of healthy rocks. Different archives were consulted to obtain information relating to geology, geomorphology, pedology, ecology, climatology, demography, economy of the study area and its surroundings.

3. Results

Geological studies have shown that the terrestrial environment of Bukavu is covered by Tertiary-Quaternary lava which constantly erupted in several eruptive episodes and piled up on top of each other over several hundred meters, covering a Precambrian substratum. The following terms are represented in Bukavu as indicated by the geological map (**Figure 2**).

Legend: Upper Basalts; 2 - 7: Mio-Pliocene alkaline lavas; 2: Basanite; 3: Hawaiians and Mugearites; 4; Ankaratrite; 5: Benmoreites; 6: Volcano-sedimentary level of Panzi; 7: Phonolites and trachytes. The faults are represented by dotted lines.

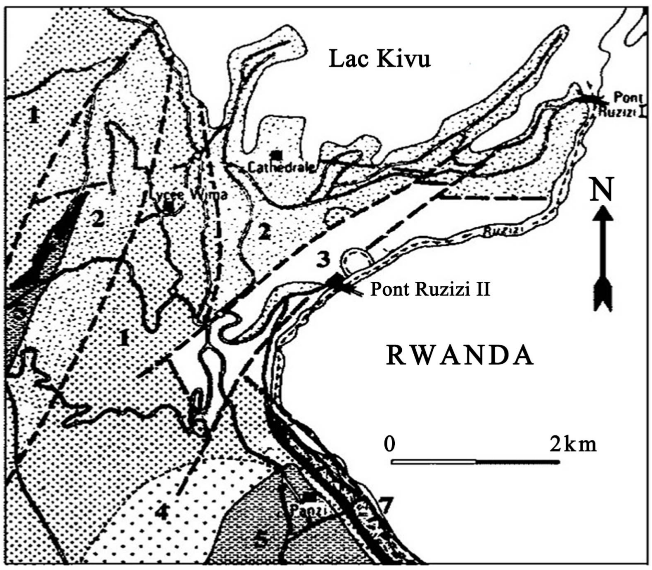

Figure 2. Geological map of Bukavu [6].

This part deals with problems related to tectonics and geomorphology. Given the location of Bukavu, its local tectonics is intimately linked to regional and continental tectonics.

At the continental level, precisely in Djibouti, there is a point of convergence of 3 Y-shaped rifts:

- The NW/SE branch which constitutes the rift of the Red Sea;
- The NE/SW branch is the Aden rift;
- The N-S branch is the African rift.

These rifts separate Somalia-Egypt-Arabian regions that were welded together. At the beginning of the Tertiary this plinth was lifted and broken in 3 main directions above. The first breaks date from the lower Miocene and the Aden and the Red Sea rifts were set up. The still united African base begins at this time with the progressive separation or distension giving along the African rift to a series of active volcanoes extending from Ethiopia to Tanzania passing through Kenya and the East of the DR Congo.

Therefore, the African continent will split into two parts by the widening of the East African rift, which allows the individualization of a new plate of relatively modest size, the Somalia plate, and the development of a young ocean between the rest of the Africa plate and this new plate. The map of the rifts in the East of the African continent is illustrated in **Figure 3**.

On the regional level, after the Burundian orogeny, the region only underwent dislocations with a large radius of curvature which determined its elevation as well as the numerous faults and flexures. These dislocations occurred during the raising of the region between 900 and 3000 meters of altitude. The region was cut into a series of raised or horst compartments and the others collapsed or graben.

Kamaniola, Nyamukubi, Kabasha, Ruwenzori, …are among the horsts.

All the faults and flexures form 2 branches oriented NE-SW and NW-SE and which intersect at the level of the Kahuzi and Biega massifs whose altitudes are respectively 3308 and 2790 meters (**Figure 4**).

The NE and SE parts correspond to the piece of the African rift in the hollow of which are housed the Kivu, Tanganyika and Amin (Edouard) lakes as well as the Ruzizi and Semliki rivers.

On the Biega, there are tholeitic basalts. But these lavas are the thermometer of a high temperature. So there must be a deep hot spot responsible for this abnormal temperature contribution and which caused the bulging of the basement [12]. Most of the region's limestone travertines and hot waters are directly related to these faults and Graben and are located along the fault scarps. There are also some vast marshes bordering these escarpments.

It is intense, brittle, recent and current tectonics due to rifting that will segment the region into a series of main compartments (levels) of which those to the east are subsided and separated by faults whose scarps are their expressions. Morphology in the field. The bearings are all the older as they are found at a higher altitude. These are the bearings:

- Katana-Kavumu-Mudaka. Its altitude varies from 1600 to 1700 meters.
- Kabare and Ngweshe, whose altitude is respectively 1925 and 1735 meters
- Musisi is located at the foot of the Biega and Kahuzi mountains with an altitude of about 2200 meters.

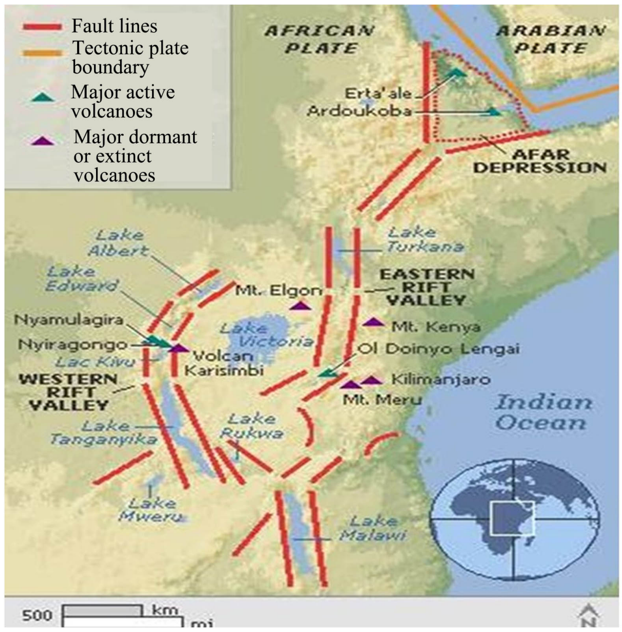

Figure 3. Map of rifts in the East of the African continent [10].

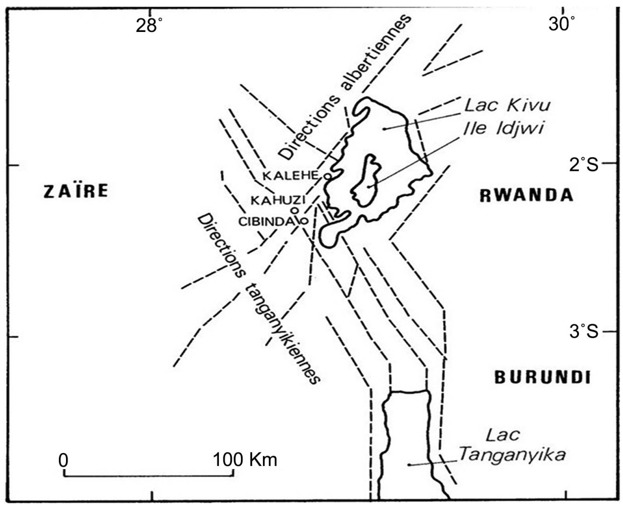

Figure 4. West African Graben fracture field [11] Simplified.

The Bukavu sector and its surroundings were also subjected to brittle tectonics. At Kadutu, the main N-S and east-facing faults have segmented the block into a series of stepped compartments and tectonics thus becoming a dominant morphogenetic element. Their escarpments are still their morphological expressions on the ground and therefore participate in the control of the relief [4] [7].

Normal faults oriented N-S (arranged in relay) and NW-SE shaped the serial morphology of the plateaus from Bukavu to Kabare. These faults will also create a large permeability and will put in communication water reserves trapped in certain voids and planes.

For the N-S faults, these are the Buholo, Cimpunda, Nyakavogo faults and the Bukavu microrift (according to its name by Moeyersons) and the NW-SE fault is the Kasha fault. The view of Kadutu from the IDAP ISP is an illustration of this. Other faults subparallel or transverse to the main N-S faults have also formed. All these flaws have continued to play until today. Indeed, as earthquakes are frequent in this region, they cause the rejection of existing faults (or the height of slopes). The rejection increases, the embankment becomes important and can be unbalanced to end up breaking and thus causing landslides. The same earthquakes can also create new faults (Figure 5).

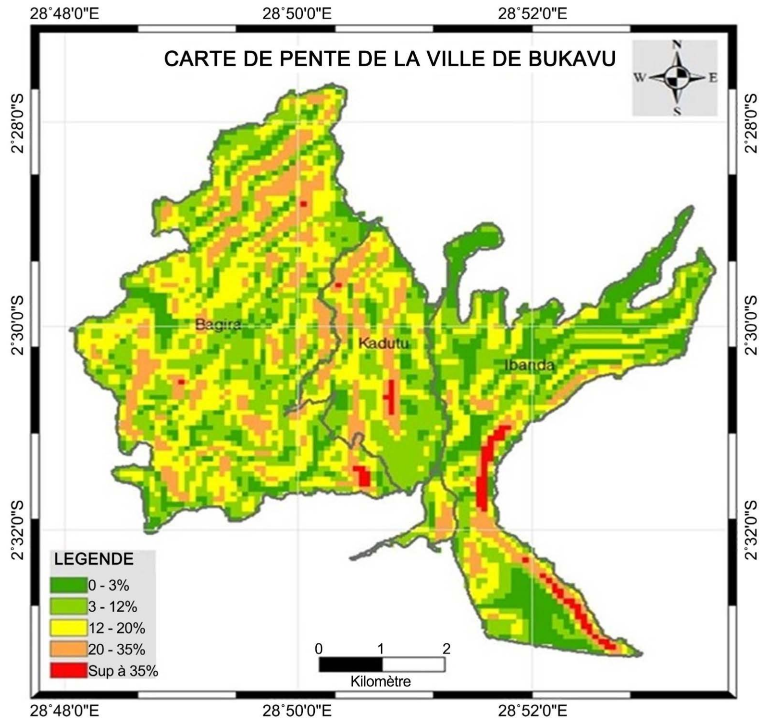

Figure 5. Map of slopes.

The different orientation of the slopes leads to different exposure to solar radiation and atmospheric precipitation (Table 1). A total of 8 classes which form 8 different directions have been highlighted, each comprising 45˚: These classes are: North (337.5˚ - 22.5˚), North - East (22.5˚ - 67.5˚), East (67.5˚ - 112.5˚), South - East (112.5˚ - 157.5˚), South (157.5˚ - 202.5˚), South - West (202.5˚ - 247.5˚), West (247.5˚ - 292.5˚) and North - West (292.5˚ - 337.5˚). Figure 6 shows the landslide hazard map of the city of Bukavu.

Table 1. Classification of slopes (%).

Code	Slope class
1	None to low (0% to 3%)
2	Moderate (3% to 12%)
3	Steep (12% to 20%)
4	Very steep (20% to 35%)
5	Extreme (Above 35%)

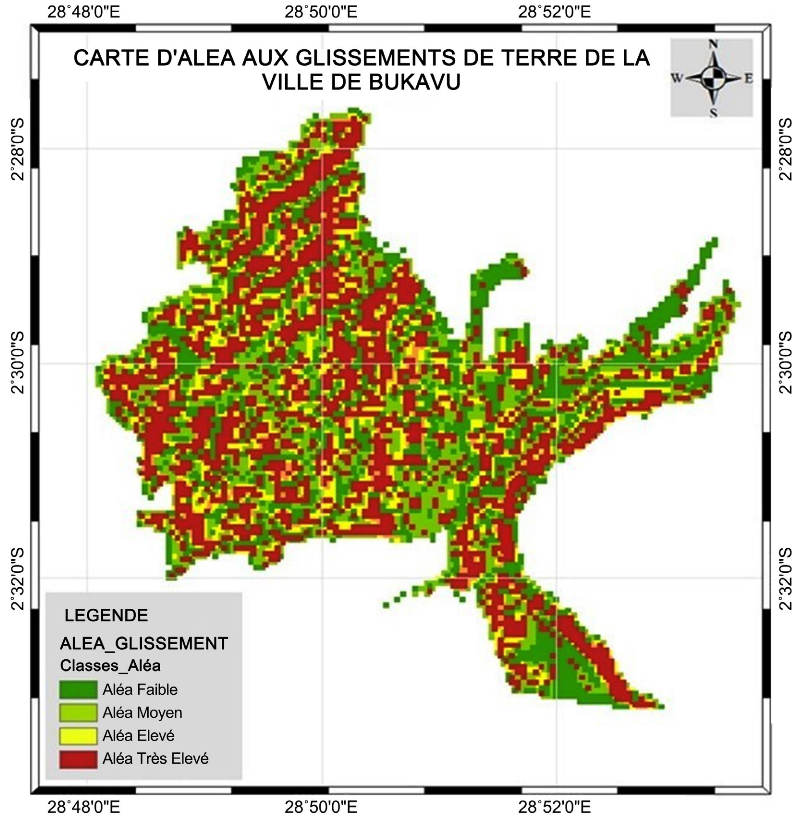

Figure 6. Earthslide hazard map of the city of Bukavu.

In Kadutu, several pullout burls are observable on the Cimpunda fault and a good part of Kadutu is seated on a thrust land resulting from landslides. Such terrain remains unbalanced for a long time; the slide continues over several years.

Note that the hot springs are aligned along the major faults of the rift and are the source of certain calcareous deposits. Earthquakes or earthquakes, which are brutal shaking of the ground caused by the arrival of elastic waves initiated at depth, usually begin with a generally pre-existing fault. They will occur when the earth's crust gives way under excessively high internal forces or pressures that have slowly accumulated over time until they reach a critical value that the rocks can no longer support.

Bukavu is, therefore, in a seismic region and earthquakes cause a lot of damage there. Direct, indirect and collateral damage is recorded there caused by these earthquakes on populations, public or private infrastructures and the environment in general: loss of human life, the collapse of buildings, triggering of landslides, degradation of roads, drains, gutters and the water supply network, etc.

4. Discussion

The terrestrial environment of Bukavu is covered by Tertiary-Quaternary lava which constantly erupted in several eruptive episodes and piled up on top of each other over several hundred meters, covering a Precambrian substratum.

Each outpouring, once in place, was subjected to intense weathering influenced, among other things, by the humid tropical climate of the environment as we will see later in the studies of the current outcrops. When the period which separated 2 successive eruptions was long, the lavas in place underwent a pedological evolution over a certain thickness and the soil formed will then be baked in its upper part by the next eruption to give a level of red clay bed and we thus ended up with paleosols or red beds, which separated these 2 successive eruptions. The negative zones of each surface of a flow were characterized by terrigenous detritism and constituted a fossil valley [7].

With regard to the current outcrops, these rocks placed on the surface under conditions of pressure and temperature lower than those endogenous where they were born and in a hydrated atmosphere can necessarily be in a state of thermodynamic imbalance which causes the instability of the constituent minerals starting with their superficial part exposed to bad weather which will constitute the future oxidized zone. In the general conditions of the surface of the globe, the pressure does not intervene since it is constant and equal to the atmosphere. Thus a petrographic study was carried out on basic rocks of the basalt type and rocks of the trachyte type identified in outcrop and consisted of a macroscopic description of the outcrops, this being subsequently refined by a study by the laboratory in the thin section for these 2 poles [7].

In basalt, olivine is the first mineral to weather in basalt. This is what made [13] that this decomposition would be metasomatic. The nature of this secondary weathering mineral has been described by many authors and under various names. Iddings (1962) cited by [14] was the first to suggest that these substances originated from the weathering of olivine. For [15], the red variety contains iron (in the form of goethite). [16] observes that iddingsite may result from weathering. Also [17] shows that iddingsite results from weathering. Also [18] notes meteoric alteration for some Kivu basalts.

The availability of olivine to weather first in basalt is not random. Indeed, a double sequence of common minerals has been established by Goldich, 1938 cited by [19] in the order of decreasing vulnerabilities:

Olivine	Plagioclase Ca
Augite	Plagioclase Ca Na
Hornblende	Plagioclase Na Ca
Biotite	Plagioclase Na

Feldspaths potassiques
Muscovite
Quartz

This general diagram shows that olivine is the mineral that deteriorates first. Thus the alteration of minerals in basalt conforms to this double sequence of Goldich1938 cited by [19] and we will have the following order: olivine—plagioclase—augite. Plagioclase being bytownite and labrador in our case. This order follows that observed in the field and under the microscope.

The rest of the minerals, sometimes the plagioclases, undergo fragmentation and evoke alteration. Augite is apparently intact.

In trachyte, the advanced weathering, the whole section is transformed into opaque substances which retain the initial shape of the hornblende. The other minerals are apparently intact. From this study, it is clearly seen how the constituent minerals of the volcanic rocks in Bukavu are subjected to alteration starting with the most vulnerable minerals and their architecture is undermined; as a result, the rocks are exposed to the erosion that continues the work. The lavas of Bukavu therefore sometimes alternate with paleosols or red clay, pyroclastic debris, volcano-sedimentary and are found under all lithological aspects and at all stages of alteration: compact lavas and very hard organs, pulverulent lavas, an intermediate range between these two, indurated or non-hardened pyroclastites, porous lavas, tuffs and cinerites. The different fractures within these lavas, the division planes, the shrinkage joints, the cavities, the interstices, the pores and even certain fossil valleys give the whole enough space for the lodging of the waters attested by the numerous source observed in the field. All these conditions provide this lithology with heterogeneity at depth and laterally. Hence the presence of planes (surfaces) and zones of various shapes and sizes with less resistance within this heterogeneous whole [7].

Red beds that are impermeable behave like soap diapers and can trigger landslides. The groundwater stored in the various voids mentioned above reduces the internal cohesion of the massifs by having replaced the air there. Since water is heavier than air, the ground can become overloaded, which plays in favor of gravity to the detriment of the cohesive force and the massifs are susceptible to collapse, especially when other factors are added. The sediments torn from the ground currently by erosion are transported to depressions such as valleys, valleys and alluvial plains at the edge of the lake. The sites occupied by these elements endowed with thixotropic properties are sensitive to earthquakes with related consequences in the destabilization of the terrain [7].

The Bukavu sector and its surroundings have been subjected to brittle tectonics. At Kadutu, the main faults N-S and looking east have segmented the block into a series of compartments arranged in a staircase, the current topography settles and tectonics thus becomes a dominant morphogenetic element. Their escarpments are still their morphological expressions on the ground and therefore participate in the control of the relief. With the alternately dry and humid climate combining, we will witness active mechanical erosion on rocks not yet colonized by vegetation. The masses of rock still unbalanced on the slope are moved in scree or avalanche down the slopes. The steep slopes created are conducive to land movement and increased erosion. The current topography in Bukavu has therefore been established thanks to several main factors: tectonics, to which must be added volcanic activities, erosions, mainly regressive erosion, the earthquake, and the anthropogenic action currently observed by Delvaux *et al.* [20]. Edelman [21] reported such cities to face more immediate problems than those in the developed world and have fewer resources to deal with them.

It is not for nothing that Dewitte *et al.* [22] consider it to be one of the factors of susceptibility to ground movement in the sense that it can act on reactivation by influencing the physical properties of the slope. The different orientation of the slopes leads to different exposure to solar radiation and atmospheric precipitation. It is the ArcGIS software, which was used for the determination of the different classes of the orientation of the slopes by the "Aspect" function; which made it possible to extract a layer of data from the altitudes. This function assigns each pixel the direction of the adjusted plane when calculating the slope. It gives slope values ranging from 0˚ to 360˚.

From a geophysical point of view, the instability of the Graben results in numerous and repeated earthquakes [23]. Cornet [24] outlines the zone with seismic vocation and indicates that for the Congo region, the seismic phenomena were felt almost exclusively in the East of the Congo and particularly in this region of the Graben.

Figure 7 shows the epicenters of large earthquakes that occurred in East Africa between 1963 and 1970 [25] and confirms that the earthquakes are linked to trenches but that their distribution goes beyond them.

Legend: Major tectonic line of the East African rift and major earthquakes: 1: fault, 2: normal fault, 3: main rupture line, 4: epicenters of the largest earthquakes that occurred from 1963 to 1970 [25], 5: direction of movement: A: Amaro ditch, C: Cameron Bay ditch, K: Kavirondo ditch, LC: Lake Chirwa ditch, N: Lake Nyanza ditch, S: Gulf of Speke ditch, T: Turkana ditch, V: Virunga ditch, W: Walungu ditch.

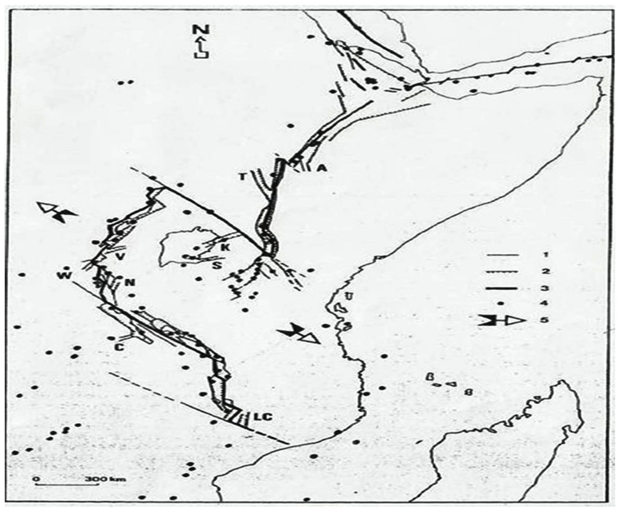

Figure 7. Epicenter's of major earthquakes in East Africa between 1963 and 1970 [24].

Other maps established by Sutton *et al.* [26] confirm the concentration of the epicenters in the rift, their overflow in the borders, and the fact that they coincide well with the geomorphological data: the deformation took place essentially in the rift and nearby. Already Berg [27] had identified in the Graben of Central

Africa two lines of epicenters of earthquakes recorded at the stations of Lwiro, Uvira, Astrida and Rumangabo between 1956 and 1959. For this author, these lines constitute the edges of large stable blocks. It is therefore an area subject to considerable tectonic stresses. It does not seem excluded that these 2 stable blocks are in motion relative to each other, hence the appearance of volcanoes and earthquakes at their border. The intensity of these earthquakes is variable, ranging from a simple tremor felt only by the instruments to major tremors. It was accepted that the earthquakes felt in Bukavu did not exceed magnitude 4 on the Richter scale [12], which is no longer the case today.

Indeed, on October 24, 2002, the central part of the Lake Kivu basin experienced a major earthquake (Mw 6.2) in the territory of Kalehe, which was strongly felt in Goma, Bukavu and Kigali. This earthquake is the strongest observed in this basin since 1900 [28] [29]. On February 3, 2008, another major earthquake (Mw = 6.0) occurred 20 km north of the city of Bukavu. During this earthquake, 9 people lost their lives, 400 people were seriously injured and 1500 houses collapsed [30]. On August 7, 2015, two earthquakes (Mw 5.8 and 5.7) hit the Katana-Kalehe region, causing 3 deaths, around 60 injuries and some destruction. During this same seismic crisis, some sources dried up and others appeared in Mahyuza and temperature variations were recorded. During the same period, several open cracks in the ground and oriented N-S to NNE-SSW were observed at Ihusi, Kabamba and Kasheke. On September 24, 2016, a couple of earthquakes (Mb 4.5 and 4.8) frightened the population of Bukavu, causing 2 deaths despite their moderate magnitude [31].

Our sector can also record other non-tectonic earthquakes generated by volcanic or human causes: it is as the rise of magma from the Nyiragongo Volcano or a landslide in its magma chamber for volcanic causes and artificial explosions as well as the passage of heavy equipment for those due to human activities. The seismicity linked to volcanism in the region is low even if during the January 2002 eruption, earthquakes of magnitude 3.5 or more were recorded [32].

The seismicity catalog compiled for the Lake Kivu region by Delvaux *et al.* [20] contains 1054 earthquakes between 1931 and 2015 and of equivalent magnitude Mw up to 6.3. It also includes all available aftershocks and calculated focal mechanisms of selected earthquakes.

Between 1888 and 2015, several earthquakes of magnitude greater than or equal to 4 were recorded in the Kivu rift [33]. On May 30, 1999, at 2:20 p.m., an earthquake of magnitude 3.5 was felt in Bukavu but fortunately did not cause any damage. The central part of the Lake Kivu basin experienced a major earthquake (Mw 6.2) on October 24, 2002, in the territory of Kalehe, which was strongly felt in Goma, Bukavu and Kigali.

5. Conclusions

The Bukavu Sector is seismically oriented. Among the last earthquakes recorded in the area recently, there were those of strong magnitude (up to 7) and had caused a lot of damage: death of men, cracking of walls and collapse of houses, drying up of springs.

From a lithological point of view, since the end of the Tertiary and the beginning of the Quaternary, lavas have constantly poured out and piled up on top of each other, sometimes alternating with paleosols, over several hundred meters. This lithology is favorable to degradation. These series sets up were then subjected to brittle tectonics. The main N-S faults have segmented the block into a series of stepped compartments, of which those to the east are collapsed. The morphology, set up by these lavas jointly with the tectonics, has continued to undergo modifications by the continuous play of faults and erosions.

However, the population and the government must respect the standards of urban construction (respect for the dimensions of a plot and the cadastral plan of construction by properly tracing the avenues, etc.). Measures to protect or mitigate the impact of the earthquake must be taken. We know that earthquakes are manifested by shocks and of short duration, which is why we must act spontaneously. It is necessary to popularize the safety instructions before, during and after the earthquake to minimize the possible losses of people and goods. For the vulnerability of constructions: dwelling houses, dams, and other special constructions in Bukavu deserve special attention during their construction; they must be built according to seismic standards, considering the nature of the soil, architectural choices and seismic insulation.

Conflicts of Interest

The authors declare no conflicts of interest.

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