International Journal of Innovation and Applied Studies
ISSN 2028-9324 Vol. 10 No. 4 Mar. 2015, pp. 1213-1224

http://www.ijias.issr-journals.org/

THE FIRST VIEW ON STRESS DROP OF SMALL EARTHQUAKES IN THE KIVU REGION, WESTERN BRANCH OF EAST AFRICAN RIFTS SYSTEM

***B. SILVANOS FIAMA*[1]*, T. GEORGE MAVONGA*[2]*, M. JEAN ROBERT NSHOKANO*[3]*, CLARISSE BALEGAMIRE NJOVU*[1]*, SERGE BUTARA MUBANE*[3]*, M. ALBERT JEJE*[1]*, and L. JUSTIN LONGI*[1]**

[1]Department of Geophysics,
Centre de Recherche en Sciences Naturelles (CRSN/Lwiro),
South Kivu/DS Bukavu, DR Congo

[2]Observatoire volcanologique de Goma (OVG/GVO),
North Kivu, DR Congo

[3]Centre de Recherche Géologique et Minière (CRGM/Lwiro),
South Kivu, DR Congo

ABSTRACT: Digital seismograms recorded at seismic station of Lwiro, between August 1993 and March 1994, are used to investigate the spatial distribution of stress drop estimated following the spectral Brune's model in the Kivu region and its vicinities. It is revealed that a small stress drop (<=1) is observed in these zones. The high stress drops are observed in the granitic intrusion in the zone A and D (Idjwi Island) and B, on fracture linked Nyiragongo and Nyamuragira volcanoes, and the lowest is very scattered in the zone C, D and E. The study has revealed that the stress drops correlate with fault types as the high value corresponds to reverse faults in the zone B, and the lowest to normal and strike slip faults in other zones. The Idjwi Island also presents a high stress drop where three types of faulting appear. Small stress drops are attributed to strong barriers of seismic rupture or no long rupture propagation along the pre – existing fractures, great heterogeneity, low strength of crustal material and hydrothermal activities, where great stress accumulation is hindered. The high stress drops are supposed to be the results of great strength of crust, consolidate materials and intrusion rocks. The variation of stress drop can contributed to earthquake monitoring and tectonic process of the region.

KEYWORDS: spatial distribution, Stress drop, corner frequency, small earthquakes and Kivu and vicinities.

1 INTRODUCTION

The scaling law of seismic spectrum in which large and small earthquakes satisfy a similarity condition was proposed in [1]. Some formulas which allowed the determination of stress drop, sources radius and seismic moment from spectral of S-waves were given for the understanding of seismic source spectra ([2], [3]). Those formulas were extended to the study of P-waves [4]. It showed that earthquakes from different origin have different values of stress drop [5].

To obtain further information about earthquakes in addition to geographical coordinates of epicenters, depth of focus, origin time and magnitude, it is necessary to determine other parameters describing the individual shocks. Amplitude spectra of seismic waves allows us to compute the additional physics parameters, for instance the seismic moment M_0 which describes the source strength; the source dimension r defined the radius of an equivalent circular source area, and the stress drop $\Delta\sigma$ describing the difference between the shear stress on the fault surface before and after the shock. These parameters can be used to estimate the magnitudes of earthquakes such as local and moment magnitudes [8].

Characteristics of stress field and focal mechanism of this rift zone have been proposed ([9], [10], [11]). Normal faulting, strike slip and reverse faulting according to the stress field generated by earthquakes in the region ([9], [10], [11]). The scattering of earthquake foci was interpreted to be mainly due to the initial break-up of the African continent related to the multi branched stage as a result of failure under stress of the pre – existing zones of weakness ([12], [13]). It has been suggested that apparent stress drop (the half of the stress drop) may vary as a function of faulting type, lithosphere strength and tectonic setting [14].

The references [15] and [16] have shown that the stress drop can be an indicator of the different types of stress conditions in the Earth's crust. The high values of corner frequencies are the characteristics for small events ([15], [6]), whereas the low one imply abnormal small stress drops due to possible high pore pressure, or slow ruptures [17]. Generally, earthquakes that occur in the rift zone have low stress drop related to the presence of softer material in the shallow depth [18]. The reference [19] has explained the large stress the drop by the presence of barriers created by greater strength of material or consolidate materials [20] reflecting the small heterogeneities. [14] and [21] have agreed that the low stress drop are found in more fractured regions and where are great hydrothermal activities. The high stress drop in the volcanic region may be attributed to magmatic thermal fracturing of host rocks [22]. The high frequency has been reported by [6] in Irangi and Masisi – Walikale.

Likewise, the stress drop which reveals the stress regime in the crust from seismic analysis would depend on the geology, tectonic system of the regions and can contribute to seismic risk analysis.

In this paper, stress drop of small earthquakes occurring in the Basin of Kivu Lake and vicinity are investigated in order to examine the spatial distribution of stress related to tectonic setting. The Lwiro station has worked on digital recorder during the period of August 1993 to March 1994. Therefore this study has used those digital data to give a spectral analysis for getting the stress drop by the estimation of the corner frequencies and seismic moments. The area related to the observation is confined in the Kivu and North Tanganyika Lake basins and vicinities Figure (1, 3 and 4). In [23], Mavonga studied strong motion by attenuation relationships and got great stress drop during some aftershocks sequences of the typical main events such as the Masisi April 29, 1995 (Mb 5.1) and the Kalehe October 24, 2002 (Mb 5.9) earthquakes in the Kivu. He did not speak about the spatial distribution and geological and tectonic feature related to hat seismic parameter. The seismicity and some information about stress field and faulting types of the region were reported by many authors ([24], [25], [26], [27], [28], [29], [10], [11], [31], [30], [7], [32], [33]). Our results suggest that stress drops are varied spatially with geological features and tectonic setting within Kivu and its vicinities. The investigation of seismicity in the Kivu Lake has shown that seismic activity is very high not only in the rift valley but also outside this rift, especially in the Masisi zone, located at 50 Km west of the Western Rift valley of Africa ([6], [7]).

2 GEOLOGY - TECTONIC AND SEISMOLOGY SETTING

In the Kivu area, the main tertiary faults are parallel to the Lake shore and to the western margin of the Rift Valley while the secondary ones transect the Idjwi Island North – Easterly [34]. At Southern end of the Kivu Lake, fault structure is divided into two groups: the Eastern group run North – Southward into the Ruzizi valley which is a well-defined a Graben of about 20 Km of East – west extent; others faults group strike South – Westward into the Ngweshe Precambrian escarpment complex (Figure 1). The basin is bordered by the most prominent more than 1500 m – high escarpment of the West Kivu border fault segment to the West and the least prominent escarpment of the East Kivu border fault segment [35]. The fault systems are generally made up of arrays of faults dipping tower the rift axis and bear characteristics of normal faults. Moreover, the Kivu rift basin marks the transition for the predominant NW–SE orientation of Ruzizi– Tanganyika rift basin to the more SW–NE trend of the Kivu, Virunga and Rutsuru–Lake Edouard rift basins [35] (Figure 1). The faulting activity is believed to continue at the present time. Most of the fault lines trend NE-SW, sub parallel to the rift axis [36]. The Lake Kivu is presently at tectonic stage characterized by volcanic, seismic and hydrothermal activity (figure 1).

The volcanism of the Western Rift valley is confined into three zones (Figure 1): (1) the Democratic Republic of Congo (D.R.C) – Uganda border zone to the north of Lake Edouard; (2) the Virunga volcanic to the north of Lake Kivu and the south Lake Kivu volcanic zone. The Uganda and south Kivu volcanisms dated back to the Cenozoic period and have no eruptive activity in the present time ([37], [38]).

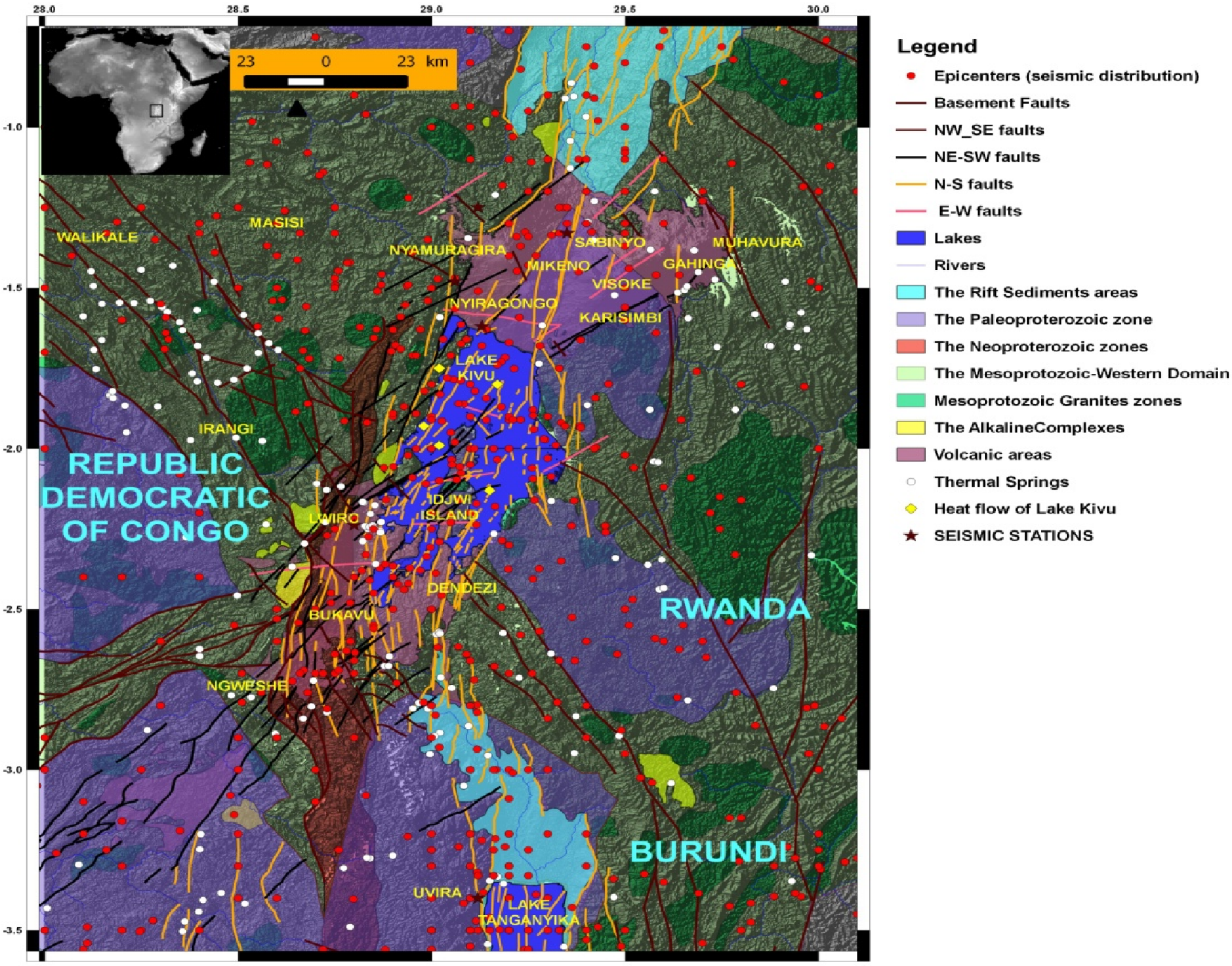

Figure 1: The general geology system, tectonic setting and seismicity of the Kivu provinces and their vicinities.

The Virunga (Zone B, Figures 1, 3 and 4) a volcanic region is the most important throughout the East African System (Figure 1). It includes height main volcanic edifices with numerous adventives cones namely from East to West, Muhavura, Gahinga, Sabinyo, Visoke, Karisimbi, Mikeno, Nyiragongo and Nyamuragira (Figure 1). At present, the eruptive activity is limited to Nyiragongo and Nyamuragira volcanoes which are the most active.

Precambrian metamorphosed sediments and Proterozoic platform sediments occur in the Western part of the Rifts System of Eastern Africa [36]. Thick sedimentary (8 000 to 10 000 m) with acid magmatic intrusions (alkaline granites) and basic are formed there. Outside the Precambrian base, the geology of the South Kivu presents two types of volcanicity: the volcanicity of Cibinda-Kalehe in the east bordered the Lake Kivu and that of Kahuzi-Biega in the west. The Eastern parts of the Lake Kivu and North Tanganyika are covered with metamorphic and granitic rocks [39]. The granitic intrusion rocks are found on the Precambrian basement around the Lake Kivu and mostly present in the Zone A (Masisi and Walikali region) (Figure 1, 3 and 4). The Zone C presents some aspects of granitic intrusion at the boundaries of the Lake Kivu.

The Western branch of the Eastern Rift System of Africa appears to be more active seismically than the Eastern Rift ([27], [28], [6], [7], [9], [23], [25], [24], [31], [32]). The epicenters exhibit much more geographic scatters, and seem to be associated with the Tertiary border faults and the Pleistocene faults ([24], [40], [25], [26], [28]). Earthquakes in the Kivu provinces appear to be aligned along fault lines, particularly at the Western border fault of the Lake and for several faults transecting the Northern part of Idjwi Island (Figure 1). The general seismicity of the Lake Kivu and North Tanganyika basin is related to tectonic setting corresponding to following subgroup (Figure 1, 2 and 3).

1. The Masisi – Walikale zone A (Figure 1, 3 and 4) located to northwest of Lake Kivu outside the Rift valley but adjacent to the rift margin [7], is characterized by normal faults of southeast – northwest direction and perpendicular tension axis

striking the fault traces [10]. It has been remarked that its seismic activity is mainly confined into small area [7]. In the eastern area of the area, earthquakes occurrence is of swarm type. The western area is characterized by isolated earthquakes with high frequency than that eastern part.

2. The Virunga zone B: the seismic activity of Virunga zone (Figure 1, 3 and 4) is general confined to the magnitude ≤ 3.0 (Wafula and Zana, 1990). The volcanic seismicity is classified as A- type (High frequency), B- type (low frequency), C- type and volcanic tremors ([41], [42]). The studies of ([10], [11], [9]) based on A- type volcano tectonic earthquakes revealed that this zone is characterized by reverse faulting. It is also found that the direction of that stress field is nearly perpendicular to the main fissures crossing the active volcanoes Nyiragongo and Nyamuragira.
3. The Lake Kivu and the Idjwi Island (zone C and D) (Figure 1, 3 and 4). The seismic activity of these areas confirms the distribution of the surface tectonic features. The tertiary faults found in this area run parallel to the western shore line of the Lake Kivu and the western border of the island. The seismic activity of the Idjwi Island and the southern part of Lake Kivu has been reported in previous studies ([24], [25], [7]). This zone is characterized by faults strikes North to South (figures 1, 3 and 4) and the stress field of normal faulting with nearly vertical pressure axis and horizontal tension in the east to west direction ([10], [9]). Another type of strike slip faulting (Figures 1, 3 and 4) using the focal mechanism of July 30, 1981 earthquake (mb = 5.2; 2.68S and 28.56 E, h = 33 km) [9]. Indeed, by using the InSAR data, it found that the latest earthquake (February 3, 2008, mb = 5.9 at 2.4216 S, 28.9425 E and h = 9.8 Km) occurring in the Lake Kivu near Bukavu and Cyangungu was characterized by a normal fault striking North to south and dipping 50 – 60° eastward [31].
4. The Ngweshe seismic zone (Figures 1, 3 and 4) located to the southwest of Lake Kivu reveals also a high seismic activity confined in a zone extending northwest – south-eastward ([24], [7]). According [10] the tension axis is horizontal but the pressure is nearly vertical, and the stress field evidently indicates normal faults.
5. The Northern Tanganyika (Figures 1, 3 and 4) has a high seismic activity ([29], [30]). The largest earthquake occurred in this region was that of September 22, 1960 (mb = 6.5) followed by many aftershocks ([30], [10], [29]). The surface traces of faults run from north to south along both sides of the Lake Tanganyika (Figure 1) and are normal faulting with nearly horizontal tension axis ([10], [30]).

The stress field of the Virunga including active volcanoes (Figures 1 and 4) have different feature comparatively to non – volcanic regions ([10], [11]). The Northern Tanganyika could revealed two stress regime related to normal faulting (north Uvira) and to strike slip at south ([28], [10], [30], [9]). The seismic depths are between 1 and 16 Km; very less hypocenter deeper than 20 Km are observed ([25], [7], [9]). Recently, the Kivu basin recorded three great earthquakes occurred on April 29, 1995 (Mb = 5.1) within Masisi area (zone A); on October 24, 2002 at Kalehe [43] and on February 2008 between Bukavu and Cyangugu [31] in the zone C and D (Figure 3). The Kivu region is located between the latitudes 1° and 4° South and longitudes 28° and 30° east, on the Western branch of the Rift of the East Africa (figure 1).

3 DATA AND METHODS

The observation network is composed of six stations (Figures 3 and 4): Katale, Luboga, Bulengo and Kunene located around volcanoes Nyiragongo and Nyamuragira; Lwiro station (Figure1, 3 and 4) located at about 100 Km from Virunga volcanic zone and Uvira station. The Uvira and Virunga's stations were equipped with short period seismograph (T_o=1 sec) with analog recorders Kinemetrics PS-2 made by Kinemetricx company. The time is corrected manually using time signal provided by BBC broadcasting. The accuracy of this time is about 0.1 sec. Lwiro station was equipped with Benioff short period seismograph (T_0=1 sec, T_g=0.25 sec, Mag=100K) and short period digital seismograph (SEIDAS) composed of small data logger with global positioning system (GPS) developed in [44]. The time correction is made by GPS at 05 minutes every hour and can be read on LCD display.

The observation period was from August 1993 to March 1994. Only events recorded at Lwiro station with good signal and noise ratio and identified to Uvira and Virunga's stations were used for the study. The hypocenters were determined using the hypo71PC program established in [45]. The results (figures 3 and 4) were considered when the root mean square error of time residuals was less than 1 sec.

The stress drop (the difference between the average state of stress on the fault plane before and after an earthquake), is the most important parameter for earthquake sources and the understanding of the regional stress field [42]; it can be determined seismically. The source parameters can be determined from spectral analysis include seismic moment (M_O), and source dimensions. These parameters will be determined form the estimation of the corner frequency and the asymptotic amplitude at a constant level (Figure 2). The IASPEI software program edited by Valdes and Novelo – Casanova [46] was used for these digital seismograms (digital sampling 100 Hz). The stress drop was estimated via seismic moment and source radius ([2], [3], [4]). The portion of digital seismogram containing the P- wave onset was windowed; we applied a base-line correction and a Hanning taper to the vertical component of the P-wave seismogram. The window length was selected at 1.5 sec, and the amplitude spectrum was calculated by using a Fast Fourier Transformation (FFT) (Figure 2). We characterised the spectra at a constant level Ω_0 for the lower frequencies, and with a fall-off above a corner frequency f_c (Figure 2). This method is well exposed in detail in [47]. The spectra are corrected for the effect of instrumental response and anelastic attenuation. The seismic moment is calculated from asymptotic long period level of source spectrum. The source radius was computed from the corner frequency obtained from the intersection between the constant long period asymptote and high frequency fall off. An example of waveform at P onset recorded at Lwiro station and displacement amplitude spectrum is shown in figure (2). Thus, the spectral shape proposed in [2] and [4] was used like as:

$$u\,(f)=\frac{\Omega_0}{1+\left(\frac{f}{f_C}\right)^n}$$

where Ω_0 is the long-period amplitude at a constant level, f_c is the corner frequency, n is the high - frequency falloff rate and u (f) is the spectral displacement following the frequency f. We calculated source dimension (radius of circular source area) r (in cm) [48], seismic moment M_o (in in Nm), stress drop Δσ (in bars) according to fallow equations:

$$r=0.32\,\frac{V_P}{f_c}$$

$$M_0=\frac{4\pi\rho.V_P\Omega_0.R}{R_{(\Theta\Phi)}}$$

$$\Delta\sigma=\frac{7}{16}\frac{M_0}{r^3}$$

$$\text{Or}\ \ \Delta\sigma=M_0\left(\frac{f_c}{0.42\beta}\right)^3$$

With $V_P \cong 6$ Km/sec: P-wave velocity; $\rho=2.7$ g/cm^3: density; R the epicentral distance, $R_{(\Theta\Phi)}=0.72$, the coefficient of radiation pattern.

We have to note that the Brune-type stress drop estimates are not necessarily equal to the true static stress drop of the earthquake (e.g., [49], [50]). The magnitude of events was estimated from the maximum amplitude of the vertical component at Lwiro station using modified Watanabe’s formula [52]. Waveforms and displacement amplitude spectrum of the P- waves of the selected events are shown in figure (2). From these spectra, we estimated the asymptotic long period level and the corner frequency.

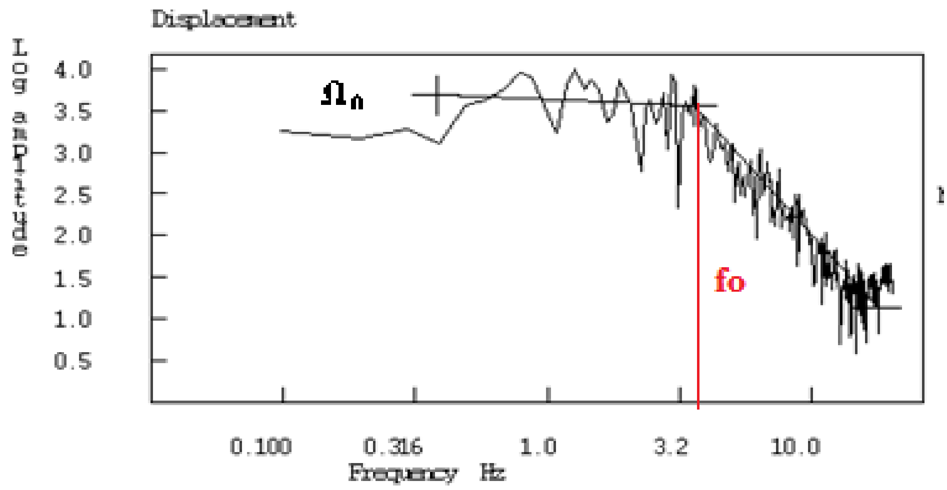

Figure 2: P waveform and its amplitude spectrum. The red rectangles on the vertical displacement seismogram highlight the analysed time window. The two lines fitted to the estimated spectral amplitude define Ω_0 and f_0 or f_c. The waveform recorded at Lwiro station.

For better examination at small scale the distribution of stress related to small tectonic earthquakes in the Kivu region and Vicinity, the seismic area was divided in six zones delimited as represented in the Figure (3 and 4). The results have been obtained following their spatial distribution and the geology features and the tectonic setting within the region.

4 RESULTS

4.1 SPATIAL DISTRIBUTION OF EARTHQUAKES AND STRESS DROP ESTIMATED

The earthquake distribution during August 1993 to March, 1994 recorded by Lwiro short period digital seismograph and Uvira and Virunga's stations is shown in figures (3 and 4). During that period, high seismic activity was observed in the North of Idjwi Island (Zone C), Masisi (Zone A) and zone D (Figures 3 and 4). The seismicity was mainly associated with the tertiary faults running parallel to the western border of the Lakes Kivu and North Tanganyika and through the NW – SE faults and spatial distribution of stress drop (Figures 3 and 4).

The magnitude of events at Lwiro station was ranged from 0.7 to 4.5. The corner frequencies of spectrum at Lwiro are ranged from 3.4 to 12 Hz (Figure 3). The stress drop varied between 0.05 bar to 42.8 bars (Figure 4). The seismic moment of events at Lwiro is ranged from 22×10^{18} to 3.4×10^{21} dyne – cm. The results have given a discrepancy between those zones and their geology. In general, a small stress drop (<=1) was found in all zones. Therefore, high stress drop (>1) was found for small number of isolated events. The stress drop was observed being low near the boundaries of each zone to other (Figure 4).

The zone A has presented a high corner frequency range from 4.40 to 11 Hz. The high f_c (>8.4 Hz) is identified on the granitic rocks and near the N – S faults (Figure 3). And, the stress drops is mainly high at the granitic rocks and lower anywhere.

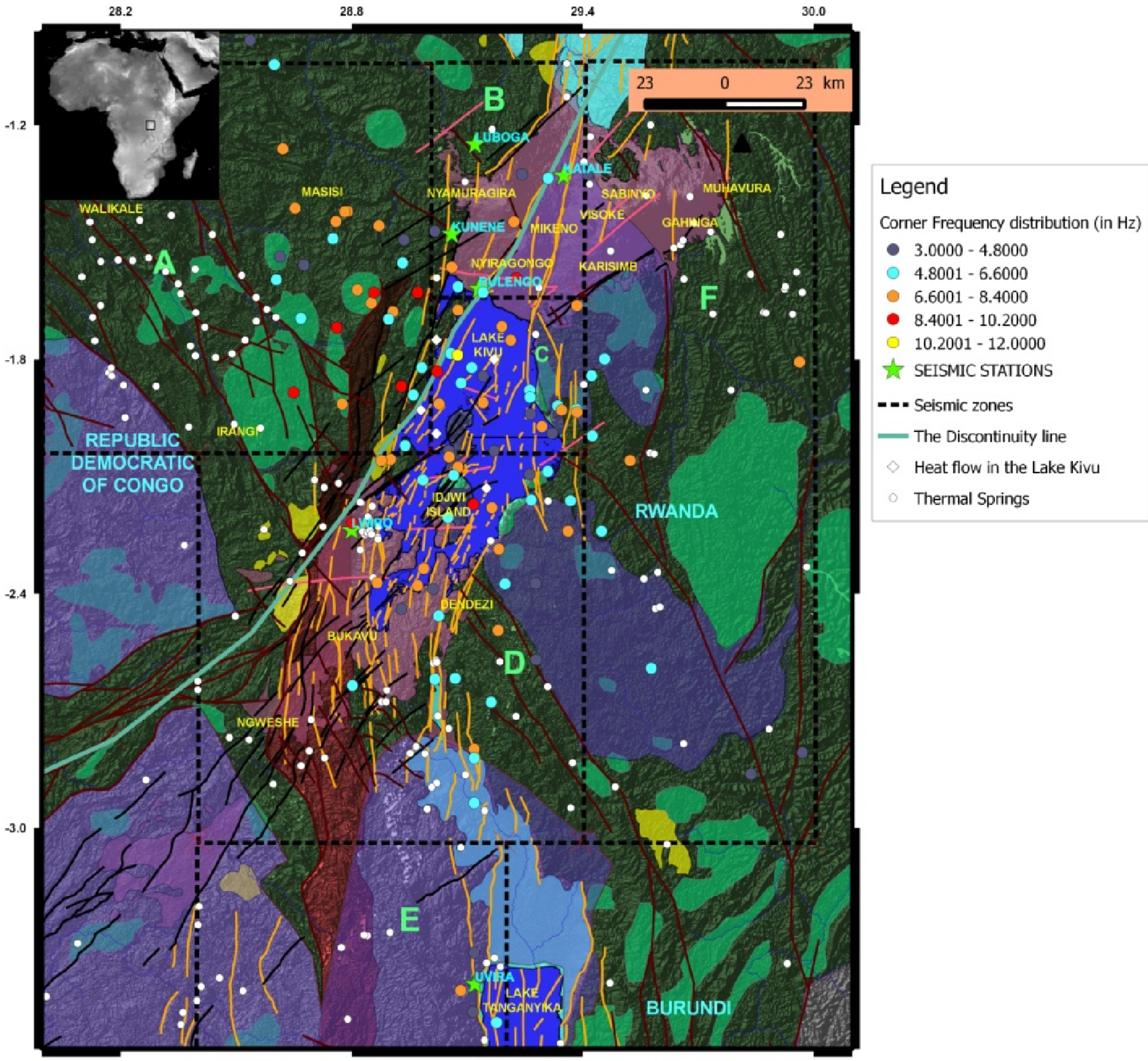

Figure 3: The distribution of earthquake's corner frequency related to the geological and tectonic setting of the area of the study in the Kivu provinces and vicinities.

The zone B is characterized by earthquakes of low f_c<5.5 Hz linked to low Δσ<0.5bar and the great source radius range from 41227 to 51190 cm. Stress drops (Δσ<0.5 bar) with high f_c=6.3 Hz have been observed at low earthquake magnitude (Ml = 2.0). And generally, at high frequency we observe the zone of high earthquake stress drops, high seismic moment and low source radius (r). A high $\Delta\sigma$ is observed at the fissure line jointing the Nyiragongo and Nyamuragira volcanoes. The maximum stress drop in this region is about 42.8 bars with f_c= 9.20 Hz, Mo =1.41E+21dyne – cm.

The zone C presented a scatter of low stress drop principally at the western part of the Kivu Lake and some high values at the East one (Figure 4). In the zone D, major earthquakes have low stress drop; the south part of the Idjwi Island presented some high stress drop for the granitic rocks and in junction to three types of faults (Figure 4). The zone D is characterized by high hydrothermal activity and ancient Cenozoic volcanic and sedimentary rocks in the first part of the Ruzizi.

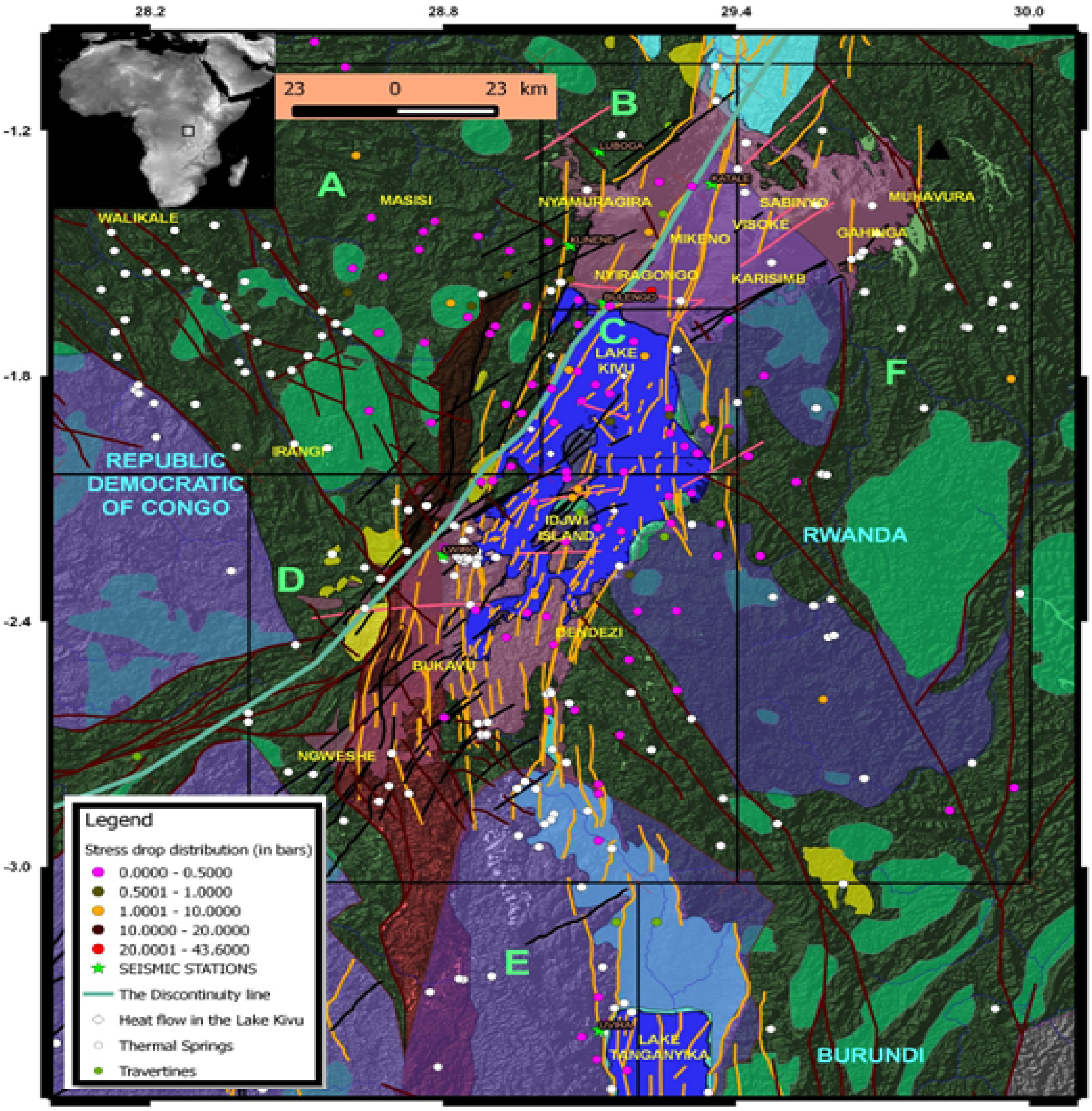

Figure 4: The distribution of the stress drop related to the Geology and tectonic setting in the Kivu provinces and vicinities.

4.2 STRESS DROP AND GEOLOGY FEATURES

The values of the stress drop are scattered depending to the geology setting of each zone. High stress drops are observed in the granite formation in the Zone A, C and D. For these two last zones, the relatively high stress drops (between 0.5 and 1 bar) were confined at Lake Kivu east border. The low stress drop is very manifested in the Precambrian basement for the all zones in general observation. The Idjwi Island (Zone D) presented a high value of stress drop at the junction of different faulting types and on granitic feature. The zone D characterized by hydrothermal activities and Cenozoic volcanoes in inactive state (Figures 1, 3 and 4) was the base of very low stress drop (< 0.5 bar). Very low stress drops are also observed in the sedimentary rocks like in the Ruzizi. The zone E (Uvira area) has showed a very low stress drop values (Figure 4). Controversially, the Virunga volcanic region, showed a high stress drop (>1bar) (Figure 4) near the active volcanoes (Nyiragongo and Nyamuragira).

No high stress drops were observed in zone E; these resulted to N – S faults triggered in sediment rock and nearly the hydrothermal field. The F zone have some high stress drops to far its boundaries of others zones; the high value corresponded to Ml = 3.5, fc = 8.6 Hz and Mo = 2.25E+20. The high stress drop corresponded to small source radius in the zone B but the other zones have showed a very fluctuation in the scattering of the source radius related to their stress drop (Figure 4).

4.3 STRESS DROP AND FAULTING

No exactly correlation with faults is seen in the zone A because the faulting was not very clearly found, except at the north-eastern part. The low stress drop could observed near the basement faults oriented NW – SE. The zone is characterized by normal faults [10]. High stress drop values (> 1 bar) are found in the zone B which is volcanically active at the Western part of the Virunga region. These high values are in relation with some fractures which are characterized as a reverse faulting for this zone. The fracture that links Nyiragongo and Nyamuragira volcanoes revealed also a great stress drop value. This is a controversy result because the volcanic region must release low earthquake stress drop because of high temperature and magma. The highest stress drop value (42.6 bars) (Figure 4) is pointed on the E – W faults - fracture and the very low stress drop has corresponded to North – South faults. The zone C was special because high and low stress drops appeared together on the same faults (Figure 4). Those stress drops are correlated with North – South faults (Figure 4). Some high and low stress drop values appeared exceptionally on the Junction of three types of faults in the Idjwi Island. The Northeastern - southwestern strike slip faults [9] and normal faults (North – south) have low stress drop. The stress drops in the zone E were very low and corresponded like the above zone to faults of North – South orientation. For the zone F we could not correlate stress drop to faults because of no more information about the structural geology.

5 DISCUSSION

Spatial distribution of the stress drops of small earthquakes occurring in the Kivu region and have been investigated. In general, low stress drops were observed during August 1993 to Mach 1994. For [18] generally earthquakes occurring in the rift zone have low stress as indicating the presence of softer material in the shallow depth. Therefore, isolated events with large stress drop were observed. Large stress drop reflects greater strength of material. This can be explained by the presence of barriers [19] and reflect the heterogeneities in small scale in the distribution of stress in these zones. The low corner frequency imply however, abnormally small stress drops due to possible high pore pressure (large amount of fluid), or slow ruptures [17]. And Stress wave propagations are highly dependent on material properties [41].

The earthquakes studied in this paper have local magnitude range from 0.2 to 4.5. So, for [51] local earthquakes with duration magnitude in the range of 1.7 to 3.3 are characterized by stress drop values that are equal or less to 10 bars. The high value of stress drop found in the highest magnitude earthquakes can be explained by the greater tectonic stress that is released in the pre – fractured carbonate basement [51]. This could be the results of the shallower and consolidate materials that make up the volcanic edifice [20]. That was observed in the zone B where two highest stress drops have been identified, these values have also a high local magnitude (Ml=3.1 and 4.5; fc = 7.5 and 9.2; Mo= 4.88E+20 and 1.41E+21; r=29935 and 29186 cm, respectively). This zone had much spectacular eruption before and after this period [32] for which some occurred around the fracture of highest stress drop (between Nyamuragira and Nyiragongo) (Figure 4). These activities contributed to the consolidation of these fault – fractures in the Virunga region. The high stress drops are also found in the zone A where consolidate metamorphic rocks were formed by granitic intrusion (figures 1 and 4). According to [5], normal values for tectonic earthquakes lie within the limits of 1.0 – 10 bars. Most determination for volcanic earthquakes lie in the range of 0.1 – 1 bar; that is the region of small stress value. The high stress drop values in that volcanic region are probably products of magmatic thermal fracturing of host rocks. Some volcano – tectonic earthquakes could have two characteristics in their stress drop analysis [22]. An average corner frequency of 10.67 Hz for the high stress drop earthquakes is due to magmatic thermal fracturing of host rocks and reverse fault types together and the low stress drop at 4.39 Hz reflecting the magma movement [22]. This is the same observation in the Virunga (zone B) for our study. The high stress drops of 6 to 36.4 bars and 1.5 to 16.5 bars, were also found for the Kilauea volcano in Hawaii by Zunig et al. (1987) quoted in [53]; this has been related to the no evidence of rupture propagation observed. High corner frequency and stress drop (in the order of 580 bars) were reported for the zone A for small earthquakes [6] as the present study obtained. This could be related to the presence of the rocks of Precambrian age [6] in the Kivu and for the Eastern part of the United State of America [55].

The zones C, D and E are characterized by very low stress drop values and are very fractured and owned great hydrothermal activities. This could be the effects high pore fluid pressure which contribute to low stress drop ([14], [21], [17]). This could be also attributed to the low strength of crustal materials in the area, where great stress accumulation is hindered [56]. That is why these zones recorded two great earthquakes long time after, the October 22, 2002 earthquake at Kalehe [43] and that of February 3, 2008 between Bukavu and Cyangungu [31]; while just after this period August 1993 – March 1994, the Masisi earthquake took place on April 20, 1995 [43] in zone A where great stress drop was obtained.

The virunga zone B of reverse faults ([11], [9]) have high stress drop; the Masisi – Walikale zone A normal faults have low stress drop at the South and high at the North part near faults crossing the Virunga zone B. High stress drop was also correlated to thrust faults areas such as Coalinga, California [21]. The low stress drops in the zones C, D and E correlated with normal faults and the moderately high corresponded to reverse and strike slip faults within the Idjwi Island. Higher stress drop faults have lager asperities where large slip occurs and contribute in the internal frictional strength [56]. The reference [2] invokes premature arrest of slip on the faults to account for the low stress drop events.

6 Conclusion

Spatial variation of stress drop has great importance for better understanding of the tectonic processes. Different materials or tectonic environment can influence source parameters, such as the stress drops which vary significantly depending on the region for the present study. High stress drops have been observed where granitic intrusion rocks are observed (zone A: Masisi – Walikale) and for consolidate ancient rocks in zone B (western part of the Virunga). The lowest stress drops have constrained within zones C, D and E (Lake Kivu and the high Ruzizi River) where soft materials, low strength of crustal and high pore pressure and great hydrothermal activities are manifested. Thus, these zones were not susceptible to allow great stress accumulation because of soft materials and presence of pore fluid pressure (great hydrothermal activity). This hindering of great stress accumulation gave two great earthquakes long time after in these zones while in the Masisi where great stress is pointed out an important earthquake took place one year after. This can be contribute to earthquake monitoring in the region.

The stress drop varied with fault types; higher for the reverse faults and lower for normal and strike slip faults observed in the Kivu region and vicinities. Particularly, the high stress drop value in the active volcano region (zone B) can be a product of magmatic thermal fracturing of host rocks and reverse fault types together. The Idjwi Island is a special case because granitic rocks, reverse, strike – slip and normal faults are observed; this contribute to high stress value, and low on other geological features. The low corner frequency implying however small stress drop due to possible high pore fluid pressure and slow rupture for hydrothermal, great heterogeneity and small scale crust structures. The high frequency is related to Precambrian rocks, consolidate and granitic intrusion rocks in this region.

Spatial and temporal variation of the stress drop based on many seismic stations within a region will help us to assess the seismic risk and forecast earthquakes occurrence and the structure and tectonic setting of the Kivu provinces.

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