# Seismic hazard parameter estimation of the Mount Cameroon volcanic region (Cameroon) based on a combination of mixed catalogs

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**Abstract:**

The Mount Cameroon volcanic region is one of the most seismically active areas of Cameroon, with earthquakes of duration magnitude $M_D \geq 0.5$ occurring at an average rate of one to three events every three days. The seismic hazard parameters of this region have been assessed on the basis of a procedure that combines historical events with complete instrumental data and takes into account uncertainty in the determination of the earthquake magnitude. The historical events include all felt and reported events that occurred prior to the establishment of a seismic network, whereas the complete instrumental data comprise of all instrumentally recorded events. The dataset of earthquake catalogs used in this study covers the period from 1909 to 2006. The overall seismicity pattern of the Mount Cameroon region during this period is characterized by the predominant clustering of earthquakes in four distinct regions denoted as: region A and B in the northern and southern part of the elongated axis respectively, region C in the Douala region, and region D in the offshore area. For each region, the maximum regional magnitude $m_{max}$, the activity rate of seismic events $\lambda$, and the $b$-value of the magnitude-frequency Gutenberg-Richter relation were determined. The estimated $b$-value during the studied timeframe ranged from a minimum of $0.81 \pm 0.07$ to a maximum of $1.52 \pm 0.03$ across the four seismic regions. The highest $b$-value was observed in the NE-SW seismic zone B and the lowest $b$-value was found to correlate with the northern part of the elongated axis of the volcano (region A). Focal depths of seismic events from zone B (between 35 and 55 km), coupled with the anomalous high $b$-values obtained, confirms the existence of a vertical magma conduit as inferred from previous studies. The mean activity rates for moment magnitude $M_W$ 3.5 range from about 2 to 14 events per month across seismic zones B and C, respectively. The maximum magnitude estimate has its highest value in seismic source zone B and the lowest value in the offshore region (seismic zone D). Differences in the estimated seismic hazard parameters from zone A to zone D reflect the seismogenic complexity of the Mount Cameroon region.

**Keywords:** Mount Cameroon; seismic hazard; maximum likelihood; return periods; $b$-value.

## 1. Introduction

Mount Cameroon (Mt. Cameroon) is one of the largest continental volcanoes and the most active volcano in West Africa with a volume of ~1200 $km^3$ and at least seven eruptions (1909, 1922, 1954, 1959, 1982, 1999, and 2000) in the course of the last 100 years (Fitton et al. 1983; Favalli et al. 2012; Global Volcanism Program 2013). Frequent lava flows (e.g. Suh et al. 2003; Wantim 2011) and seismic activity (e.g. Ubangoh et al. 1997; Ateba et al. 2009) have caused casualtiesand damage to properties and infrastructure. The resultant mudflows and landslides killed 24 and 4 people in 2001 (Ayonghe et al. 2004) and 2006 (Thierry et al. 2008), respectively. Furthermore, forests and plantations were destroyed during the 1999 eruption (Ubangoh et al. 1997). These natural disasters highlight the need to assess volcano-related hazards in this densely populated region (e.g. Thierry et al. 2008; Njome et al. 2010; Favalli et al. 2012).

Seismic hazard can be analyzed in at least two different ways: a) deterministically where a particular earthquake scenario is assumed, and b) probabilistically, in which uncertainties in earthquake size, location and time of occurrence are explicitly considered (Gupta 2002; Kijko 2011).Volcano-related hazard assessments should be expressed in terms of probabilities so that the uncertainties of the parameters can be incorporated (Sparks 2003). Most probabilistic seismic hazard assessment procedures require the identification of the seismic source zones and the knowledge of their hazard parameters such as activity rate $\lambda$, level of completeness, Gutenberg-Richter (G-R) parameter $b$, and the maximum possible magnitude $m_{max}$. However, the probabilistic seismic approach possesses significant shortcomings, such as the difficulty to include historical data in an earthquake catalog and the incompleteness of a dataset that may often yield unreliable results. To overcome these limitations, Kijko and Sellevoll (1989, 1992) and Kijko et al. (2016) proposed a method to obtain a maximum likelihood estimate of seismic hazard parameters, together with their uncertainties, by combining historical and instrumental data. The historical part contains the largest seismic events that have occurred over a period of few hundred years. The complete part can be divided into several sub-catalogs, each one complete above a given minimum magnitude $m_{min}^{i}$ where i = 1, … s and s is the number of sub-catalogs..

The first seismic activity documented in the Mt. Cameroon area was in 1852 (Ambraseys and Adams 1986). Nevertheless, instrumental measuring (instrumental seismicity) only took place during the last 30 years. The Geophysical and Volcanological Research Unit of Ekona currently monitors the activity around the volcano (Thierry et al. 2008). In general, occasional earthquake swarms and single earthquake events occur in the investigated area on an average of two events every three days, with duration magnitude of 0.5 or greater (Tabod et al. 1992; Ambey et al. 1992). The first seismotectonic studies of Mt. Cameroon volcano based on data collected between 1985 and 1987 yielded $b$-values ranging from 0.18 ± 0.01 to 0.86 ± 0.06 (Ambey et al.1992). These values are not realistic as they are not characteristic of volcanic areas. However, they were linked to a period during which sub-crustal earthquakes of local magnitude2.8 ± 0.1were regularly recorded in the southeast flank of the volcano (i.e. one to two events every three days). Recently, Ateba et al. (2009) determined a$b$-value of 1.43 ± 0.02 for the Mt. Cameroon region using seismic data (with a single largest event of duration magnitude $M_D$4.2) recorded during the 2000 volcanic eruption. These previous findings show that continuous follow up of the temporal and spatial evolution of the b-value may help to characterize the state of stress under the volcano.

The aim of this paper is to evaluate the seismic hazard level of the main seismogenic zones of the Mt. Cameroon volcanic area using earthquake catalogs gathered from different sources (Ambraseys and Adams 1986; Ambey 1989; Bertil 1991; Gallacher et al. 2012). The probabilistic algorithm based on the method described by Kijko and Sellevoll (1989, 1992) and Kijko et al. (2016)is used to estimate the seismic parameters in the four identified main seismic zones of the Mt. Cameroon volcano. These methodologies are applied to make provision for the highly uncertain and incomplete seismic catalogs for the Mt. Cameroon region.

## 2. Local geology and tectonic settings

Mt Cameroon is a ~4095 m high, elliptical stratovolcano, found mid-way along the Cameroon Volcanic Line (Déruelle et al. 1991). The Cameroon Volcanic line (CVL) has been active for the past 65 million years (Fitton and Dunlop 1985) and represents a 1600-km-long zone of passive rifting (mantle upwelling coupled with lithospheric extension), characterized by a chain of volcanic centers (e.g. Lenhardt and Oppenheimer 2014, and references therein) that have evolved in both oceanic and continental domains during the opening of the Atlantic Ocean (Morgan 1983; Déruelle et al. 1987).

The origin of the CVL is still not well established. Two lines of thought regarding its genesis exist. The CVL is described as an expression of the weakening of the lithosphere caused by the movement of the African plate over a hotspot, or the displacement of the African plate relatively to the asthenosphere (Morgan 1983; Milelli et al. 2012).However, the lack of evidence of a systematic age progression (Fitton and Dunlop 1985; Déruelle et al. 2007; Ngako et al. 2006; De Plaen et al. 2014) makes this hypothesis difficult to explain. The second generation of hypothesis suggests that the CVL originates from small scale mantle convection in the asthenosphere (Koch et al. 2012; Gallacher and Bastow 2012). This is supported by the presence of a deep hot zone (between 50 and 200 km) of a low velocity anomaly inferred from seismic studies (Reusch et al. 2010; Noel et al. 2014; Adams et al. 2015; Guidarelli and Aoudia 2016). The low velocity feature beneath the CVL is located underneath Mt. Cameroon (Reusch et al, 2010; De Plaen at al. 2014). Even though most of the CVL is aseismic (Tabod et al. 1992; Noel et al. 2014), these results indicate that Mt. Cameroon and surrounding areas are at high risk for the duration of magma activity (Reusch et al. 2010; Guidarelli and Aoudia 2016).

Mt. Cameroon is essentially dominated by successions of lava flows and pyroclastic cones attributed to Strombolian and Vulcanian activity (Suh et al. 2003; Fig. 1). The basaltic lavas date between 2.83 Ma to Present time (Tsafack et al. 2009). The SW flank of the volcano is characterized by nephelinites represented by Mount Etinde (Nkoumbou et al 1995). Other formations around Mt. Cameroon include the deposits of volcanic mudflows (lahars), mostly composed of basaltic rock fragments, set in a matrix of pyroclastic material (Wantim, 2011). The volcano is built upon thick Cretaceous to Quaternary sediments, which have been deposited over Precambrian metamorphic rocks (Déruelle et al. 1987;Kervyn et al. 2014).To the SE and NW of Mt. Cameroon, the Douala and Rio del Rey sedimentary basins are located, respectively (Fig. 1). Both basins comprise of mechanically weak sedimentary layers (Mathieu et al. 2011).

- Place **Figure 1** near here –

As shown in Fig. 1, many fault structures are recognized around Mt. Cameroon (Mathieu et al. 2011; Ateba et al. 2009; Suh et al. 2003; Ateba and Ntepe 1997). The most important include the Tiko and the Boa fault zones in the SE and NW parts of the volcano, respectively (Gèze

1953).Recent field observations (Mathieu et al. 2011; Kervyn et al. 2014) indicate that they may be thrust faults delineating a lobate structure. Many small fractures and crevasses trending NE-SW and NW-SE can also be found on the plateau of the summit (Gèze 1953).The NW flank of the mountain is marked by NW-SE striking structures identified as the Bokosso faults (Fig. 1), which are seismically very active (Ubangoh et al.1997; Ateba and Ntepe 1997).Furthermore, an interesting geological feature that cuts through the NW flank of the volcano is the 'Elephant Valley' that has been interpreted as 1) a result of glacial erosion (Déruelle et al. 1987); 2)a rift caused by the spreading of the volcano (Suh et al. 2003); or 3) a product of the collapse of the transtensional Bokosso faults (Mathieu et al. 2011).

## 3. Dataset and Seismic source zones

### *3.1. Earthquake database*

The seismic event catalog of the Mt. Cameroon area is characterized by incompleteness and uncertainty intermittently spanning a period from 1907 to 2006. Various sources were consulted in an attempt to obtain as many events for the seismic event catalog as possible. Large historic data described in terms of intensities (larger than IV) for the Mt. Cameroon region are available for the period 1907 to 1954 (Ambraseys and Adams 1986). Seismic network stations were first installed in and around Mt. Cameroon in 1984 to study the seismo-tectonic characteristics of Mt. Cameroon from 1984 to 1987 (Ambey 1989; Ambey et al. 1999; Ambey et al. 1992). Between 2005 and 2007, a total of 32 broad-band seismic stations were installed throughout Cameroon (Gallacher and Bastow 2012), and seismic events localized within the study area were added to the catalog. Prior to 1991, some seismic events were detected by the Lamto seismic stations in Côte d'Ivoire (Bertil, 1991) and were added to the catalog. Data from the International Seismological Center (ISC) were found to be limited in comparison with the above-mentioned sources and therefore discarded. The combined dataset was tested for duplicate events, which were eliminated. The plot of the epicentral distribution of earthquakes of magnitude $M \geq 0.5$ used in this study is shown in Fig. 2.

- Place **Figure 2** near here –

It is worth emphasizing that the seismicity of the Mt. Cameroon volcano was closely monitored for the first time only after the 1982 volcanic eruption, i.e. in 1984 (Ambey et al. 1989). Very little data is available for 1991. Subsequently, a high amount of usable data is only available for the time after the 1999-2000 Mt. Cameroon eruption. Consequently, the seismic catalog used in this study does not include events directly related to the eruptive activity of the volcano.

### *3.2 Unification of the magnitude scale*

Seismic catalogs utilized in this study are gathered from various seismological centers that may have used data from different stations when determining the source parameters. Consequently, different magnitude scales were used to describe the sizes of earthquakes. It is therefore necessary to choose a suitable magnitude scale to individually homogenize each catalog prior a seismic hazard assessment. In this paper, the moment magnitude $M_W$ was the standardized magnitude scale selected since it is directly linked to the seismic moment, an important characteristic of an earthquake source (Joyner 1984).

Various equations exist to transform the different magnitude scales to $M_W$. Here, we use the equation by Scordilis (2006), which relates the surface wave magnitude $M_s$ to$M_W$:

$$M_W = 0.67(\pm 0.005)M_s + 2.07(\pm 0.03) \qquad 3.0 \leq M_s \leq 6.1. \tag{1}$$

Seismic events for the periods 1975-1976 and 1989-1991 (Bertil 1991) originating from the Mt. Cameroon region were reported in the duration magnitude scale $M_D$. However, some seismic events located in neighboring countries were reported in both the duration and local magnitude scales, and correlated through a linear regression (Fig.3) with the following relation derived:

$$M_L = 1.28M_D - 1.19 \tag{2}$$

- Place **Figure 3** near here –

Hanks and Kanamori (1979) show that the local magnitude $M_L$ is connected to the moment magnitude $M_W M_0$ through the following equations:

$$\log_{10} M_0 = 1.5\, M_L + 16.0 \qquad (3)$$

$$M_W = 2/3 \log_{10} M_0 - 10.7 \qquad 3 \leq \mathrm{M}_L \leq 7 \qquad (4)$$

where $M_0$ is the seismic moment in Dyne cm. Eq. (2), (3) and (4) were used to standardize the duration magnitude events for the periods 1975-1976 and 1989-1991 into $M_W$ .The size of earthquake events in the instrumental sub-catalogs corresponding to the period 1985-1986 and 1987 were also expressed in terms of the duration magnitude. However, the Richter local magnitude $M_L$ and the magnitude from signal duration $M_D$ are linked by the relationship established by Ambey (1989):

$$M_D = M_L \qquad (5)$$

To homogenize events of the instrumental catalogs for the period 1985-1987into $M_W$, Eq. (3) and (4) were used for $M_L \geq 3$. Nevertheless, since the coda duration magnitude of events$M_D$ are linked to $M_L$via Eq. (5), Eq. (3) and (4) were also used to convert local magnitude $M_L < 3$ into moment magnitude $M_W$(Hanks and Kanamori 1979).Seismic events corresponding to the period 2005-2007 (Gallacher and Bastow 2012)expressed in the local magnitude were converted into the moment magnitude $M_W$ using Eq. (3) and (4).

*3.3. Seismic source zones*

Most of the fault structures recognized around Mt. Cameroon are distributed along its elongated axis (Fig. 1). The overall seismicity of Mt. Cameroon and environs is characterized by seismic swarms and discrete events clustered on the NE flank, mostly associated with the Bokosso faults. Additionally, clustered events, though not connected with a fault system, are located on the SW flank of the volcano and around the Bimbia area (Ambey 1989; Ambey et al. 1989; Ateba and Ntepe 1997, Ntepe 2015). A considerable number of events were located both in the south-eastern part of the elongated axis of the volcano and in the offshore and Douala regions during 2005 and 2006 (De Plaen et al. 2014). The majority of earthquakes are distributed throughout the crust. The depth of these events may imply that there is a brittle behavior throughout most of the crust and upper mantle (Ambey 1989). The observed moment magnitudes ranged from 0.5 to 5.0, although most events are smaller than 3.0. On the basis of the tectonic features of the area, described in Section 2 and the seismicity above, four seismic zones were identified represented as quadrilaterals A, B, C, and D (Fig. 2).

#### *3.3.1. Region A: The NE-NW seismic zone*

Earthquakes in this region usually occur both as discrete and swarm events. This area is located on the northern side of the volcano's long axis. The concentration of events around Bokosso represents the short but intense Bokosso swarm that started on the 13 February 1986 and lasted for 10 days (cf. electronic supplementary material 1). Focal depths of earthquakes identified in this region reveal that these events were relatively shallow, i.e. less than 20 km deep. Most events located in the northeastern part of the volcano occurred during the years 2005 and 2006 (De Plaen et al. 2014).

#### *3.3 2. Region B: The NE-SE seismic zone*

This area is situated along the southern part of the elongated axis of Mt. Cameroon. Earthquakes occurred as clustered and discrete events respectively at the SE and NE flanks of the volcano. The southeastern part of the volcano represents the most seismically active area of the Mt. Cameroon region (Ambey et al. 1999; Ateba et al. 2009). The hypocentral distribution of events was calculated with a 95% confidence level (Ambey 1989). Even though most seismic events coincide with the Tiko fault, the fact that they are relatively deep (between 35 and 55 km; electronic supplementary material 2) makes it unlikely that they are generated as a result of movements of this fault. The occurrence of these events is likely due to the presence of a zone of weakness such as a magma conduit (Ambey 1989; Ateba and Ntepe 1997) or the expression of the lithospheric stress field under the forces of plate motions (Ambey 1989).

#### *3.3.3 Region C: The Wouri-Douala seismic zone*

The small concentration of earthquakes around the Bomono area was observed as a sequence of two minor swarms. Some events are also scattered in the Wouri estuary and around the coastal boundary. Earthquakes located in this region have been interpreted as a result of the Mt. Cameroon volcanic activity (Ateba and Ntepe 1997; Ntepe 2015). The focal depths for these events range between 20 and 30 km (electronic supplementary material 3).

#### *3.3.4 Region D: Offshore Bimbia*

This area appears to be characterized by episodic swarms rather than an area of continuously occurring activity. Earthquake swarms were frequent in this region during the period 1985-1987 as oppose to the period 2005-2006 (cf. electronic supplementary material 4). The focal depths of events range between 13 and 22 km (cf. electronic supplementary material 3).

### *3.4.Probabilistic Seismic Hazard Analysis*

Probabilistic seismic hazard parameters of the four major seismic zones of Mt. Cameroon were evaluated on the basis of a technique that uses data containing large historical events and recent complete observations (Kijko and Sellevoll 1989, 1992) and Kijko et al. (2016). The applied methodology explicitly takes into account incomplete catalogs, magnitude uncertainty as well as uncertainty regarding the occurrence models.

During standard probabilistic seismic hazard analysis, the estimation of the three seismic recurrence parameters is required, namely the mean annual rate of occurrence, $\lambda$, the $b$-value of the Gutenberg-Richter relation, and the area-characteristic maximum possible magnitude $m_{max}$.

The temporal distribution of the number of earthquakes occurring within a specified area can be described by a Poisson process (Cornell 1968). The Poisson parameter $\lambda$ represents the mean activity rate of occurrence for earthquakes with magnitudes larger or equal to a threshold value $m_{min}$. The probability that a total of *n* earthquakes will be observed during the time interval *t* is described as

$$P_n(\lambda, t) = \frac{(\lambda t)^n}{n!} \exp(-\lambda \mathrm{t}), \qquad n = 0,1,2 \ldots, \tag{6}$$

in which $\lambda \equiv \lambda(m_{min})$. The earthquake magnitude distribution within a specified time interval is assumed to follow the classic Gutenberg-Richter frequency-magnitude relation (Gutenberg and Richter 1944, 1954)

$$\log_{10} N(m) = a - bm \tag{7}$$

in which $N(m)$is the number of seismic events with a magnitude larger or equal to the level of completeness magnitude $m_{min}$. The parameter $a$characterizes the general level of seismicity in a given area during the period of study such that the total number of events of magnitude greater than 0are $N_{total} = 10^{a}$.The Gutenberg-Richter parameter $b$-*value*quantifies the slope of the frequency-magnitude distribution and describes the ratio between the number of small and large events. Equation (7) translates to the cumulative distribution function (CDF) of the form first defined by Aki (1965)

$$F_M(m) = 1 - \exp(-\beta(m - m_{min})) \tag{8}$$

for $m \geq m_{min}$, $\beta = b \ln(10)$, and $m_{min}$ the level of completeness of minimum magnitude above which all events are observed and recorded.

The standard seismic hazard analysis procedure requires that seismic catalogs are de-clustered to remove all fore- and aftershocks. This is to avoid violation of the dependence assumption of the Poisson process, which assumes that the seismic hazard parameters $\lambda$ and $b$ remain constant over time. However, literature reports that temporal uncertainties in both these recurrence parameters are typically observed in volcanic-induced, seismic event catalogs (e.g. McNutt 2005; Roberts et al. 2015). For instance, it has been shown that $b$-values underneath Mount Etna volcano are usually high (between 1.5 and 3) during the eruptive phases and very close to those obtained for tectonic earthquakes (< 1) during resting periods (Roberts et al. 2015). Additionally, spatial variability of $b$-value is reported in volcanic areas with anomalous high $b$-value at depths of 3-4 km and 7-10 km (McNutt 2005; Bridges and Gao 2005; Farrell 2009). The former depth range is the approximate depth at which magma with 4 % gas starts to exsolve (McNutt 2005). The presence of swarm earthquakes can also lead to poor accuracy for activity rate estimates.

Kijko et al. (2016) introduced the use of mixture distributions to explicitly account for such deviations from the Poisson process (Eq. 6) and CDF of magnitude occurrence (Eq. 8). Mixture distributions are considered an efficient manner to address uncertainty in the parameters by assuming that they are random variables. This approach sometimes is also defined in terms of Bayesian statistics where the uncertainty is introduced as prior information.

For this paper, the gamma distribution was used to describe the variation and uncertainty in the recurrence parameters $\lambda$ and $b$. Similarly, the area-characteristic maximum possible magnitude $m_{max}$is calculated using the Kijko-Sellevoll-Bayes method described in Kijko (2004) and Kijko and Singh (2011) where the variation in the recurrence parameters are included. If disregarded, it can lead to biased estimates for $\lambda$, $b$ and $m_{max}$.

Another advantage of the methodology described in Kijko and Sellevoll (1989) and Kijko et al. (2016) is that it allows for the use of sub-catalogues during the process of estimating the seismic recurrence parameters. The sub-catalogues can be a function of varying levels of completeness $m_{min}$ over time, as well as a function of time gaps in the catalogue. A detailed description of the applied methodology is available in Kijko et al. (2016).

## 4. Results

In this paper, the method described above was applied to the Mt. Cameroon region to estimate the hazard parameters of each seismic sources zone underlined in Fig. 2.

The combined seismic event catalogue was subdivided into smaller sub-catalogs for each of the identified seismic source zones. Due to the time gaps observed in the combined seismic catalog, we subdivide the data to create the six sub-catalogs for the different time periods, namely the largest historic events for the period 1907-1954, sub-cat #1 for the period 1975-1976, sub-cat #2 for the period 1975-1976, sub-cat #3 for the period 1975-1976, sub-cat #4 for the period 1975-1976, and sub-cat #5 for the period 1975-1976.

For sub-catalog in the different source zones, the level of completeness was determined using the maximum curvature technique (Wiemer and Wyss 2000). The magnitude of completeness, the minimum magnitude above which it can be assumed that all the seismic events were observed and recorded, is estimated based on the departure of the Gutenberg-Richter frequency-magnitude distribution (Eq. 7) from its linear trend. Table 1 summarizes the dates, minimum magnitude $m_{min}$and the number of events above$m_{min}$in each sub-catalog.

- Place **Table 1** near here –

The frequency-magnitude plots for each seismic zone and each sub-catalog are presented in Fig. 4. The occurrence of the Bokosso swarm with magnitude $M_W$ less than 3 can be observed as the sub-catalog #2 in seismic zone A deviates from the Richter-Gutenberg relation (Eq. 7). Another intriguing feature in seismic zone D, is that sub-catalog #5 contains by far more events with $M_W >$ 2 than sub-catalog # 3 (Fig. 4(iv)) whereas the magnitude of completeness is higher in sub-catalog #2. This is likely due to the fact that sub-catalog #5 is produced by a regional seismic array and sub-catalog #3 is recorded by local seismographs.

- Place **Figure 4** near here

It was assumed that the magnitude errors on the reported events in the historical and instrumental catalogs are 0.3 and 0.2, respectively. A total of 25% variation was included in the estimation process for both $\lambda$ and the $b$ −value to account for temporal variation and the effects of swarms. Bayesian inference was use to estimate the parameters by assuming a prior information for the $b$-value following a normal distribution. An arbitrary value of $b_{\text{prior}}$ of 1.5 and a standard error of $\sigma_{prior}$ = 0.5 were chosen on the basis of $b$-values reported from other volcanic regions which can vary up to~2 (Bridges and Gao2006). The obtained estimates of $b$-value, mean activity rate occurrence $\lambda$, and area-characteristic maximum possible magnitude $m_{max}$ for each seismic zone of the Mt. Cameroon region, together with their standard deviations are given in Table 2. For the seismic source zones A, B, C and D, Fig. 5 illustrates the return period of magnitude $m \leq m_{max}$ and Figs. 6 to 8show the probabilities of exceedance for the next 25, 50 and 100 years, respectively.

- Place T**able 2** near here –

The seismicity of the NE-NW striking area (seismic zone A) is distributed along the elongated axis of the volcano. There is about50% probability that at least one event will exceed the magnitude $M_W$= 4.5 in the next 25 years.

The southeastern flank of the volcano, situated in the NE-SE seismic zone, is seismically very active (Ubangoh et al. 1997). The largest observed earthquake of magnitude 5.09 ± 0.30, which occurred on 29$^{th}$April 1909 was the most intense in the history of earthquakes of the Mt. Cameroon region. There is more than 85% probability that at least one event will exceed the magnitude $M_W$ = 4.5 in the next 25 years.

In seismic zone C, i.e. the Wouri-Douala region, all earthquake events are of magnitude less than 3 except the largest historical earthquake of magnitude $M_W$ = 4.95 ± 0.30. There exists a 50% probability that at least one event will exceed the magnitude $M_W$ = 4.5 in the next 25 years.

The Offshore-Bimbia region (zone D) seismic catalog events are confined within the periods 1985-1987 and 2005-2006. In this seismic zone there is over 80% probability that at least one event will exceed the magnitude $M_W$ = 3.8 in the next 25 years.

Seismic hazard parameter $b$-values (Table 2) vary slightly from zones A, C and D showing that the seismicity of these zone are more likely to be tectonic-related. Zone B, however, exhibits more of a volcanic-induced seismicity with an estimated $b$-value of 1.5.For a given magnitude between 2.0 and 3.9, the parameter $\lambda$ is highest in zone B and lowest in zone C, hence we get lowest return period for zone B and the greatest return period for zone C. From Fig. 5 it is clear that the seismic zones A, C and D show greater return periods than zone B, implying that strong events occur more frequently in Zone B. The probability of occurrence plots for 25, 50, and 100 year return periods (Figs. 6-8) imply that the probability of occurrence of earthquakes decreases with magnitude in zones A to D.

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## 5. Discussion

For a magnitude of 4.5, the activity rate $\lambda$ is highest in zone B and lowest in zone C and hence, we can expect the greatest return period in zone C, the lowest in zone B (Figs. 5 and 8). The maximum possible earthquake magnitude estimate (Table 2) shows that greater magnitudes are to be expected in zone A, B and C as compared to zone D. The seismic hazard parameters estimated in this article are found to be the highest in seismic zone B. Additionally, most events occur in this region as discrete events compared to regions A and C, which are affected by swarm events. On the basis of these assumptions, we can conclude that this zone is the most seismically active part of the volcano as previously observed (Ambey et al. 1992; Tabod et al. 1992; Ateba et al. 2009; Ntepe, 2015).

The Gutenberg-Richter $b$-value provides an indication about the mechanism of a medium releasing accumulated energy (Gibowicz and Kijko 1994). The $b$-value parameters estimated in this study (Table 2) given as indication regarding the heterogeneity of the material within zones A to D. In tectonic areas, the $b$-value is generally around 1.0 (Gibowicz and Kijko 1994). In contrast, volcanic areas are characterized by $b$-values greater or less than 1.0 with values as high as 3.0 (McNutt 2005). Nevertheless, high $b$-values (> 1) are usually reported in volcanic areas (Sánchez et al. 2005; Bridges and Gao 2006; Murru et al. 2007). These high $b$-values are either associated with the transport of magmatic fluid or could be related to a low-stress regime, resulting from the release of earthquakes. The $b$-values derived from this study vary from 0.81 in seismic zone A to 1.52 in zone B. The seismicity associated with the $b$-value of $0.81 \pm 0.07$ in region A can be interpreted as evidence fora higher than normal crustal stress regime. This might result from the movement occurring along the Bokosso fault zone (Mathieu et al. 2011; Fig. 1).

Very little is known about the magma chambers that feed the eruptions of Mt. Cameroon. Fitton et al. (1983) examined the lava of the 1922, 1959 and 1982 eruptions and found isotopic similarities only between 1959 and 1982 lavas. As a result, eruptions are probably fed by isolated batches of lavas from slightly heterogeneous sources rather than from a single chamber that evolves with time (Fitton et al. 1983). Further geochemical analysis of the lavas of the 1999-2000 eruptions show that the composition of the 1999-2000 lavas differs from previous eruptions (Suh et al. 2003). In the line with these findings, Geiger et al. (2016) used petrological analysis of lavas of the 1999 and 2000 eruptions to show that lavas that erupted during these period crystallized in depths between 26 and 39 km. One of the major conclusions drawn from his research is that, the Moho beneath Mt. Cameroon (≈ 24 km deep) may act as a barrier where magmas stop and crystallize before ascending further to the surface. According to the above findings, the persistence of hot magma in such a small reservoir suggests that the chamber is not shallow (Ntepe 2015).

Deep seismic activity (up to 60 km depth) that occurred after the major 1982 eruption was associated with phreatic explosions (Ateba and Ntepe 1997). Moreover, Suh et al. (2003) suggested that there might be a magma conduit associated with deep earthquakes (35 to 55 km depth) during the resting period of the 1999-2000 eruptions. Furthermore, the seismograms recorded for the 1999-2000 eruptions show that the two periods were separated by a relative quiescent period during which a decrease of the frequency and magnitude of the signal was observed. The first period consists of discrete signals and seismic swarm activity, the second period corresponds to simultaneous record of felt earthquakes and the occurrence of high amplitude tremor (Ntepe 2015). These observations may reflect migrating magma pockets during the inter-eruptive episode (Geiger et al. 2016). Additionally, Ateba et al. (2009) estimated an average Gutenberg-Richter b-value of $1.43 \pm 0.02$ from the earthquake activities of the 2000 eruption of Mt. Cameroon, showing a potential relationship between the seismicity and the magmatic activity during that period. With all that said, we suggest that the magma plume intruding the lithospheric mantle of the volcano is likely to be responsible for the anomalous high $b$-value of 1.52 in zone B.

The Douala basin consists of weak heterogeneous sediment layers (~3-4 km depth), characterized by abnormal pressures observed in the Bomono swell (Mathieu et al. 2011; Kervyn et al. 2014). Most seismic events recorded in this zone (zone C) ranged between 20 and 30 km depth (Ambey et al. 1992; De Plaen et al. 2014). We suggest that the state of the stress in the substrata linked to the volcanic activities of the volcano as inferred by Ateba et al. (2016) is more likely to be responsible for the$b$-value of $0.88 \pm 0.10$estimated in this seismic zone.

So far, no particular tectonic feature has been delineated in region D. Nevertheless, due to its proximity to the volcano, it is likely that the observed seismicity of this zone is related to the activities of the volcano.

There are many possible causes for a higher than normal $b$ −value at volcanoes. One reason could be the stress regime in the magma chamber due to the exsolution of gases from fumaroles (vents around the volcano from which hot gases, especially steam, are emitted) as observed in most Mt. Cameroon eruptions (Wantim 2011). As a result, the interaction between the rising magma and groundwater at shallow depth consequently reduces the stress level and allows the recurrence of small earthquakes which increase$b$-values (Bridges and Gao 2006).

Another possible explanation fora high $b$-value anomaly could be the concentration of hydrothermal fluids due to the intrusion of magmas. As hot magmatic fluids are injected into the system, temperatures happen to increase and the crust would therefore weaken as a result of the dissipation of stress to allow hydrothermal fluid flow. The high temperatures and weakened crust cause the formation of numerous small fractures that increase the occurrence of earthquakes of small magnitude. This mechanism would alter the frequency-magnitude distribution of earthquakes towards high $b$-values (Sánchez et al. 2005; Farrell et al. 2009).

Several factors can influence the reliability of hazard parameters, especially for volcanic areas. The choice of the model for the distribution of earthquake magnitudes are one of these factors and can greatly affect the results of a seismic hazard analysis (Kijko 2004). In volcanic regions, the existence of earthquake swarms can lead to a nonlinearity of the frequency-magnitude distribution and therefore increase the observed $b$-values (Bridges and Gao 2006). In this article, we accounted for temporal variation by introducing 25 % uncertainty in the estimates of the seismic recurrence parameters by treating the mean activity rate$\lambda$ and $b$-value as random parameters (Kijko et al., 2016).

Moreover, seismic hazard parameters were estimated using Bayesian Inference with catalogs covering only about 58-years and containing clustered earthquakes events. The results obtained in this study present a preliminary picture on seismic hazards of the Mt. Cameroon region. Additional seismic data are required to stabilize the seismic hazard results for the Mt. Cameroon area. This would help to reinforce current findings and deepen our understanding of the relationship between the magma chamber properties and the local seismicity.

The analysis of the $b$-value as a function of space and time has been proven effective to localize the magma chamber and to study the change related to a volcano's eruptive activity (e.g. Bridges and Gao 2006; Roberts et al. 2015). Nevertheless, it requires continuous monitoring with a well distributed permanent network to produce a higher quality seismic event catalog (in terms of earthquake location) with a larger number of events (Murru et al. 2007; Sánchez et al. 2005). This will enhance the feasibility of a ground motion analysis using the earthquake stress drop technique (e.g. Oth et al. 2017). We also suggest that future works should involve seismic tomography to determine a 3D velocity structure beneath Mt. Cameroon as successfully attempted by Guiderelli and Aoudia (2016).

## 6. Conclusion

Considerable effort was made to collect, combine and homogenize seismic events around the volcanically active Mt. Cameroon. The resulting catalog spans the period 1907 to 2006, but is highly incomplete with large time gaps and clustered data. A seismic hazard procedure that could take these deficiencies in the data into consideration was applied to assess the volcanic-induced seismic hazard recurrence parameters.

The seismic potential of each seismic zone of the Mt. Cameroon region is defined on the basis of the seismic hazard parameters $\lambda$, $b$-value and $m_{max}$. The results show that the overall seismicity pattern of the Mt. Cameroon region is underlain by the occurrence of earthquakes with magnitude less than 3 as observed in the seismic catalog. Return period and probability of exceedance graphs show that the recurrence of earthquake decreases as the magnitude increases.

Overall, the seismic activity level is relatively high in zone B, intermediate in zones A and D, and the lowest in zone C for an event of magnitude 3.5. Based on the $b$-values estimated, the seismic activity in the surroundings of Mt. Cameroon can be interpreted as either a movement along its tectonic structures in the northern section of the elongated axis, or associated to the magma activity that could trigger the deep earthquakes recorded in the SE part of the volcano.

Seismic zone B includes the principal towns of Buea and Tiko, and is found to be the region with the highest hazard level where the occurrence of earthquakes with magnitude equal or greater than 4.0 is 0.3 events/year and the return period is 3.22 years. Information provided from seismic hazard parameters $\lambda$, $b$-value and $m_{max}$ of each seismic zone is very useful from the engineering point of view. In this regard, care should be taken to inform the local communities about the areas subjected to relatively high seismic hazard and proper risk evaluation should be done before going for constructions in such a zone.

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## Figures

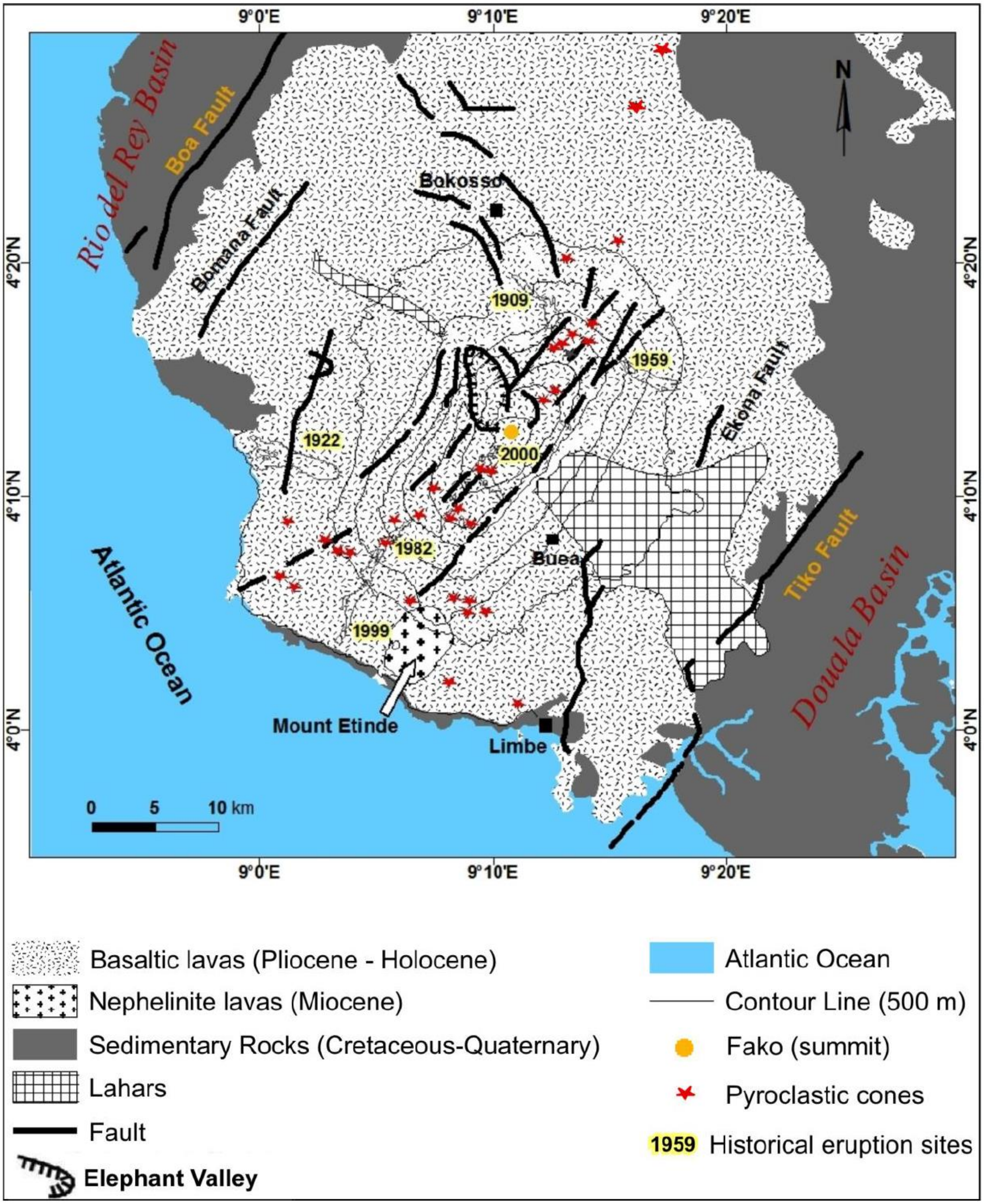


**Figure 1.** Geological map of the Mt. Cameroon region, showing the main faults, fractures and the surrounding sedimentary basins (adapted from Ateba et al. 2009)

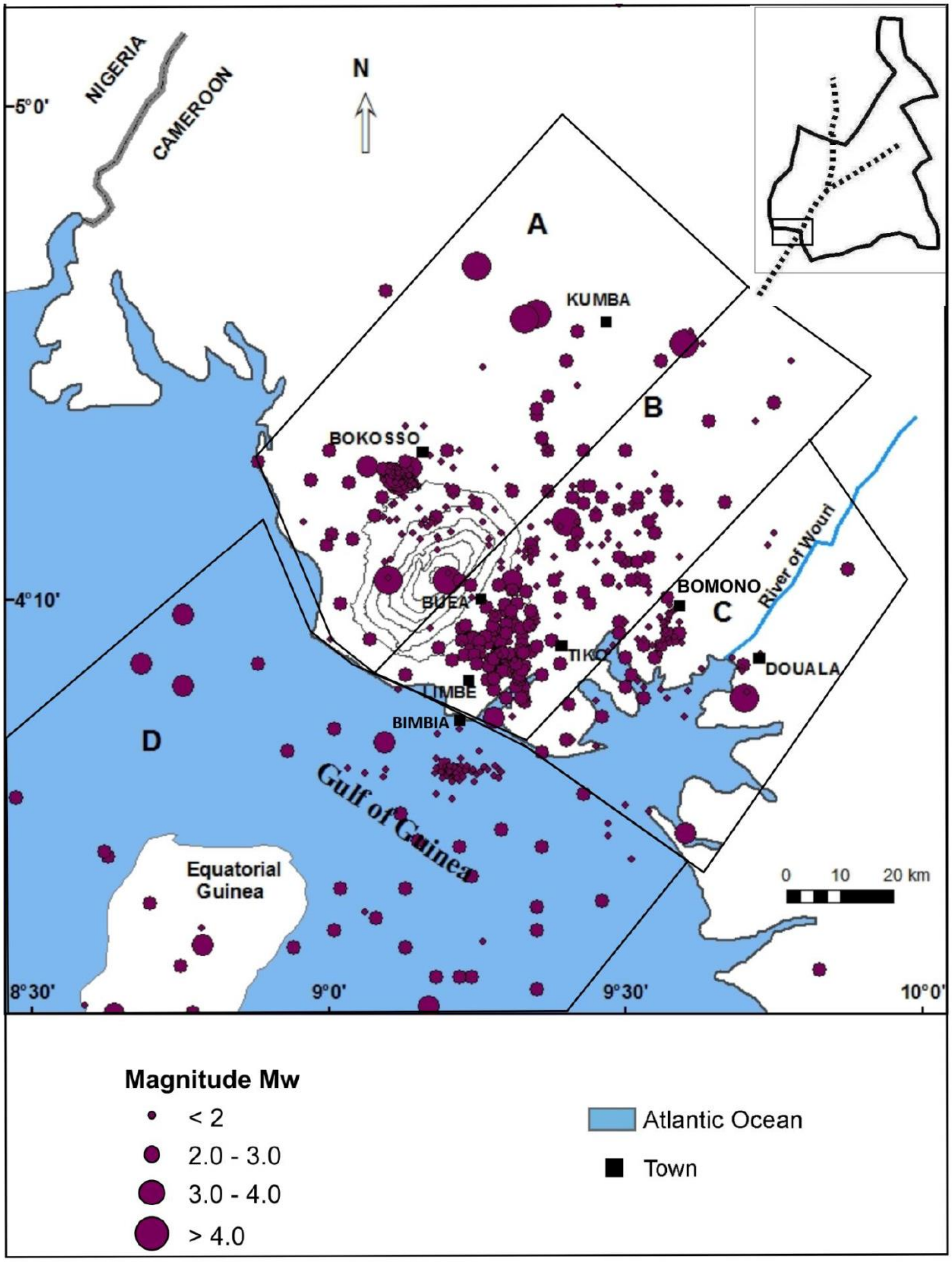


**Figure 2.** Epicentral map of the Mt. Cameroon region for the period 1900 to 2006. The identified seismic zones for this analysis are shown by rectangles denoted A, B, C, and D (after Ambraseys and Adams1986; Ambey 1989; Bertil 1991)

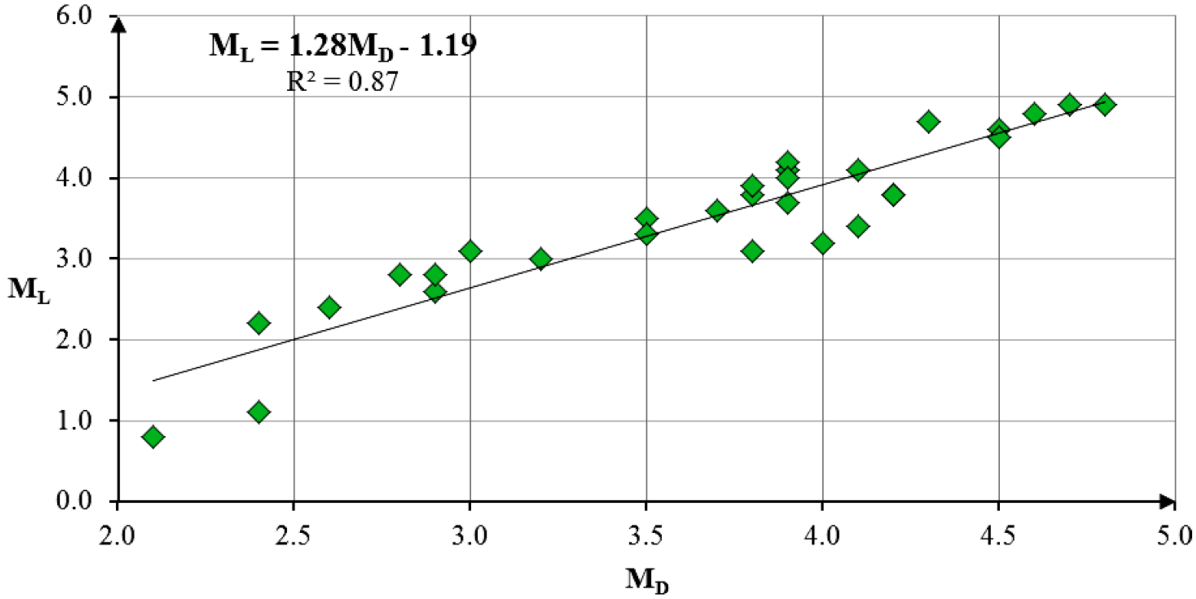


**Figure 3.** Linear regression of values of $M_L$ versus $M_D$ of selected events observed in West Africa from 1965 to 1991 (data are from Bertil1991)

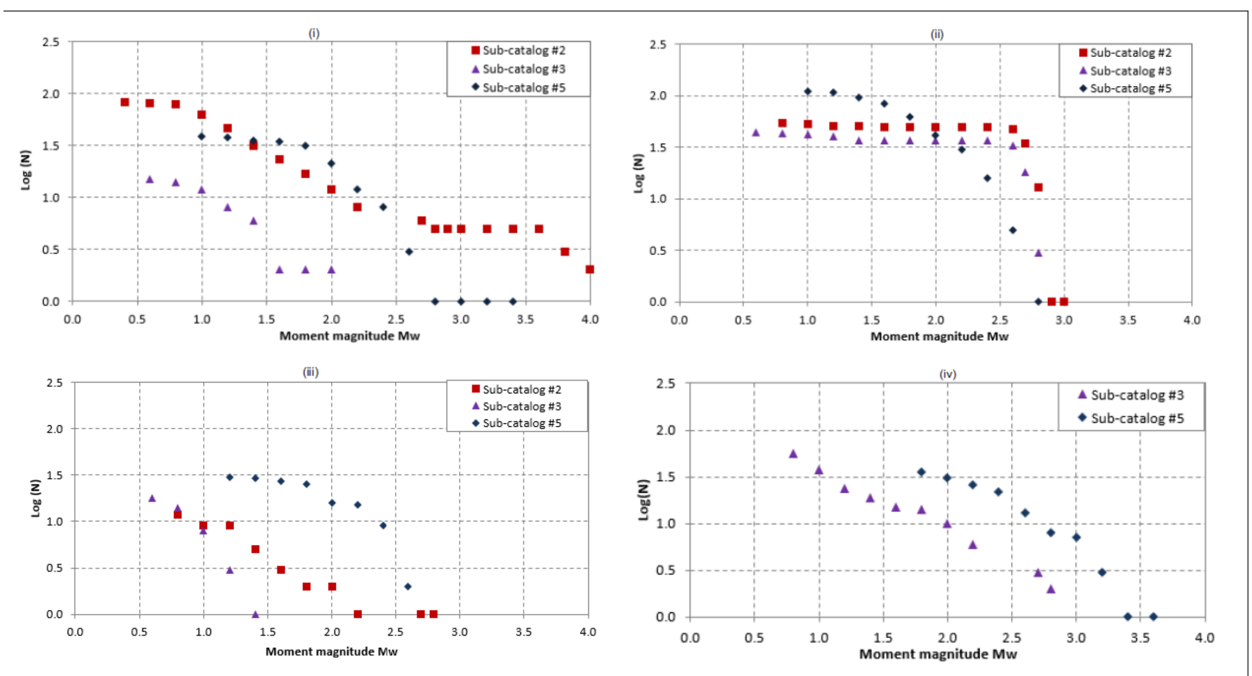


**Figure 4**. Graphs (i) to (iv) show the frequency – magnitude distribution of the instrumental seismic sub-catalogs of seismic sources A to D, respectively. The magnitude bin is 0.2. The level

of completeness of each seismic zone represents the magnitude at which the curve deviates from its linear relationship.

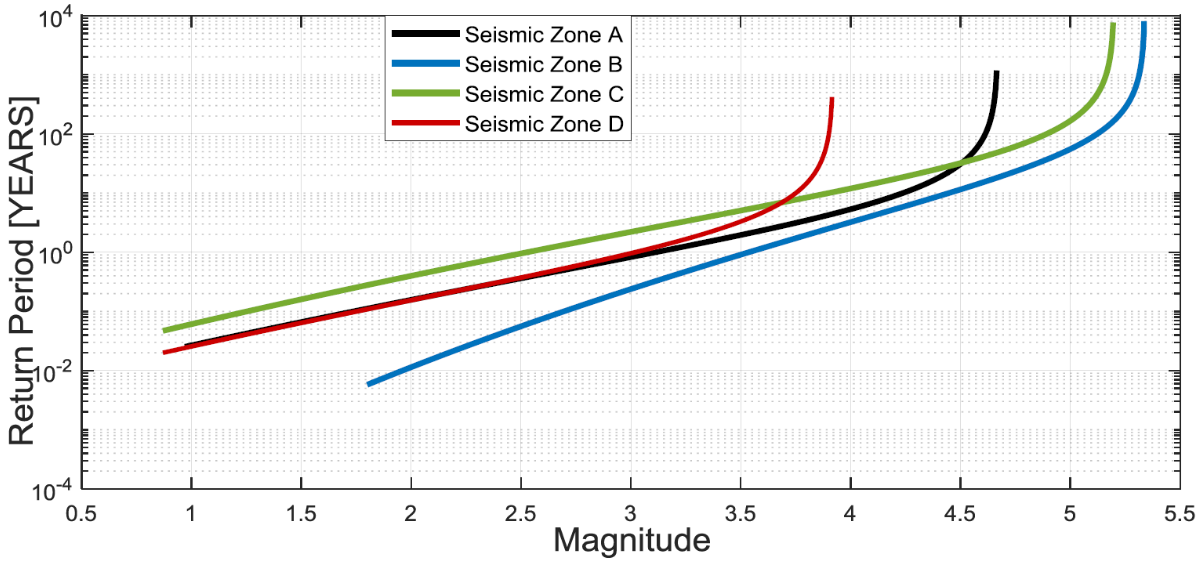


**Figure 5.** Return period of magnitude events from the four seismic zone of Mt. Cameroon volcano.

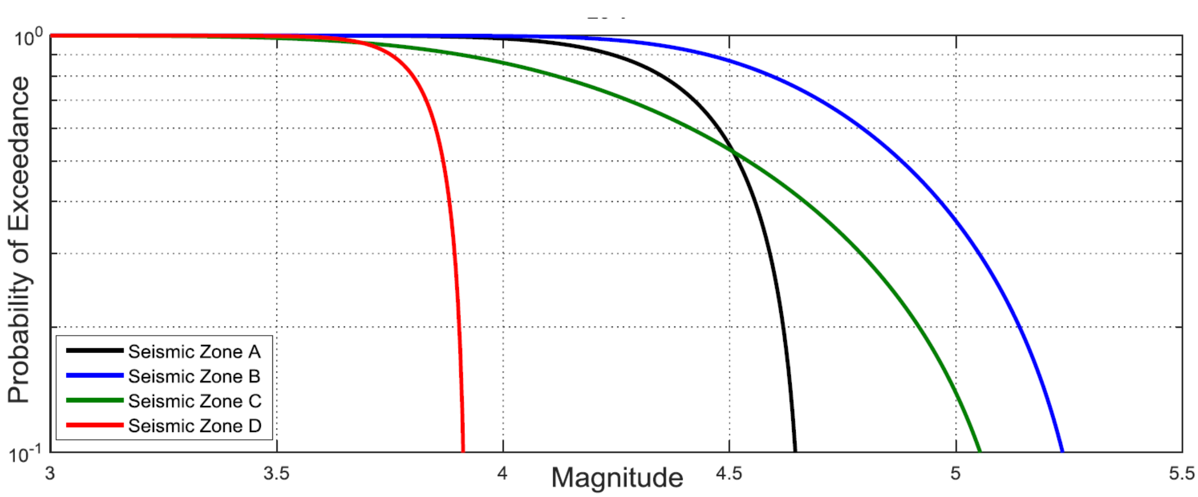


**Figure 6.** Graph showing the probability of exceedance of earthquake events from seismic zone A to D for the next 25-years.

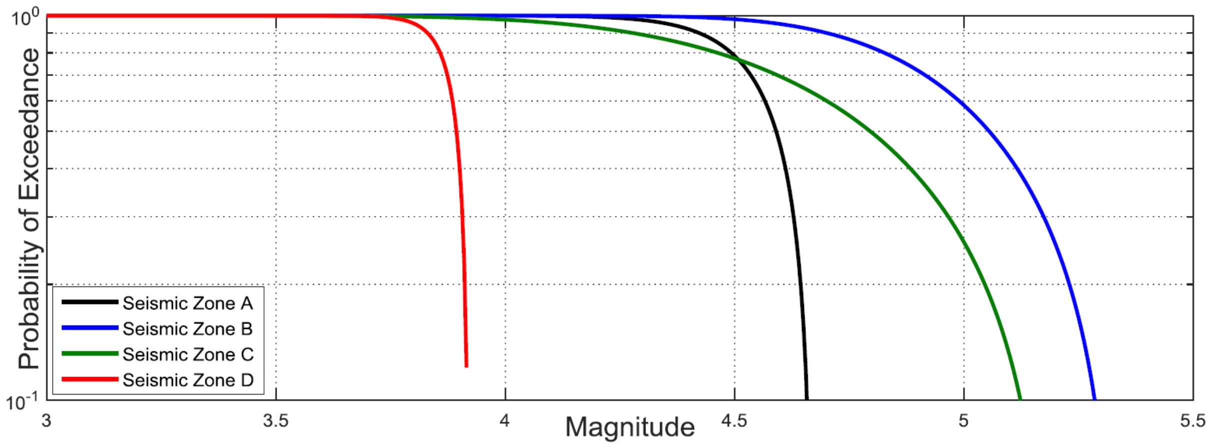


**Figure 7.** Graph showing the probability of exceedance of earthquake events from seismic zone A to D for the next 50-years

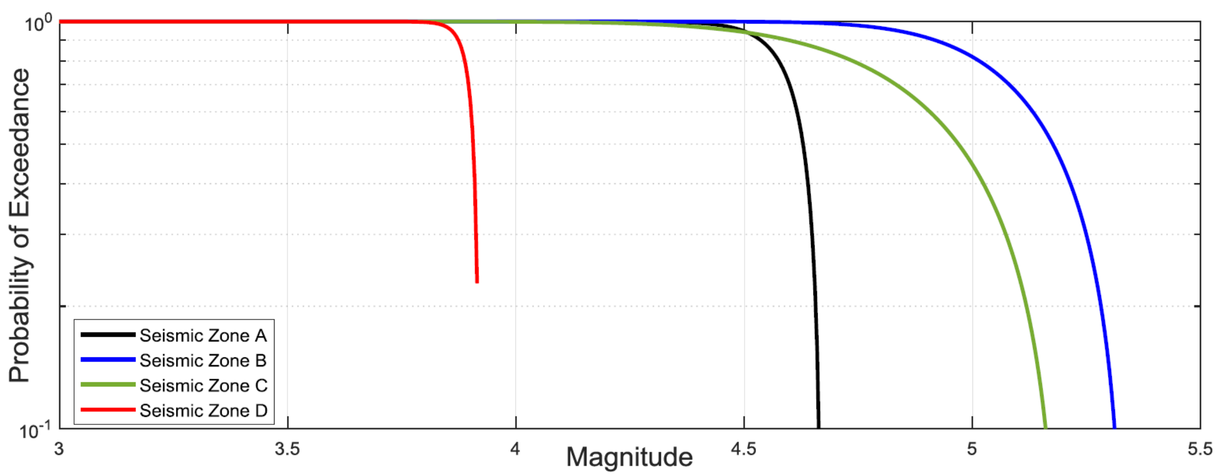


**Figure 8.** Graph showing the probability of exceedance of earthquake events from seismic zones A to D for the next 100-years

## Tables

**Table 1.** Number of earthquakes of historical and instrumental catalogs with magnitude greater than the threshold magnitude (indicated in bracket) of each seismic source zone of Mt. Cameroon Volcano (compiled from Ambraseys and Adams 1986; Ambey 1989; Bertil 1991; Gallacher and Bastow 2012)

| Seismic Source zone | Hist Events 1$^{st}$Jan 190731$^{st}$ Dec 1954 | Complete Part of the Catalogue | | | | | Maximum Observed Magnitude |
|---|---|---|---|---|---|---|---|
| | | Sub-cat #1 1$^{st}$ Jan 1975 31$^{st}$ Dec 1976 | Sub-cat #2 1$^{st}$ Jan 1985 31$^{st}$ Dec 1986 | Sub-cat #3 1$^{st}$Jan 198731$^{st}$ Dec1987 | Sub-cat #4 1$^{st}$ Jan1989 31$^{st}$ Dec 1991 | Sub-cat #5 1$^{st}$ Jan 2005 31$^{st}$ Dec 2006 | |
| A | 2 (4.42)* | 3 (4.03)* | 63 (1.07)* | 14 (0.97)* | 1 (3.77)* | 31 (1.8)* | 4.42±0.30 |
| B | 3 (4.42)* | 0 | 34 (2.77)* | 33 (2.67)* | 1(3.77)* | 62 (1.8)* | 5.09±0.30 |
| C | 1 (4.95)* | 0 | 12 (0.87)* | 14 (0.87)* | 0 | 25 (1.8)* | 4.95±0.30 |
| D | 0 | 0 | 57 (0.87)* | 1 (2.27)* | 0 | 32 (2.0)* | 3.67±0.20 |
| *Minimum magnitude of the catalogue | | | | | | | |

**Table 2.** Seismic parameters of the four seismic source zones of Mt. Cameroon volcano. Rp is the return period (years) of events with magnitude $M_W$ >3.5

| **Source** | $\boldsymbol{b \pm \sigma b}$ | **$\boldsymbol{\lambda}$ (per year)** | $\boldsymbol{m_{max} \pm \sigma}$ | **Rp** |
|---|---|---|---|---|
| A ( NE-NW seismic | 0.81 ± 0.07 | 1.21 (Mw=3.0)* | 4.67 ± 0.31 | 1.95 |
| B (NE-SE seismic zone) | 1.52 ± 0.03 | 4.20 (Mw=3.0)* | 5.34 ± 0.34 | 0.90 |
| C (Wouri-Douala seismic | 0.88 ± 0.10 | 0.45 (Mw=3.0)* | 5.20 ± 0.41 | 5.06 |
| D (Offshore-Bimbia | 0.82 ± 0.08 | 1.04 (Mw=3.0)* | 3.92 ± 0.21 | 3.30 |
| *Magnitude of the estimated activity rate | | | | |