ORIGINAL PAPER

Probabilistic seismic hazard assessment for the main cities along the continental section of the Cameroon volcanic line

Etoundi Delair Dieudonné Ndibi[1,2] · Eddy Ferdinand Mbossi[1,2] · Nguet Pauline Wokwenmendam[1] · Bekoa Ateba[1] · Théophile Ndougsa-Mbarga[3]

Abstract

A probabilistic seismic hazard assessment has been carried out along the continental section of the Cameroon volcanic line (CVL) in West Africa. We compiled a catalogue of local earthquakes from different sources and homogenize the magnitudes to moment magnitude (Mw). The seismicity of the CVL is concentrated around Mount Cameroon the active volcano and diffuse on the rest. Three seismic source zones were identified: one in Mount Cameroun, the second NE of the volcano in the grabens of Kumba-Tombel, and the third seismic source corresponds to West Cameroon horst. The recurrence model is that of Gutenberg and Richter, ZMAP software was used to decluster the catalogue and to determine seismic parameters for each source zone. To calculate the hazard, we choose two ground motion prediction equations, and to account for uncertainties, a logic tree approach was implemented using CRISIS software. We estimated the peak ground acceleration (PGA) for eleven cities spread along the CVL, for return period (RP) 475 and 2475 years. The results show that for RP 475 years, Buea, located at the foot of Mount Cameroon, has a PGA of 10% *g*. This value decreases as one moves away from Buea. The seismic hazard was also calculated for the period of 0.2s. Uniform hazard spectra for RP 475 and 2475 years are plotted for three cities, each chosen in one of the seismic source zone. For each city and RP, the spectral acceleration increases with the period, up to around 0.1s, and then it decreases as the period increases.

Keywords Cameroon volcanic line · Seismicity · Probabilistic seismic hazard assessment · Ground motion prediction equation

Introduction

The Cameroon volcanic line (CVL) in West Africa is a chain of volcanic islands of the Atlantic Ocean and Cenozoic to Quaternary intraplate volcanic and plutonic massifs (Fig. 1) that extends over a distance of approximately 1600 km (Fitton 1983;

✉ Bekoa Ateba
    b.ateba@yahoo.com

1   Institute of Geological and Mining Research (IRGM), PO Box 4110, Yaounde, Cameroon

2   Department of Physics, Faculty of Science, University of Yaounde 1, PO Box 812, Yaounde, Cameroon

3   Department of Physics, Higher Teachers College, University of Yaounde 1, Yaounde, Cameroon

Fitton and Dunlop 1985). Volcanism has been active along the CVL from Eocene and remains active to date on Mount Cameroon (Déruelle et al. 2007; Njonfang et al. 2018). For petrographic and geochemical point of view, the CVL presents a wide variety of volcanic rocks, both alkaline and transitional in nature (Nana 1988; Njilah 1991; Nkoumbou et al. 1995; Kagou et al. 2001; Moundi 2004; Fosso et al. 2005; Wandji et al. 2008; Wokwenmendam 2019). Isotopic data indicate that the rocks have a mantel origin and have undergone low crustal contamination (Jacquemin 1981; Kamgang et al. 2010).

Several hypotheses have been proposed on the origin of the CVL. The alignment of the volcanoes suggested the existence of an underlying hot spot over which the African plate was moving. Unfortunately, the age progression of volcanoes was not established as in Hawaii (Fitton and Dunlop 1985). The alignment of volcanoes could also have been guided by the presence of faults masked by lava flows (Moreau et al. 1987). According to Fitton (1983), the CVL and Benue trough belongs to the West African rift system. Other authors argue that volcanism along the CVL results from the activity of a mantle plume, or the upward limb of a small-scale convection cell
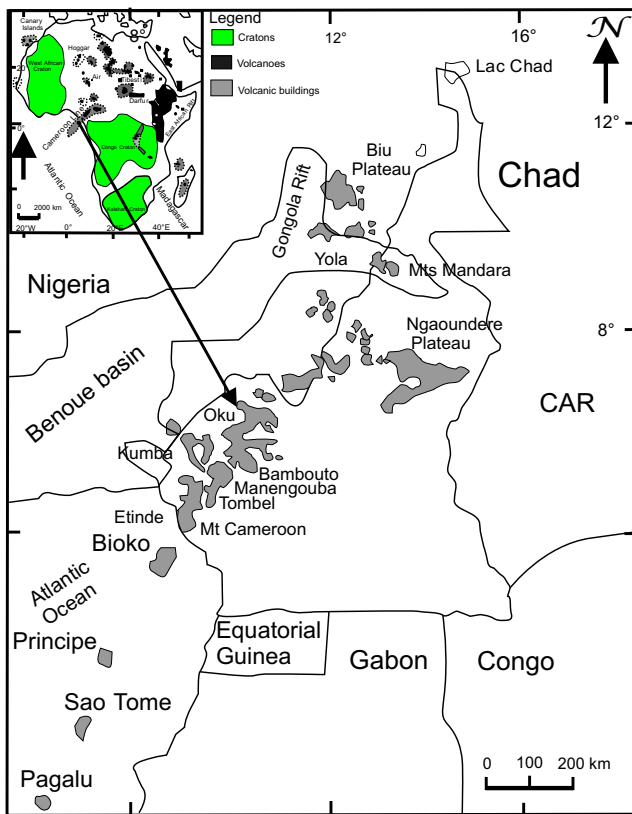
Fig. 1 The Cameroon volcanic line (redrawn from Black et al. 1985). In green are the African cratons; gray shaded areas represent volcanism

between the Congo and West African Craton (Reusch et al. 2011; De Plaen et al. 2014).

The seismicity of the Cameroon area has been studied by several authors including, among others, Ambraseys and Adams (1986), Ambeh et al. (1989), Tabod et al. (1992), Ateba and Ntepe (1997), Ateba et al. (2009), De Plaen et al. (2014), and Eloumala Onana et al. (2014). The studies concluded that seismicity is distributed along the CVL with Mount Cameroon as the most active center. The magnitude of the earthquakes is in general less than 5. During quiescent periods of the volcano, the monthly frequency of earthquakes recorded varies between 20 and 30 small magnitude (<3) events in the Mount Cameroon region. Nevertheless, stronger events have been recorded during the 1999 Mount Cameroon volcanic eruption, which resulted in damage to buildings. Five of them are listed in International Seismological Centre (ISC) bulletin. Ambeh et al. (1992) determined normal fault and strike slip focal mechanism in Mount Cameroon area.

According to the Statistical Yearbook of Cameroon, 2016 edition, the mean density of the population was 48 inhabitants/ km^2 in 2016. The regions along the CVL, due to fertile volcanic soils, attract farmers and have densities that exceed generally 100 inhabitants/km^2. Despite known seismic activity,

people continue to build houses without any respect to the building code.

In a recent study, Campbell et al. (2018) identified the main seismic sources in West Africa; CVL is one of them. They conducted a preliminary assessment of seismic hazard in major cities such as Accra, Lagos, and Douala. Two limited seismic hazard assessment studies were carried out in Cameroon: one by Sandron et al. (2018), for the construction of a deep see port in Kribi, and the other by Ngongang et al. (2018) on the Mount Cameroon region. In this study, we go beyond Mount Cameroon and focus on the densely populated mainland part of the CVL. The objective is to provide preliminary ground motion parameters that potential investors can use and to sensitize populations and local authorities. We use data from local seismicity catalogues and the results of geological and geophysical studies to delineate seismic source zones and determine their input seismic parameters needed for probabilistic seismic hazard assessment software.

Data and methods

Mainly two methods are used to assess seismic hazard: the deterministic and the probabilistic approach. In the deterministic approach (Kramer 1996), the basis is to develop earthquake scenarios, defined by location and magnitude, which could affect the site under consideration. The resulting ground motions at the site, from which the controlling event is determined, are calculated using ground motion prediction equations (GMPE) as a function of the distance from the source. The difference between the two approaches is that the probabilistic approach has units of time and deterministic does not (Bommer 2002).

Probabilistic seismic hazard assessment

For this study, we opted for the probabilistic approach. According to Barani et al. (2009), Cornell (1968) invented probabilistic seismic hazard assessment (PSHA) by introducing a method of evaluating the likelihood of exceedance (or occurrence) of any level of earthquake ground shaking at a site during a given time period. This is achieved by combining the effects of all the possible magnitudes and earthquake locations that could affect the hazard at the site investigated. Three steps are needed before the calculation (Kramer 1996): the definition of seismotectonic source zones, a model of earthquake recurrence with respect to the magnitude, and a GMPE. Then the probabilities that the ground motion intensity exceeds a certain value are computed for different time frames. Several free software are available to evaluate the seismic hazard (example OPENQUAKE, OpenSHA). For this study, we preferred CRISIS (Ordaz et al. 2015) in which many GMPEs are included.

Earthquake catalogues

The catalogue of the local seismicity is an essential element which helps to know the studied area's activity and its characteristics. In order to compile the catalogue of the continental section of the CVL, we extracted available information on seismic events that took place in our study area, from seismological bulletins distributed by international dissemination data centers, such as the ISC, the National Earthquake Information Center (NEIC), and the United States Geological Survey (USGS). It is enriched by data from local networks of the Institute of Geological and Mining Research (IRGM), as well as the locations given in some publications (Ambraseys and Adams 1986; Tabod et al. 1992) and doctoral thesis (Ambeh 1989; Bertil 1991; Nnange 1991; Ateba 2009). Depending on the source, the magnitudes are given in duration or local magnitude and also in body or surface wave's magnitude. To homogenize the catalogue, we used conversion relations to bring all the magnitudes to Mw (Hanks and Kanamori 1979; Scordilis 2006; Grünthal et al. 2009). Events of high magnitude (M≥6) are generally well catalogued. On the other hand, low magnitude events (less than 4) are not always well located by global seismological monitoring networks, but are better captured and located by local seismograph networks, like those deployed by IRGM (Fig. 2a, b).

The results of the compiled earthquake catalogue from 1900 to 2010 are shown in Fig. 3. The biggest magnitude events (Mw≥3.9) are given in Table 1. Magnitudes are less than 6, and all hypocenters are located in the crust. The strongest felt earthquake with Mw 5.3 was associated to Mount Cameroon 1999 volcanic eruption. As stated earlier, the seismicity is concentrated around Mount Cameroon region and diffuse in NE of it. The Mount Cameroon region is characterized by seismic swarms recorded in North West, South, and East flanks and summit area (Ambeh 1989; Ateba and Ntepe 1997; Ateba et al. 2000). Such earthquake swarms are not observed in the rest of CVL. Mount Cameroon region is the most active seismic zone and is the only remaining active volcano of the CVL.

Seismic source zones and seismicity model

The combination of the results of seismicity, geology, geophysics, and tectonics makes it possible to delimit the seismotectonic provinces considered seismic source zones. The first seismic source zone is depicted following the epicenters in Mount Cameroon area (Fig. 4a), excluding south and east flank where magnitudes are small (<3); moreover in the east flank, hypocenters are deep (>30 km). Located at the boundary between the continent and the ocean, Mount Cameroon is a stratovolcano of Plio-Quaternary
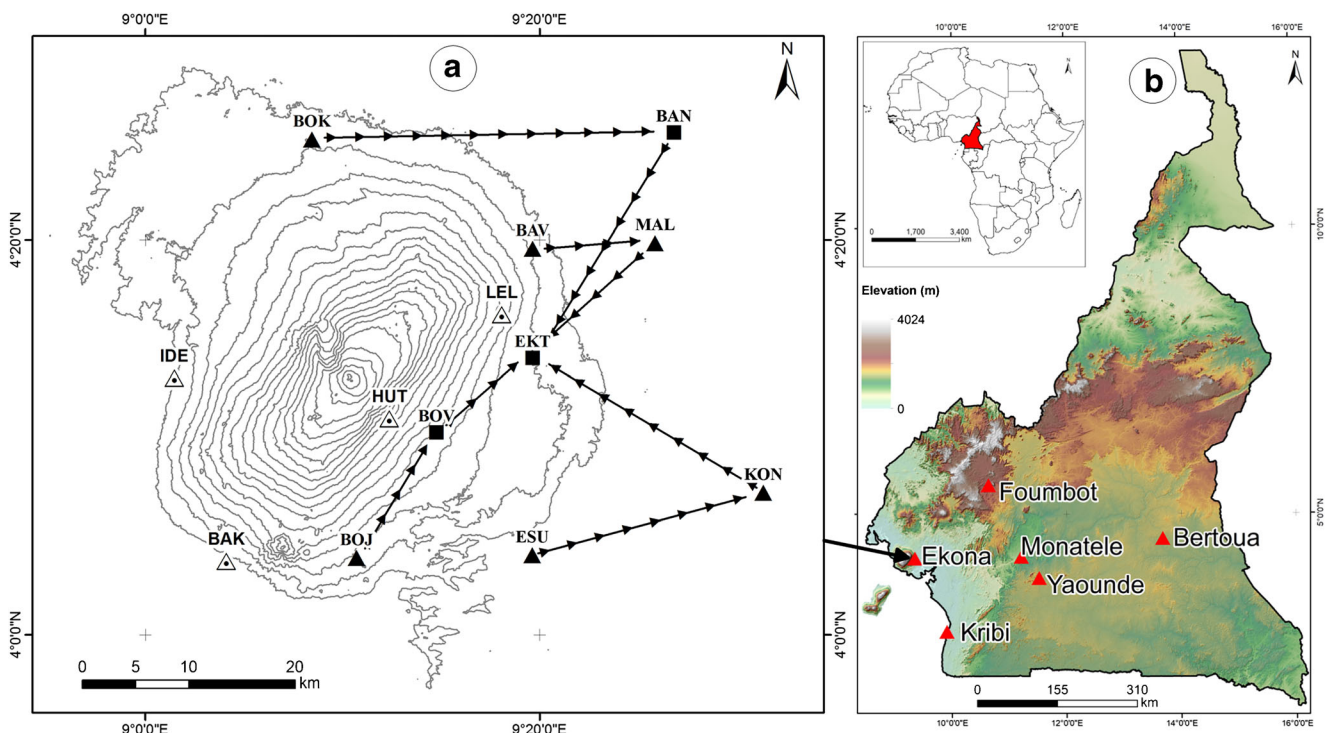

Fig. 2 Local seismic stations deployed in Cameroon by the Institute of Geological and Mining Research of Cameroon. **a** Around Mount Cameroon volcano region: filled triangles (vertical sensor), empty triangles (temporary portable seismograph), filled square (3 component sensor), difference of altitude between contours is 200 m, redrawn from Ateba et al. (2009). **b** For the rest of the country (red filled triangles)

Table 1 Main recorded earthquakes along the CVL

No	Year	Month	Day	Hr	Mn	Long	Lat	Mw	Depth
1	1907	11	16	21	0	9.600	4.600	4.8	0.0
2	1909	4	26	8	0	9.400	4.300	5.1	0.0
3	1910	2	23	1	0	9.100	4.200	4.4	0.0
4	1922	2	3	1	0	9.100	4.200	4.4	0.0
5	1969	1	24	3	30	11.100	5.400	5.2	0.0
6	1975	11	2	4	55	9.250	4.730	4.0	0.0
7	1975	11	5	7	17	9.350	4.650	3.9	0.0
8	1986	2	13	1	54	9.119	4.368	3.9	9.4
9	1990	9	20	12	13	9.070	4.331	4.2	9.8
10	1999	3	28	20	38	9.080	4.170	5.3	10.0
11	1999	3	27	18	4	9.080	4.170	5.1	10.0
12	1999	3	27	22	32	9.000	4.140	5.1	10.0
13	1999	3	28	20	12	8.850	3.770	5.1	10.0
14	1999	3	27	19	3	9.040	4.160	5.0	10.0

age (~4 100 m high). It is located between the sedimentary basins of Douala in the southeast and Rio del Rey in the northwest. The area has a thin crust of about 25 km (Tokam et al. 2010). The second seismic source zone is located in the NE of Mount Cameroon region (Fig. 4b). The seismicity is diffuse and less regular. The crust has values between 27 and 30 km (Eloumala Onana et al. 2014). The zone is characterized by Kumba and Tombel grabens. The third seismic source zone is located in Western Cameroon Highlands (altitude > 1 000 m). The seismicity is diffuse and the products of volcanic eruptions indicate ages ranging from the Eocene (52 Ma) to the Pliocene periods (Njilah 1991; Moundi et al. 2008). Many crater lakes are observed in the region of which two have been sources of gas explosions that caused loss of human and animal lives (Tanyileke et al. 2019). The geological formations made up of products of volcanic eruptions are lying on a basement rocks of plutono-metamorphic nature and of Precambrian to Pan-African

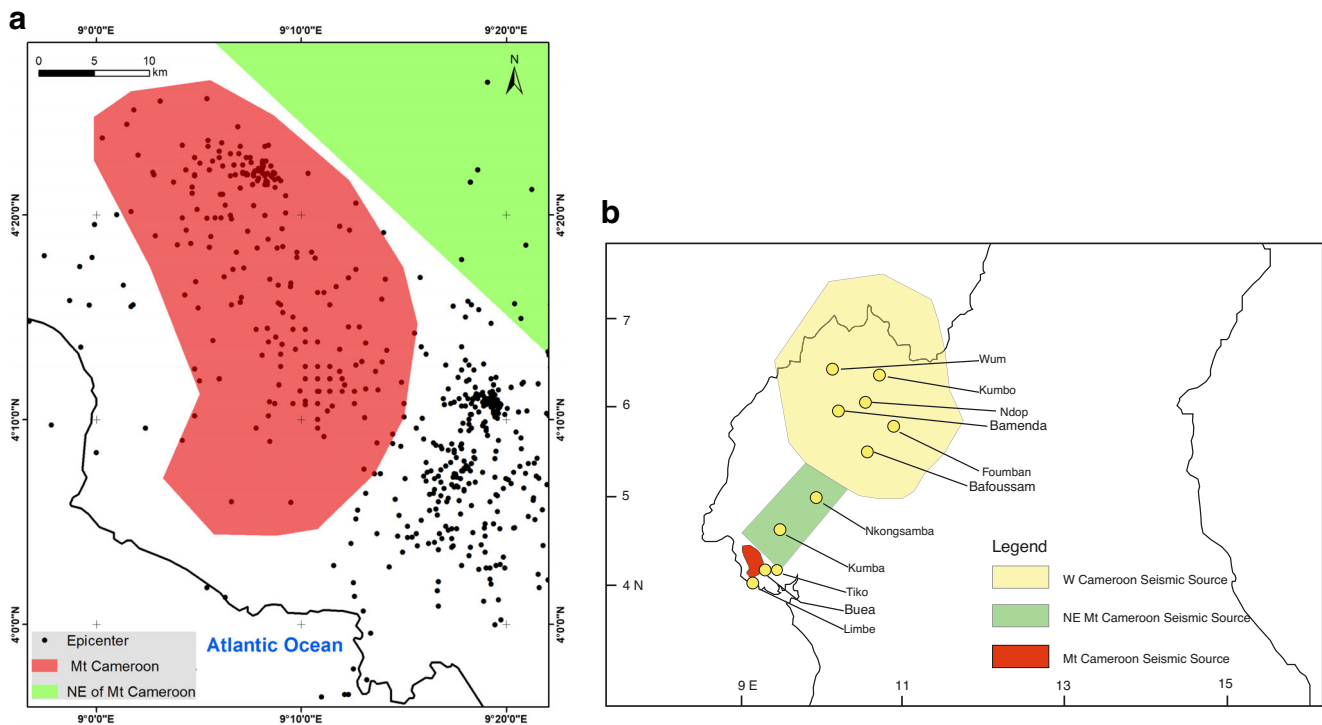**Fig. 3** Seismicity map of the western part of Cameroon, including the CVL
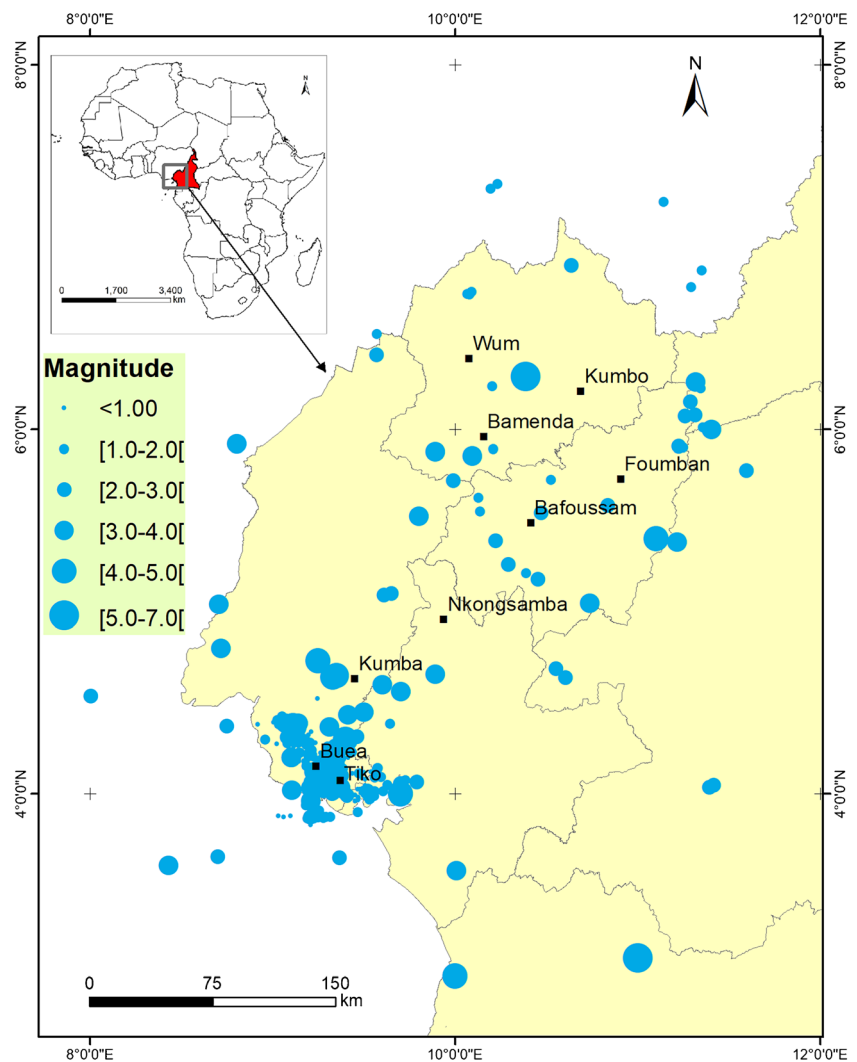
Fig. 4 Area seismic sources zones. **a** Around Mount Cameroon. **b** Along the continental section of the CVL

age (Djoukoua et al. 2008). The earth's crust in this area has a thickness of 30–32 km (Eloumala Onana et al. 2014). To summarize, two seismic sources are located on horsts structures and the third in between lies on gra-bens environment.

We assumed a seismicity governed by the Gutenberg and Richter (1954) model which states that the occurrence of earthquakes obeys the Poisson's law. Thus the earthquake events are distributed exponentially according to Eq. (1):

$$\text{Log N} = a - bM \tag{1}$$

where N is the number of earthquakes whose magnitude is greater than or equal to M and a and b are constants referred to as the a-value and the b-value.

To determine input seismic parameters used by CRISIS for each of the seismic source zones, dependent events like fore-shock, aftershocks, and seismic swarms are removed from the compiled seismic catalogue, operation known as declustering (Gardner and Knopoff 1974; Reasenberg 1985). It is per-formed using ZMAP the seismicity analysis package (Wiemer 2001). The same software is used to calculate b-value and to determine the completeness magnitude (Mc). The maximum magnitude of the seismic source zone is the observed maximum moment magnitude added 0.5Mw (Gupta 2002). The initial earthquake catalogue of close to 1000 events after declustering (Reasenberg 1985) was reduced to 679. Then, seismic input parameters were determined for each

seismic source zone. The results are summarized in Table 2. Mmax is the maximal moment magnitude; λ is the mean seis-mic activity rate. The maximum magnitudes for the seismic source zones are Mw5.8 for the first one, Mw5.3 for the sec-ond, and Mw5.7 for the third one.

Ground motion prediction equations

Recorded ground motion data are not currently available for Central and West Africa. So a specific local empirical GMPE has not yet been developed for this region (Campbell et al. 2018). For this study and to account for uncertainties associ-ated with this lack of useful data, we adopt alternative models that cover the uncertainty and are implemented in the calcula-tion using the logical tree methodology (Coppersmith and Youngs 1986). We choose the equations given by Abrahamson et al. (2014) and Boore et al. (2014). Indeed, they are implemented in CRISIS software and cover a wide range of magnitudes from 3 to 8. They are valid in the context of an active shallow crust, like in the case of the CVL.

Results

Eleven (11) major cities were selected along the CVL conti-nental section to calculate seismic hazard for 10% and 2% probability of exceedance in 50 years (or RP 475 and 2475

Table 2 Seismic input parameters of the source zones of the continental sector of the CVL

Source zone		b-value	Lamda	Mc	Mmax
1	Mount Cameroon	0.80±0.10	0.126	3.0	5.8±0.2
2	NE Mount Cameroon	0.43±0.09	0.090	3.0	5.3±0.2
3	West Cameroon	0.52±0.08	0.125	3.0	5.7±0.2

years). For this preliminary study, the sites under consideration are supposed to be located on bedrock. To account for uncertainties, a logic tree methodology is implemented for the two GMPEs, the preference goes to that giving higher intensities. Then the weights are 0.6 and 0.4, respectively, for Boore et al. (2014) and Abrahamson et al. (2014). For a return period of 475 years that serves as a reference, the PGA is around 10% *g* at Buea in the Mount Cameroon region. It decreases appreciably to values of 5% *g* (Table 3), as one moves away from the main focus, in the NE of Mount Cameroon seismic source (Kumba-Nkongsamba). In the West Cameroon seismic source (Bafoussam-Bamenda), PGA values are less than 3% *g*. For RP 2475 years, the PGA at Buea is ~25% *g* and decreases to 8% towards West Cameroon seismic source.

Hazard curves of PGA and spectral acceleration for the period 0.2 s are plotted in Fig. 5 a and b for three cities (Buea, Kumba, and Bafoussam), chosen each, in one of the seismic source zone. It shows that the seismic hazard is higher in Buea in the first seismic source zone than Kumba in the second. Bafoussam in the third seismic source has the smallest seismic hazard of the three cities. For RP 475 and RP 2475, we plotted uniform hazard spectra of the same three cities: Buea, Kumba, and Bafoussam (Fig. 6 a and b). For each city and return period, the spectral acceleration increases with the period, up to around 0.1 s, before starting to decrease as the period increases towards 1s.

Discussion

If the CVL is assumed to be a rift, one would have expected it to be the site of intense volcanism and seismicity as observed along the East African Rift System (Yang and Chen 2010). As this is not the case (Reusch et al. 2011; De Plaen et al. 2014), until recently, the CVL was not monitored by seismographs. However, volcanic activity of Mount Cameroon motivated the installment of the first network of seismographs in the volcano area in 1984. Two years later, seismological stations were extended to the north of Mount Cameroon (Fig. 2b). However, the intermittent operation of the stations due to lack of maintenance and spare parts does not allow a good continuation in the seismological data series.

The results of the PSHA depend on the choice of seismic source areas which unfortunately is not often unique. For example, two of our sources are combined into one by Eloumala et al. (2014). Under the Global Earthquake Model (GEM) project (2020), the entire CVL is part of the same source zone, which extends to neighboring Nigeria. Our results differ from those of GEM project for which the PGA around Mount Cameroon is around 3% *g* for a RP of 475 years. On the other hand further north, in the region of Bamenda-Wum, a PGA of about 1% *g* was observed. We think that in those studies, the geology and variation of the crustal structure of the region were not taken into account. Similarly, Ngongang et al. (2018) divided Mount Cameroon volcano along its major axis
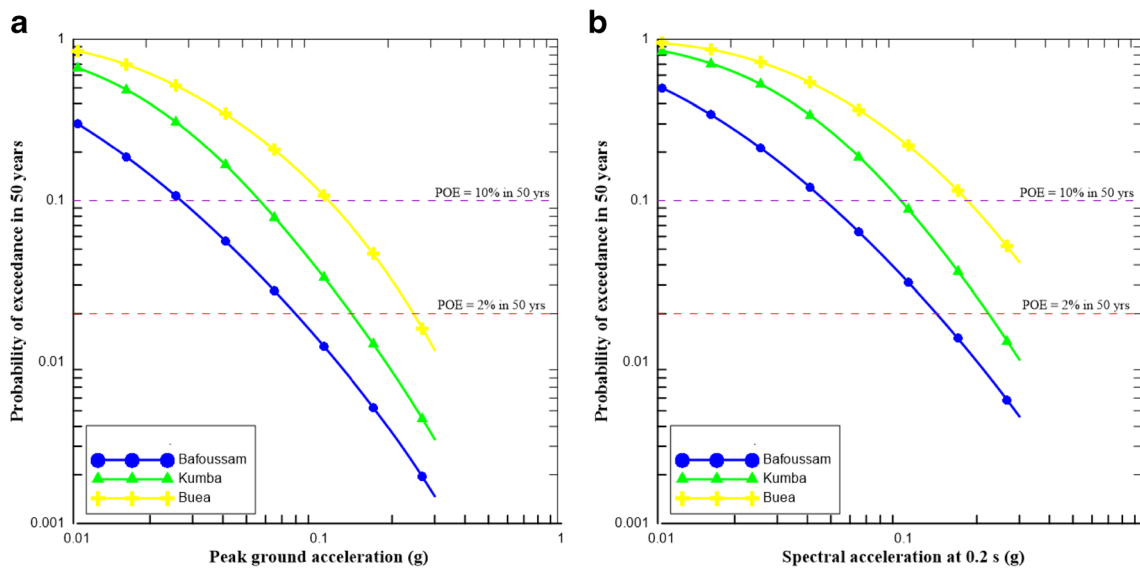
Table 3 Peak ground acceleration of main cities along the continental part of the CVL for return periods 475 and 2475 years

City	Latitude (N)	Longitude (E)	Altitude (m)	PGA (g)	
				RP 475 yr	RP 2475 yr
Buea	4.2097	9.3823	720.0	0.109	0.245
Limbe	4.0891	9.3026	90.0	0.069	0.160
Tiko	4.1626	9.4483	35.0	0.049	0.103
Kumba	4.6367	9.4517	224.0	0.057	0.136
Nkongsamba	4.9533	9.9410	827.0	0.051	0.129
Bafoussam	5.5205	10.5620	1430.0	0.025	0.079
Foumban	5.7650	10.9172	1072.0	0.027	0.080
Bamenda	5.9794	10.2263	1280.0	0.027	0.079
Ndop	6.0570	10.5083	1188.0	0.027	0.079
Kumbo	6.3521	10.6966	1866.0	0.027	0.079
Wum	6.4000	10.1633	1014.0	0.027	0.079

Fig. 5 Seismic hazard curves for PGA and 0.2s of the cities: Buea, Kumba, and Bafoussam. **a** PGA and POE (probability of exceedance). **b** Spectral acceleration for period 0.2 s

into two (E and W flanks) seismic source zones, each extending further north of the volcano, into an area where the seismic activity is probably not of the same origin as under the active volcano. Consequently, they attributed the same hazard to Kumba (in the graben), Buea (on the active volcano), and Tiko located on the Douala basin. The source of the difference in these results may be among other, linked to the selection of seismic sources zones. The PGA obtained in Kribi area by Sandron et al. (2018) for RP 475 years is almost the same like our values for Limbe and Tiko also located along the Atlantic coast. The PGA obtained by Campbell et al. (2018) is 8% *g* for RP 2475, while Tiko the nearest city to Douala for this study has a value of 10% *g* for the same life time.

We are still to investigate on faults supposed to be covered by lava flows along the CVL (Moreau et al. 1987) before taking them into consideration for the calculations of the hazards. It is likely that the faults of the Central Cameroon Shear Zone that are intersected by the CVL would influence the results.

Cities located along the CVL are experiencing a large increase in population. Unfortunately the construction of houses and associated infrastructure does not follow the urbanization plan and even less the standards of earthquake-resistant construction, especially in a city like Buea, where more and more people are constructing multistory buildings. For this reason, the results of this preliminary study should be taken into
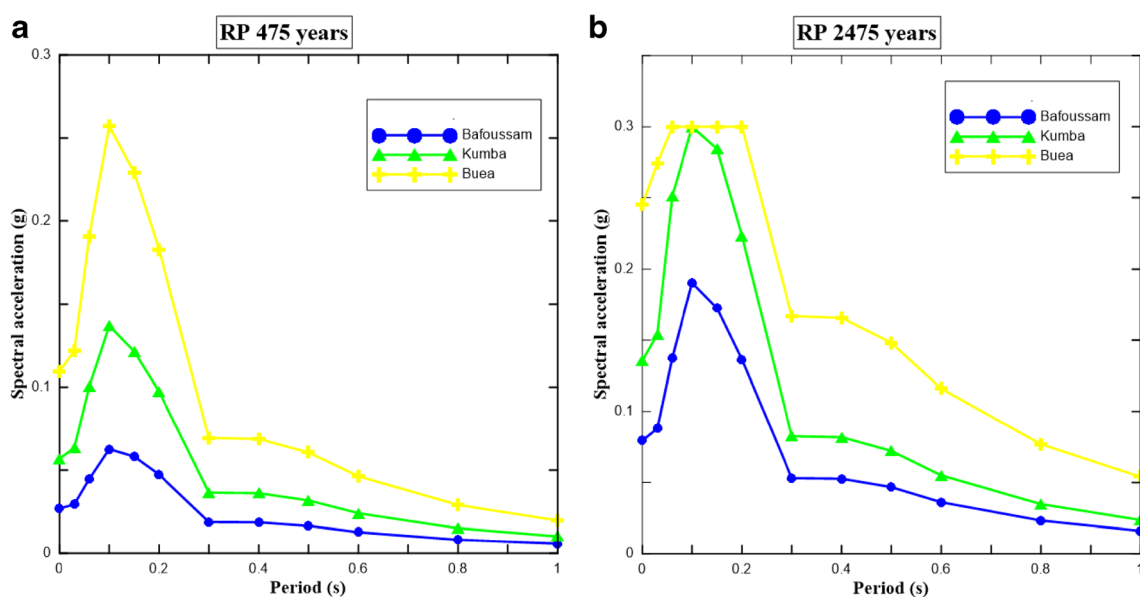

Fig. 6 Uniform hazard spectra for Buea Kumba and Bafoussam. **a** For return period 475 years. **b** For return period 2475 years

consideration by authorities in providing guidelines for the construction industry. This study is valid for basement rocks and can be backed up by site specific seismic hazard studies whose results could then be used in the seismic design of earthquake resistant structures.

Conclusions

A probabilistic seismic risk assessment has been carried out in the continental section of the CVL, a major structural feature in West Africa. We compiled from different sources a catalogue of local earthquakes and homogenized it in terms of moment magnitude. Three seismic sources area were identified using seismicity, geology, and structural analysis results. One source was in the south around the Mount Cameroon area, another to the north in the area of Monoun and Nyos crater lakes, and a third in between, an intermediate source zone. We adopted the hypothesis that the occurrence of earthquake events responds to Gutenberg and Richter law and choose two known GMPEs previously derived for active shallow crust. We used CRISIS software to calculate the PGA at the level of 11 main cities spread along the CVL, supposedly built on basement rocks, for return periods 475 and 2475 years (respectively 10% and 2% probability of exceedance in 50 years). In general, the PGA is higher in the cities located in the first source zone (10% g for RP 475 years in Buea). It decreases as one moves away from Mount Cameroon. For RP 475 years, it is less than 3% g in the third source zone (Bafoussam-Bamenda). For RP 475 and 2475 years, uniform hazard spectra plotted for three cities, Buea, Kumba, and Bafoussam located each in one seismic source zone, show that the spectral acceleration increases with the period, up to around 0.1 s, and decreases as the period increases towards 1 s. These results may change when enough data will be available on the presence of active faults in the area. Thus such values show that seismic hazard should not to be neglected along the continental sector of the CVL.

Declarations

References

Abrahamson NA, Silva WJ, Kamai R (2014) Summary of the ASK14 ground motion relation for active crustal regions. Earthquake Spectra 30:1025–1055

Ambeh WB (1989) Seismicity and seismological studies of Mount Cameroon, West Africa. PhD thesis University of Leeds. (unpubl)

Ambeh WB, Fairhead JD, Francis DJ, Nnange JM, Soba D (1989) Seismicity of the Mount Cameroon region. West Africa J Afr Earth Sci 9:1–7

Ambeh WB, Fairhead JD, Stuart W (1992) Seimotectonics of the Mt. Cameroon volcanic region, West Africa In: Gasparini, P et al. (Eds), Volcanic Seismology. IAVCEI Proc. Volcanol. 3: 45-61

Ambraseys NN, Adams RD (1986) Seismicity of West Africa. Ann Geophys 4:679–702

Ateba B (2009) La surveillance géophysique par méthode sismique d'un volcan actif comme mode pertinent de prévision d'aléas géologiques : le cas du Mont Cameroun. PhD thesis University of Yaoundé I Cameroon, 181p (Unpubl)

Ateba B, Ntepe N (1997) Post-eruptive seismic activity of Mount Cameroon (Cameroon, West Africa): A statistical analysis. J Volcanol Geotherm Res 79(1-2):25–45

Ateba B, Dorbath C, Dorbath L, Ntepe N, Frogneux M, Aka FT, Hell JV, Delmond JC, Manguelle D (2009) Eruptive and earthquake activities related to the 2000 eruption of Mount Cameroon volcano (West Africa). J Volcanol Geotherm Res 179:206–216. https://doi.org/10.1016/j.jvolgeores.2008.11.021

Barani S, Spallarossa D, Bazzuro P (2009) Disaggregation of probabilistic ground-motion hazard in Italy. Bull Seismol Soc Am 99:2638–2661

Bertil D (1991) Etude de la sismicite intraplaque en Afrique de 1'Ouest (1967-1991) à partir du réseau de stations sismologiques de Lamto Gate-d'Ivoire. PhD Thesis University of Paris 6 (unpubl.)

Black R, Lameyre J, Bonin B (1985) The structural setting of alkaline complexes. J Afr Earth Sci 3:5–16

Bommer JJ (2002) Deterministic vs. probabilistic seismic hazard assessment: an exaggerated and Obstructive dichotomy. J Earthq Eng 6(Special Issue 1):43–73

Boore DM, Stewart JO, Seyhan E, Atkinson GM (2014) NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes. Earthquake Spectra 30:1057–1085

Campbell G, Lubkowski Z, Villani M, Polidoro B (2018) A Seismic source model for West Africa. 16th European Conference on Earthquake Engneering. Thessaloniki 18-21 June 2018

Coppersmith KJ, Youngs RR (1986) Capturing uncertainty in probabilistic seismic hazard assessments within intraplate tectonic environments. Proceedings of the Third U.S. National Conference on Earthquake Engineering. Charleston, South Carolina 1: 301-312

Cornell CA (1968) Engineering seismic risk analysis. Bull Seismol Soc Am 58(5):1583–1606

De Plaen RSM, Bastow ID, Chambers EL, Keir D, Gallacher RJ, Keane J (2014) The development of magmatism along the Cameroon Volcanic Line: evidence from seismicity and seismic anisotropy. J Geophys Res Solid Earth 119:4233–4252. https://doi.org/10.1002/2013JB010583

Déruelle B, Ngounouno I, Demaiffe D (2007) The Cameroon hot line (CHL): a unique ex-ample alkaline activity of intraplate structure in both oceanic and continental lithospheres. Compt Rendus Geosci 339:589–600

Djoukoua FML, Schulz B, Schüssler U, Tchouankoue JP, Nzolang C (2008) Geochemistry of the Bafoussam Pan-African I- and S-type granitoids in western Cameroon. J Afr Earth Sci 50:148–167

Eloumala Onana PN, Mouzong PM, Ateba B (2014) Crustal structure and seismogenic zone of Cameroon: integrated seismic, geological and geophysical data. Open Journal of Earthquake Research 3:152–161. https://doi.org/10.4236/ojer.2014.34015

Fitton JG (1983) Active versus passive continental rifting: evidence from the West African rift system. Tectonophysics 94:473–481

Fitton JG, Dunlop HM (1985) The Cameroon Line, West Africa and its bearing on the origin of oceanic and continental alkali basalts. Earth Planet Sci Lett 72:23–38

Fosso J, Ménard JJ, Bardintzeff JM, Wandji P, Tchoua FM, Bellon H (2005) Les laves du mont Bangou : une première manifestation

volanique éocène, à affinité transitionnelle, de la Ligne du Cameroun. C R Géosciences 337:315–325

Gardner JK, Knopoff L (1974) Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? Bull Seismol Soc Am 64(5):1363–1367

GEM (2020) The Global Earthquake Model. Global Hazard Seismic Map. (https://maps.openquake.org/map/global-seismic-hazard-map/#5/3.960/17.578 Accessed May 11, 2020) and (https://hazard.openquake.org/gem/models/WAF/, Accessed May 11, 2020)

Grünthal G, Wahlström R, Stromeyer D (2009) The unified catalogue of earthquakes in central, northern, and northwestern Europe (CENEC)-updated and expanded to the last millennium. J Seismol, Springer Verlag 13(4):517–541. https://doi.org/10.1007/s10950-008-9144-9.hal-00535486

Gupta ID (2002) The state of the art in seismic hazard analysis. ISET J Earthq Technol 39(4):311–346

Gutenberg B, Richter CF (1954) Seismicity of the earth and associated phenomena. Princeton University Press, Pinceton

Hanks T, Kanamori H (1979) A moment magnitude scale. J Geophys Res 84:2348–2350

Jacquemin H. (1981) Contribution à l'étude géochimique des éléments en traces à la pétrogenèse des complexes anorogéniques. Exemple des massifs de Mboutou et de Golda Zuelva (Nord-Cameroun). Thèse doct. 3ème cycle, University of Nancy, France, 197p

Kagou DA, Wandji P, Pouclet A, Vicat JP, Cheilletz A, Nkouathio DG, Alexandrov P, Tchoua MF (2001) Évolution volcanologique du mont Manengouba (Ligne du Cameroun) ; nouvelles données pétrographiques, géochimiques et géochronologiques. Comptes Rendus de l'Académie des Sciences-Series IIA - Earth and Planetary Science, 333, Issue 3: 155-162

Kamgang P, Njonfang E, Nono A, Gountie DM, Tchoua FM (2010) Petrogenesis of a silicic magma system: geochemical evidence from Bamenda Mountains, NW Cameroon, Cameroon Volcanic Line. J Afr Earth Sci 58:285–304

Kramer SL (1996) Geotechnical Earthquake Engineering. Englewood Cliffs, Printice-Hill NJ

Moreau C, Regnoult JM, Deruelle B, Robineau B (1987) A new tectonic model for the Cameroon Line, Central Africa. Tectonophysics 13: 317–334

Moundi A (2004) Les basaltes des plateaux du plateau Bamoun: pétrologie, géochimie et géochronologie - Implications sur les sources des magmas, leurs contextes et évolutions géodynamiques. Thèse de Doctorat d'Etat, University of Yaoundé 1, Cameroon, 259p

Moundi A, Njilah KI, Ghogomou TR, Wokwenmendam NP (2008) New geochronological data for the continental alkaline flood basalts of the Bamoun Plateau (West Cameroon): evidence for an early alka-line volcanism of the Cameroon volcanic line. Disaster Advances 1(3):27–33

Nana JM (1988) Le complexe volcano-plutonique de Bana (Ouest-Cameroun) : géologie et pétrologie. PhD thesis, University of Paris-Sud, Orsay, 131p

Ngongang AW, Lenhardt N, Smit A (2018) Seismic hazard parameter estimation of the Mount Cameroon volcanic region (Cameroon) based on a combination of mixed catalogs. Nat Hazards 96:369–388. https://doi.org/10.1007/s11069-018-3547-x

Njilah, IK (1991) Geochemistry and petrogenesis of Tertiary-Quaternary volcanic rocks from Oku-Ndu area, N.W. Cameroon. PhD thesis, University of Leeds, 350p

Njonfang E, Laurenzi MA, Wokwenmendam NP, Cozzupoli D (2018) ^{40}Ar–^{39}Ar ages from the Sabongari and Nana igneous complexes within the central part of the Cameroon Line (Central Africa). J Afr Earth Sci 147:20–27

Nkoumbou C, Déruelle B, Velde D (1995) Petrology of Mt. Etinde neph-elinites series. J Petrol 36:373–395

Nnange JM (1991) The crustal structure of the Cameroon volcanic line and the Foumban shear zone based on gravity and aeromagnetic data. PhD thesis, University of Leeds, UK, 245p

Ordaz M, Faccioli E, Martinelli F, Aguilar A, Arboleda J, Meletti C, D'Amico V (2015) CRISIS version 2.2: computer program for computing seismic hazard. Instituto de Ingenieria, UNAM, Mexico

Reasenberg P (1985) Second-order moment of central California seismicity, 1969-82. J Geophys Res 90:5479–5495

Reusch A, Nyblade A, Tibi R, Wiens D, Shore P, Ateba B, Tabod C, Nnange JM (2011) Mantle transition zone thickness beneath Cameroon: evidence for an upper mantle origin for the Cameroon Volcanic Line. Geophys J Int 187(3):1146–1150. https://doi.org/10.1111/j.1365-246X.2011.05239.x

Sandron D, Santulin M, Tamaro A, Orci C, Benedetti G, Castellaro S, Romeo R, Rebez A, Grimaz S, Malisan P, Guadagnini G, Sciascia F, Slejko D (2018) Seismic parameter design assessment for the Kribi deep seaport in Cameroon. Bull Earthq Eng 17:1825–1861. https://doi.org/10.1007/s10518-018-0518-2

Scordilis EM (2006) Empirical global relations converting MS and mb to moment magnitude. J Seismol 10:225–236. https://doi.org/10.1007/s10950-006-9012-4

Tabod CT, Fairhead JD, Stuart GW, Ateba B, Ntepe N (1992) Seismicity of the Cameroon volcanic line, 1982-1990. Tectonophysics 212: 303–320

Tanyileke G, Ntchantcho R, Fantong WY, Aka FT, Hell JV (2019) 30 years of the Lakes Nyos and Monoun gas disasters: a scientific, technological, institutional and social adventure. J Afr Earth Sci 150:415–424. https://doi.org/10.1016/j.jafrearsci.2018.11.022

Tokam APK, Tabod CT, Nyblade A, Julià J, Wiens DA, Pasyanos ME (2010) Structure of the crust beneath Cameroon, West Africa, from the Joint Inversion of Rayleigh Wave Group Velocities and Receiver Functions. Geophys J Int 183(2):1061–1076. https://doi.org/10.1111/j.1365-246X.2010.04776.x

Wandji P, Tchokona SD, Bardintzeff JM, Bellon H, Platevoet B (2008) Rhyolites of the Mbépit Massif in the Cameroon volcanic line: an early extrusive volcanic episode of Eocene age. Mineral Petrol 94: 271–286

Wiemer S (2001) A software package to analyze seismicity: ZMAP. Seismol Res Lett 72(3):373–382. https://doi.org/10.1785/gssrl.72.3.373

Wokwenmendam NP (2019) Pétrographie, géochimie et géochronologie du complexe de Nana (plaine Tikar): implications géodynamiques et métallogéniques, PhD thesis, University of Yaounde I, Cameroon, 243p

Yang Z, Chen W-P (2010) Earthquakes along the East African Rift System: a multiscale, system-wide perspective. J Geophys Res 115:B12309. https://doi.org/10.1029/2009JB006779