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Validation of gravity data from the geopotential field model for subsurface investigation of the Cameroon Volcanic Line (Western Africa)

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Abstract

Belonging to the Cameroon Volcanic Line (CVL), the western part of Cameroon is an active volcanic zone with volcanic eruptions and deadly gas emissions. The volcanic flows generally cover areas and bury structural features like faults. Terrestrial gravity surveys can hardly cover entirely this mountainous area due to difficult accessibility. The present work aims to evaluate gravity data derived from the geopotential field model, EGM2008 to investigate the subsurface of the CVL. The methodology involves upward continuation, horizontal gradient, maxima of horizontal gradient–upward continuation combination and Euler deconvolution techniques. The lineaments map inferred from this geopotential field model confirms several known lineaments and reveals new ones covered by lava flows. The known lineaments are interpreted as faults or geological contacts such as the Foumban fault and the Pan-African Belt–Congo craton contact. The lineaments highlighted coupled with the numerous maar lakes identified in this volcanic sector attest of the vulnerability of the CVL where special attention should be given for geohazard prevention.

Keywords: Cameroon Volcanic Line, Subsurface, Gravity data, Lineaments

Introduction

The Cameroon Volcanic Line (CVL), also called the Cameroon Line (Ngako et al. 1991) or Cameroon Hot Line (Nkono et al. 2014), is made up of an alignment of mountains trending N30° and is divided into two parts: an oceanic part with volcanic islands of Gulf of Guinea and a continental part characterized by volcanic eruptions of Mount Cameroon and deadly gas emissions from lakes Monoun in 1984 and Nyos in 1986, respectively (Fig. 1). The volcanic activities observed in this continental part (lava flows, pyroclastic rocks and plugs) dates back to about 30 Ma (Dunlop and Fitton 1979). Several geological and geophysical studies have been carried out along the CVL to understand its structure, origin and evolution. The main gravity surveys in Central Africa especially were carried out by Collignon (1968), Poudjom-Djomani (1993), Poudjom-Djomani et al. (1996) and Nnange et al. (2000). Poudjom-Djomani (1993) and Marcel et al. (2010) have used these terrestrial gravity data to investigate the internal structure of the CVL and suggested a general asthenospheric uplift. Marcel et al. (2016) used gravity data derived from EGM2008 to investigate the depth of Moho discontinuity under the CVL and found values ranging from 19 to 34 km. From seismic data, Koch et al. (2012) interpreted lattice-preferred orientation frozen into the Congo Craton and subcontinental lithosphere related to relict plate motion and deformation. Moreau et al. (1987) and Nkono et al. (2014) used remote sensing and deduced the general trend of the CVL.

Volcanic flows generally cover areas where eruptions occur, which bury structural features like faults making it difficult for geological surveys to be carried out. However, geophysical studies enable to highlight structural

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features and understand the subsurface structure in such areas. For example, Noutchogwe (2010) presented a close correlation between the lineaments inferred from magnetic anomalies, the sites of thermo-mineral springs and the hydrographical network in Adamawa Cameroon. Using gravity data, Jaffal et al. (2010), Fan et al. (2014) and Abate Essi et al. (2017) showed the importance of geophysical lineaments in studying ore bodies and mineralized areas. Therefore, geophysical investigation is helpful to delineate outcropped or buried faults. The aim of this paper is to use gravity data derived from the Earth Gravitational Model EGM2008 to investigate the subsurface of the CVL with an emphasis on structural features.

Geological and structural setting

The study area comprises the main domain of the continental part of the Cameroon Volcanic Line (CVL). This volcanic line, which crosscuts the Pan-African Fold Belt, is also surrounded at its southern-eastern edge by the Congo craton (Fig. 1). The CVL is a 1600-km-long alignment of Cenozoic to recent volcanic massifs and plutons striking N30°E (Le Maréchal 1976; Déruelle et al. 1991, 2007). The oceanic section of the CVL lies within the Gulf of Guinea consisting of the islands of Pagalu, São Tomé, Principe, and Bioko, while the continental part is made of two main plateaus (Biu and Ngaoundéré) and several volcanic mountains. Main mountains are mount (Mt) Cameroon (4095 m) which is the highest and the most active volcanoes of the CVL, mainly formed by alkaline basalts (Hedberg 1968; Déruelle et al. 2007); Mt Manengouba (2420 m) characterized by basaltic, trachytic and rhyolitic formations; Mt Bambouto (2679 m) with alkaline basalts and trachytes, and Mt Oku (3011 m) consisting of transitional basalt, quartz trachyte and rhyolite flows (Tchoua 1974; Fitton and Dunlop 1985).

The continental structure of the CVL is marked by an alternation of horsts and grabens (Nkouathio et al. 2008). The horsts are made of large polygenetic volcanoes or volcanic plateaus, characterized by complete magmas series, whereas the grabens are monogenetic volcanic fields displaying basic magmas suites (basanites, basalts, and accessory hawaiites) (Tamen et al. 2007). Van Houten (1983) and Ngounouno et al. (2000) interpreted the CVL as a volcanic and subvolcanic alignment resulting from hotspot activity. Fitton (1980, 1983) presented it as an active rift system produced by a thermal anomaly in the asthenosphere. Some authors like Déruelle et al. (1991), Moreau et al. (1987) and Nkono et al. (2014) described it as the consequence of the rejuvenation of a Pan-African N70°E fracture zone which took place at the opening of the Atlantic Ocean.

The Pan-African Fold Belt of the study area (Fig. 2) includes pre, syn to late tectonic granitoids mainly calk-alkaline composition aged between 660 and 580 Ma (Toteu et al. 1987, 2004) and Neoproterozoic medium- to high-grade schists and gneisses (Koch 1953; Champetier de Ribes and Aubague 1956; Weecksteen 1957; Champetier de Ribes and Reyre 1959; Dumort 1968; Peronne 1969; Ngako 1986; Toteu et al. 2001). These Precambrian Pan-African metamorphic and plutonic formations are overlaid by a younger sedimentary cover especially at the coastal area and around Mamfe locality (cross river) which belong to the southern part of Benue Trough. The sedimentary formations are dated Cretaceous to actual (Champetier de Ribes and Reyre 1959; Popoff 1987). Pan-African Fold Belt overthrusts the northern boundary of the Congo craton composed of greenstone belt, TTG (tonalite–trondhjemite–granodiorite) aged Archean to Paleoproterozoic (Maurizot et al. 1986; Pouclet et al. 2007; Van Schmus et al. 2008; Tchameni et al. 2010).

The principal structure of the study area is the Cameroon Volcanic Line characterized by the main direction N30°. Moreau et al. (1987) represented the CVL with a set of transverse parallel fractures which are buried under volcanic lavas trending N20° to N40°. Volcanic formations are lined up toward NE–SW to NNE–SSW direction (Fig. 3). Moreover, at the Adamawa plateau (Fig. 1), volcanic line deviates to N70°. Browne and Fairhead (1983), Koch (1953) and Njonfang et al. (2008) called this brittle tectonic Central African (CASZ), or Adamawa (ASZ), or Foumban shear zone (FSZ). This major shear zone is part of the Central Cameroon shear zone (CCSZ) which extends from the Sudan region to the NE Brazil (Browne and Fairhead 1983; Van Schmus et al. 2008). Nkono et al. (2014) used Shuttle Radar Topography Mission (SRTM), Landsat satellite images and Digital Elevation Models (DEMs) to study the geodynamic setting of the CVL. They inferred two major geodynamic models: a sinistral trans-tensional strain regime on the N70° fault and a sinistral trans-tensional stress field on the N130° fault.

Another major shear zone is identified near Ngambe and Edea localities called the Rocher du Loup shear zone (RLSZ) by Ngako et al. (2008) or SW Cameroon Shear zone (SWCSZ) by Nsifa et al. (2013). It is described as a sinistral transcurrent deformation along the western border of the Congo craton.

Data and methodology

Data

In this work, we used gravity data from the geopotential field model EGM2008 released by National Geospatial Intelligence Agency (NGA), which is an improved version of the Earth Gravitational Model EGM96. EGM2008 combines marine, airborne, satellite-altimetry-derived and terrestrial gravity data (Collignon 1968;

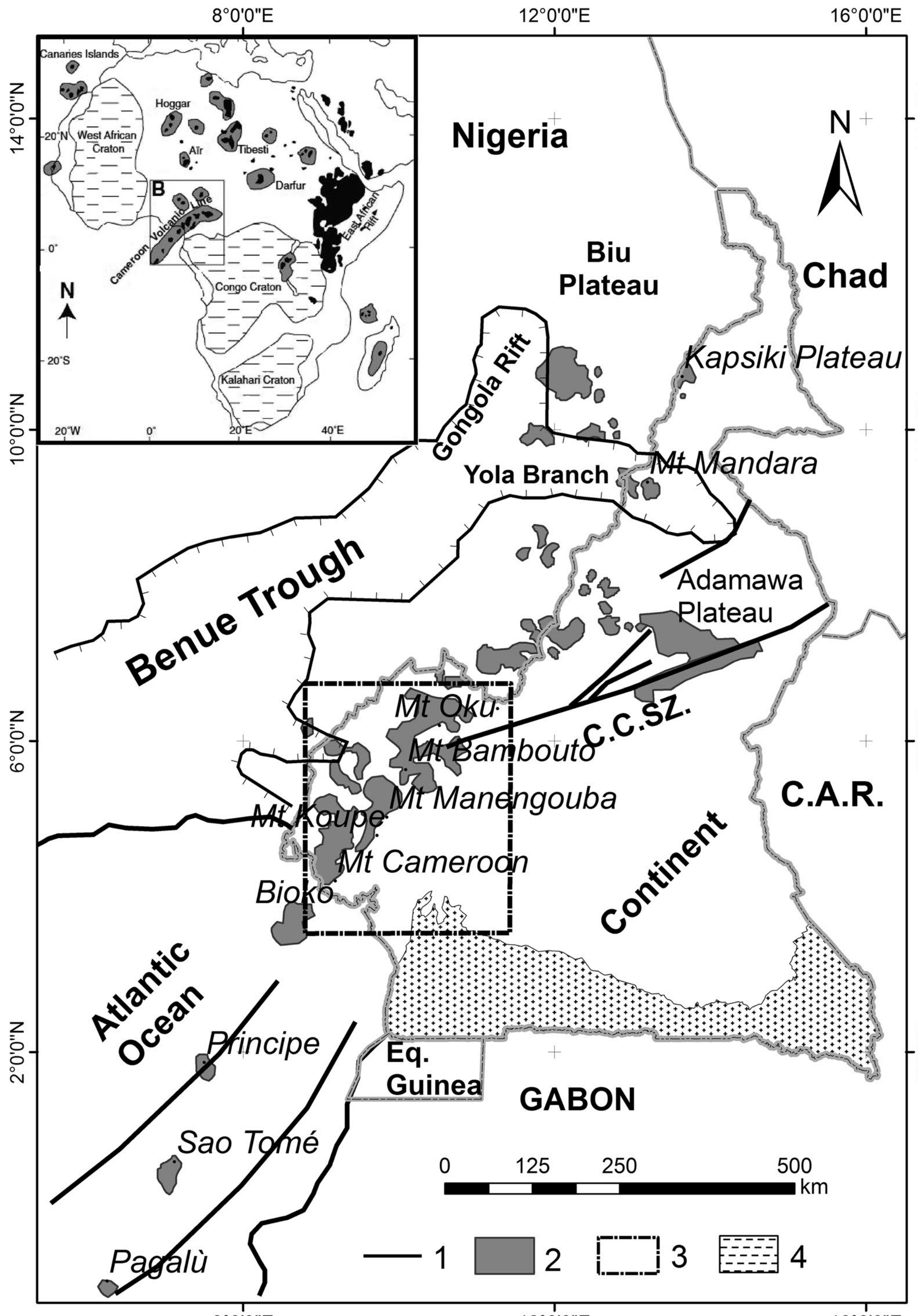

Fig. 1 Location of the Cameroon Volcanic Line. *C.A.R.* Central African Republic, *Eq.* Equatorial, *CCSZ* Central Cameroon shear zone, *1* fault, *2* Cameroon Volcanic Line, *3* Pan-African fold belt, *4* Congo craton (modified from Lee et al. 1994; Ballentine et al. 1997; Ngako et al. 2006; Nkouathio et al. 2008)

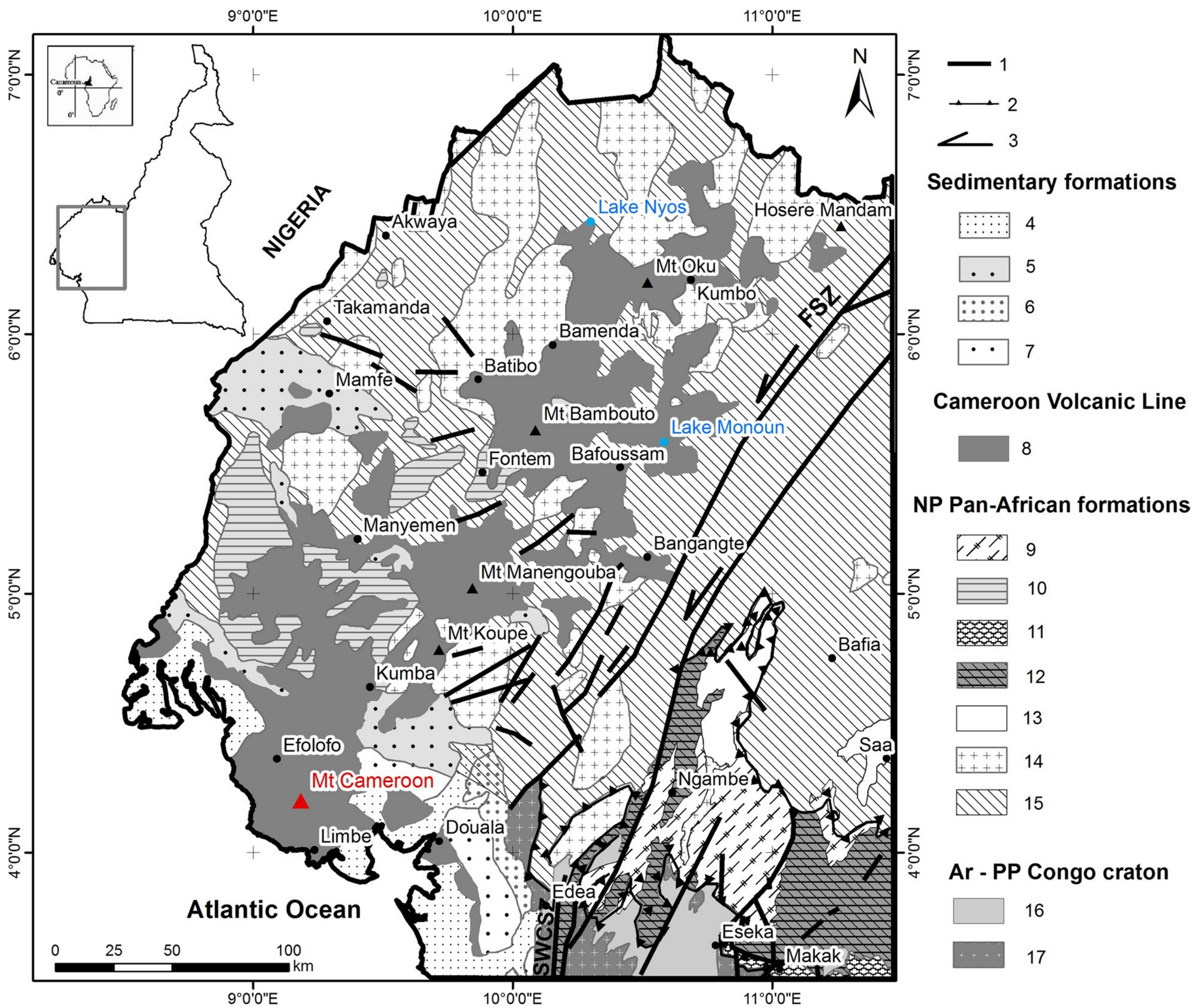

Fig. 2 Geological sketch map of the study area. *FSZ* Foumban shear Zone, *SWCSZ* South-Western Cameroon Shear zone, *NP* Neoproterozoic, *Ar* Archean, PP Paleoproterozoic, *1* fault, 2 thrust, *3* Sinistral trike slip, *4* Paleo-Neogene sand, *5* cenozoic sandstone and conglomerate, *6* upper cretaceous sandstone, *7* lower cretaceous sandstone, *8* cenozoic to actual volcanism, *9* garnetiferous gneiss, *10* lower gneiss, *11* schist from Yaounde Group, *12* gneiss and micaschist from Yaounde Group, *13* Quartzite, *14* Syn to late tectonic granitoid, *15* Pre to syn tectonic granitoid, *16* greenstone belt. Granitoid Complex of Nyong Group (modified from Koch 1953; Champetier de Ribes and Aubague 1956; Weecksteen 1957; Champetier de Ribes and Reyre 1959; Dumort 1968; Peronne 1969; Nsifa et al. 2013). The deadly maar lakes are highlighted in blue and Mount Cameroon in red

Poudjom-Djomani 1993; Poudjom-Djomani et al. 1996) to model the global gravity field with a spatial resolution of 5 by 5 arc minutes. It is complete to spherical harmonic degree and order 2159 and contains additional coefficients extending to degree 2190 and order 2159 (Pavlis et al. 2012). The spherical harmonic coefficients of the EGM2008 are used to derive a geoid referenced to WGS 1984 and to calculate free air anomalies (Eyike et al. 2010). Assuming a density of 2.67 g cm^{-3} for Bouguer slab, we applied topographic correction to free air anomalies using the digital elevation model Etopo 1 (Amante and Eakins 2008) to obtain Bouguer anomalies.

This high spatial resolution model provides a widespread information and covers areas previously lacking terrestrial data (Fig. 4). Significant similarities are found by Eyike et al. (2010) and Abate Essi et al. (2017) after comparing terrestrial gravity and EGM2008 data for Cameroon. Likewise, Marcel et al. (2016) investigated the Moho discontinuity depth along the CVL with EGM2008 data and found results in conformity

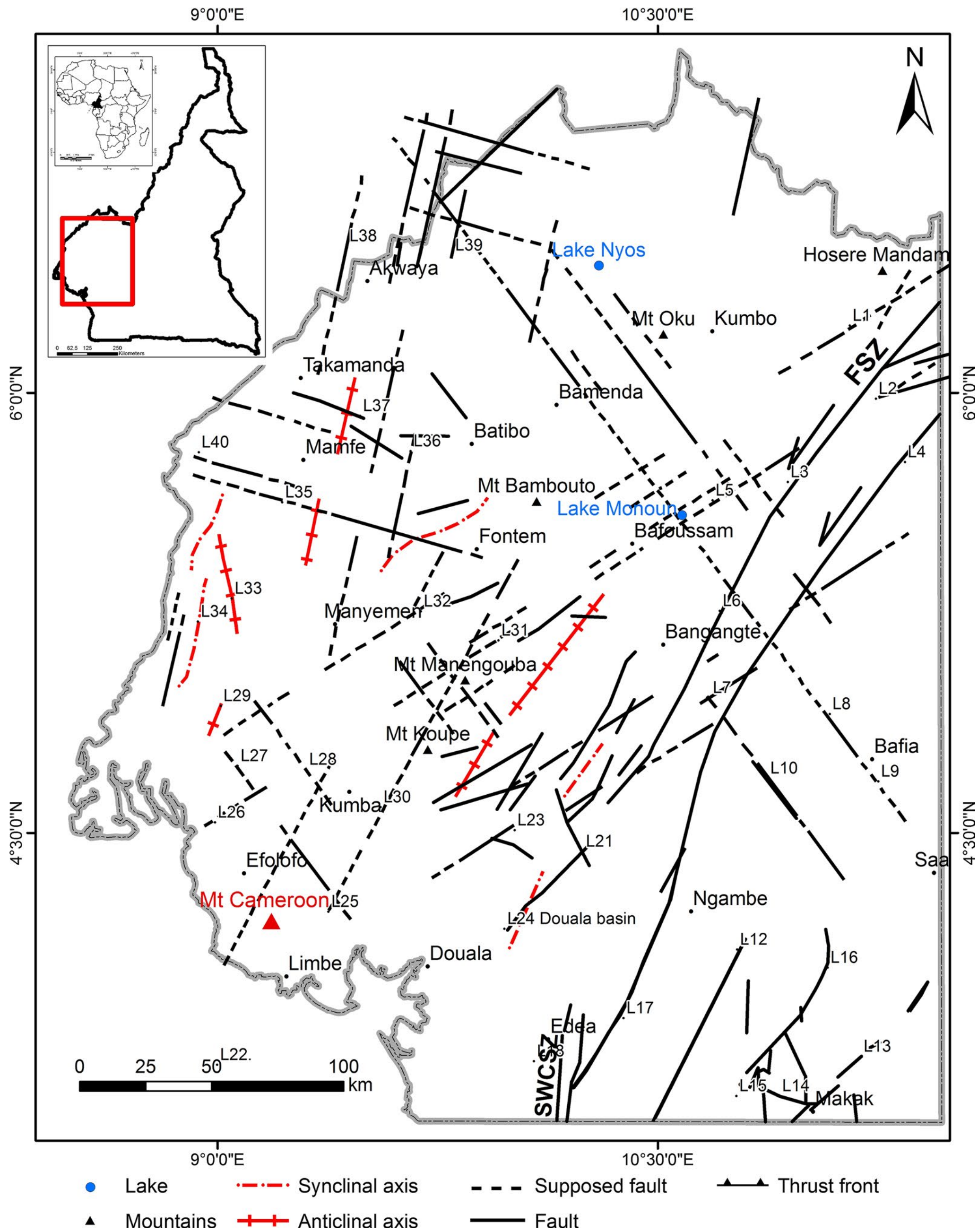

Fig. 3 Synthetic map of the main structural features obtained by previous studies in the study area (adapted from Le Maréchal 1976; Ngako et al. 2008; Van Schmus et al. 2008; Nsifa et al. 2013). The deadly maar lakes are highlighted in blue and Mount Cameroon in red

with previous studies which used terrestrial gravity and seismic data. These authors suggested that gravity data derived from EGM2008 can efficiently be used to overcome the absence and the sparseness of terrestrial gravity data. EGM2008 gravity data are therefore suitable for mountainous and volcanic areas where terrestrial gravity surveys cannot easily be covered such as the present study area.

Bouguer anomalies

The EGM2008 Bouguer anomaly map of the study area is presented in Fig. 4. The gridding method used to realize the Bouguer anomaly map is minimum curvature with a grid size of 0.01° (about 1.1 km). Ngatchou et al. (2014) have successfully experimented this grid size while studying the structure of crust beneath Cameroon from EGM2008. Gridding method generates interpolated

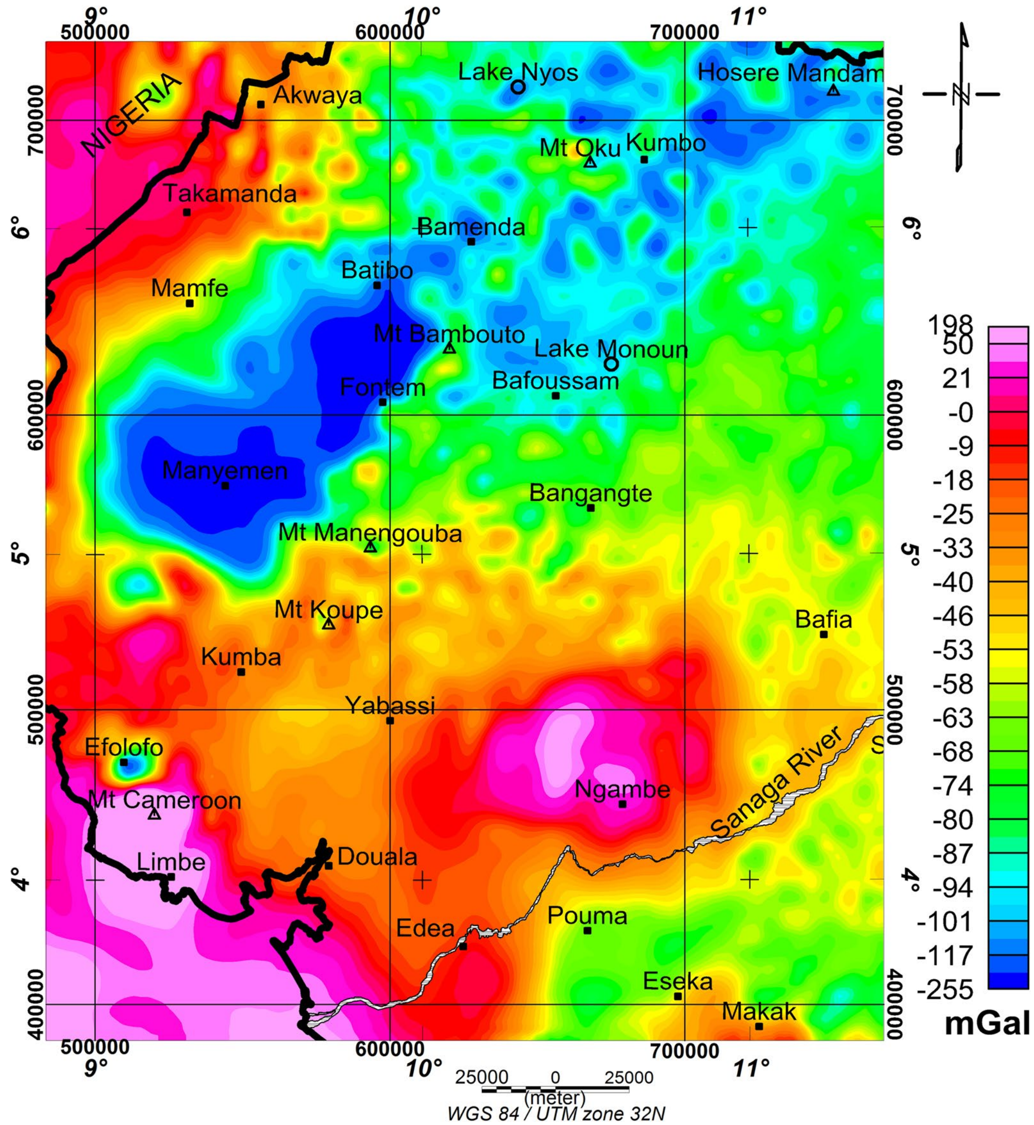

Fig. 4 Bouguer anomaly map derived from EGM2008 of the study area (modified from Marcel et al. 2016)

surface analogous to a thin, linearly elastic plate passing through each of the data values with a minimum amount of bending.

Bouguer anomaly values range from −255 to 198 mGal. From Manyemen to Hossere Mandam localities, negative anomalies (−255 to −80 mGal) appear along a corridor particularly trending NE–SW. The corridor of negative values coincides with the Cameroon Volcanic Line and a part of the sedimentary basin of Mamfe (which belongs to the southern part of Benue Trough). This corridor crosscuts an area marked by a relatively high Bouguer anomaly representing the granite–gneiss basement of Pan-African Fold Belt. The contact zone between Congo craton and Pan-African Fold Belt in Ngambe area is underlined by a positive anomaly with high amplitude (more than 100 mGal). The highest positive anomaly (greater than 150 mGal) is located in the Atlantic Ocean including Limbe and Mount Cameroon areas. From the analysis, it is possible to perform a correlation between the geological (Fig. 2) and Bouguer anomaly maps (Fig. 4).

Residual anomalies

Bouguer anomalies involve gravity signature due to the influence of both shallow and deep structures in the terrestrial subsurface. Therefore, in order to study the subsurface features, residual anomalies will be described since they provide the heterogeneity of geological formations, characterized by density variations inside the terrestrial crust (Abate Essi et al. 2017). The residual anomaly map (Fig. 5) presents values ranging from − 157 to 186 mGal mainly grouped in positive (P) and negative (N) anomalies summarized in Table 1.

Negative anomalies are nominally distinguished as N1, N2, N3 and N4. These zones referred as sedimentary basins (Fig. 5) or swamp zones, suggesting low-density materials. N1 anomaly brings out Douala sedimentary basin described as a Lower Cretaceous basin (Regnoult 1986; Nguene et al. 1992). Along Eseka and Bafia localities, negative anomalies named N2 expose low-density geological formations. This specific zone is intensely drained by Sanaga River and its tributaries, indicating that it is made of alluvias; thus, less geological outcrops are found. Both anomalies N3 and N4 represent the southern part of Benue Trough filled by cretaceous sedimentary deposits (Benkhelil 1986) of low density.

EGM2008 residual anomaly map reveals a positive anomaly (P5) with values higher than 100 mGal. In this area, the geological map (Fig. 2) exposes some granitoid intrusions. Mount Cameroon is located on a positive anomaly (P1). Similarly, successive located positive anomalies (P4) are appreciable in this volcanic area with the same orientation NE–SW of the CVL. Ngambe zone presents a circular positive anomaly around the contact between Congo craton and Pan-African Fold Belt corresponding to a particular garnet gneiss in the previous

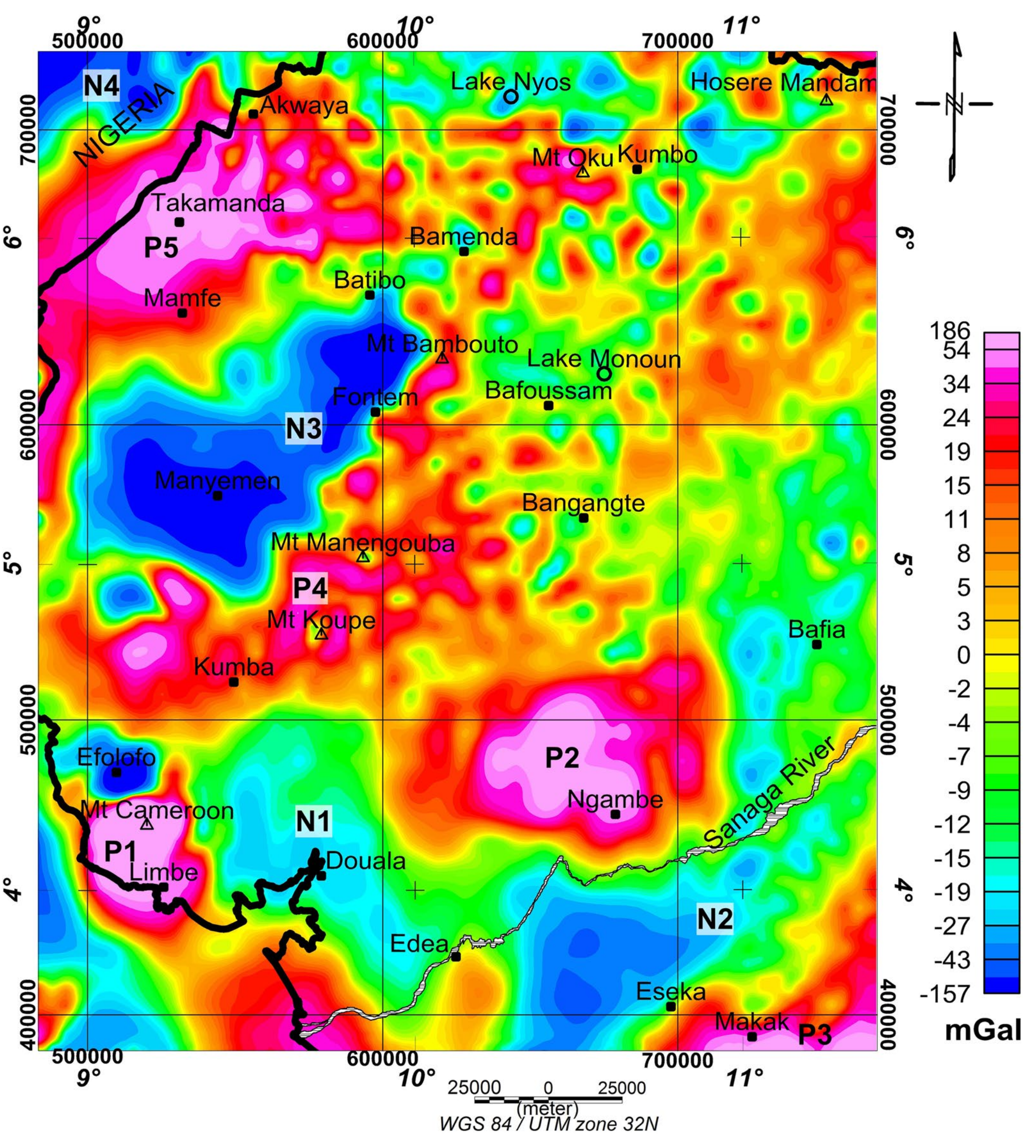

Fig. 5 Residual anomaly map of the study area. (modified from Marcel et al. 2016)

Table 1 Main gravity anomalies of residual map

Anomaly	Direction/shape	Location	Significance
N1	NW–SE	Douala	Douala Sedimentary basin
N2	N–S	Eseka-Bafia	Swamp and sedimentary alluvia (Sanaga River)
N3	NE–SW	Manyamen-Fontem	Mamfe basin (southern part of Benue Trough)
N4	Circular	North of Takamenda (Nigeria)	Benue Trough
P1	Circular	Mt Cameroon	Volcanic mountain of the CVL
P2	Circular	Ngambe	Granitoid intrusion
P3	NE–SW	East of Makak locality	Iron mineralization located at the northern edge of Congo craton
P4	Successive circular trending NE–SW	Kumba–Mt Oku	Volcanic mountains of the CVL
P5	E–W	Takamanda	Granitoid intrusion

geological map. Positive anomaly (P3) may display iron mineralization described by Ngoumou et al. (2014) around the locality of Eseka at the northern edge of Congo craton.

Methodology

Bouguer anomaly map obtained from the geopotential field data is filtered. The methodology used in this work involves a combination of techniques comprising upward continuation, horizontal gradient, maxima of horizontal gradient coupled to upward continuation technique and Euler deconvolution. This combination of techniques has the particularity in studying gravity signatures of subsurface geological features. The grid size of Bouguer anomaly map (0.01°) is maintained during the filtering.

Upward continuation

The Bouguer anomaly map is smoothed with upward continuation technique. This operation consists of the application of a low passed filter that attenuates short wavelengths while amplifying long wavelengths (Jacobsen 1987). The Jacobsen's theory suggests that the field resulting from upward continuation to a level of Z focuses on sources situated at a minimum depth of $Z_0 = 1/2Z$. Thus, this method is suitable to study deeper and major crustal structure of the regions of interest.

Horizontal gradient

Horizontal gradient is an efficient technique to delineate subsurface geological features. It highlights lineaments like fractures, faults and geological contacts characterized by local maxima of gravity field (Grauch and Cordell 1987; Philips 1998). The advantage of horizontal gradient method is its stability in the presence of noise in potential field data (Phillips 1998). Considering a gravity field $G(x, y)$, the horizontal gradient magnitude HG is given by the following expression (Philips 1998):

$$\mathrm{HG} = \sqrt{\left(\frac{\partial G}{\partial x}\right)^2 + \left(\frac{\partial G}{\partial y}\right)^2} \quad (1)$$

Maxima of horizontal gradient coupled to upward continuation method

This method combines the two techniques mentioned above. This combination is used not only to bring out lineaments but also to evaluate different dips (vertical and oblique). It entails applying the upward continuation filter to the Bouguer anomalies at progressive heights and to determine the horizontal gradient of each upward continued distance (Blakely and Simpson 1986; Everaerts and Mansy 2001; Jaffal et al. 2010; Hadhemi et al. 2016). For each upward continued map, we represent essentially the maxima of the horizontal gradient in the map (Blakely and Simpson 1986). A displacement of maxima will correspond to the dip orientation. Thus, a vertical dip will display superimposed maxima of different altitudes.

Euler deconvolution

Euler deconvolution is a semi-automatic method to estimate the position and the depth of a causative source of magnetic or gravity field (Thompson 1982; Reid et al. 1990). This method relates the gravity field and its gradient components to the location of the source of an anomaly, with the degree of homogeneity expressed as a "structural index." Thompson (1982) proposed the following homogeneity Eq. (2):

$$(x - x_0)\frac{\partial g}{\partial x} + (y - y_0)\frac{\partial g}{\partial y} + (z - z_0)\frac{\partial g}{\partial z} = -\mathrm{NG} \quad (2)$$

where (x_0, y_0, z_0) are the coordinates of the source whose gravity field (g) is detected at (x, y, z), N is the structural index interpreted as the measure of the fall-off rate of the gravity field with distance from the source. This last parameter (N) determines the dimension of a given source to bring out a specific study. For gravity data, structural index ranges from 0 to 2. However, $N=0$ implies that the gravity field is constant regardless of distance from the source model. These solutions are physically impossible for real data (Thompson 1982). Deconvolution of Euler is an adequate technique to delineate geological contact or fault with a structural index ranging between 0 and 1, but mostly near the value 0.

Results

Upward continuation for regional structure

Bouguer anomalies are submitted to upward continuation filtering at 5, 10, 20 and 40 km. This operation accentuates the effect of deep gravity sources and attenuates or even removes the influence of the superficial ones (Jacobsen 1987; Marcel et al. 2016; Abate Essi et al. 2017). Hence, this low passed filter transforms and smooths gradually the initial uneven Bouguer anomalies (Fig. 4) into smoothed anomalies highlighting regional crustal features. In Fig. 6, anomaly values range from −241 to 180 mGal (Fig. 6a) at 5 km upward continued distance, afterward −135 to 80 mGal at 10 km upward continued distance (Fig. 6b), then vary between −104 and 61 mGal at 20 km upward continued distance (Fig. 6c) and finally extend from −105 to 46 mGal (Fig. 6d). Superficial and individual anomalies are unified proportionately with the upward continuation distance. Regional structure of the study area is very well exposed on negative anomalies around Manyemen till Hossere Mandam localities (Fig. 6c, d). This regional structure trends approximatively NNE–SSW direction corresponding to the CVL orientation. In a similar manner, the oceanic part of the CVL, carrying Mount Cameroon, in the upward continuation maps presents a protuberance at Ngambe locality running parallel to the major orientation.

Horizontal gradient

Horizontal gradient is performed in Fig. 7. It is assumed that the maxima of magnitude (Blakely and Simpson 1986) is located where steep density contrasts. Horizontal gradient peaks are therefore interpreted as geological structures such as geological contacts or faults (Jaffal et al. 2010; Hadhemi et al. 2016). The geometry of horizontal gradient peaks is very characteristic of the highlighted element. Furthermore, an elongated and more or less rectilinear peak can easily tally with a fault, whereas a curved or circular peak contour will refer to geological contact of an igneous intrusion, dome or diapir.

Figure 7 presents the horizontal gradient of the study area obtained from the Bouguer anomalies of the study area (Fig. 4). Mount Cameroon and Ngambe localities expose heavy-density materials. Referring to geological map (Fig. 3), Mount Cameroon is made of extrusive volcanic deposits, while Ngambe area carries garnetiferous metamorphic formations. The eastern part of Sanaga River presents water flow related to a NE–SW fault.

Several horizontal gradient maxima (some are curvilinear and others are linear) are located along the Cameroon Volcanic Line. This result demonstrates that the CVL is a fractured zone and consists of mountains represented by circular signature. Moreover, Benue Trough coming from Nigeria is evidently revealed around Mamfe and Takamanda zones. Boundary of Manyemen gneiss is revealed in Fig. 2 although partially covered at the surface by volcanic flows of the CVL. Along the western part of Douala and Edea localities, we identify the limits of the Douala sedimentary basin.

Maxima of horizontal gradient coupled with upward continuation

Figure 8 shows the results of the combination of upward continuation and horizontal gradient technique. In this map, a progressive and regular distance of upward continuation is defined at every 1 km and the maximum upward height is 10 km. Maxima of horizontal gradient for each prolonged distance have a unique color.

A general overview of this map helps to assert that the littoral zone of the study area (SW of Edea, SW of Douala, SW of Mount Cameroon) shows lineaments dipping W to SW. The sedimentary areas highlight very few lineaments especially in Douala basin and Benue Trough (North of Efolofo and Mamfe areas). Concerning the CVL area, we note abundant fractures with both inclined and vertical dips. Deadly lakes (Nyos and Monoun) are located on this fractured area. The zone carrying Lake Nyos is characterized by the deepest maxima down to 10 km.

Euler deconvolution

The Euler deconvolution based on homogeneity equation (Thompson 1982; Keating 1998) is another tool used to delineate structures. This technique gives the geographic positions and the depth of gravity sources. We performed a window cell of 15×15 km to solve the equation with a structural index of 0.1. This structural index is chosen near zero because it helps to highlight subsurface contacts or faults. Figure 9 illustrates the results of Euler's solutions of the study area. The depth ranges between 1 km to 10 km, with a mean value of 4227 m and standard deviation of 2288 m. Sources of gravity field are not equally distributed in the map although some interesting lineaments can be observed. Littoral zone (the western part of Douala and Edea localities) presents a deep lineament trending NW–SE corresponding to the limit of the Douala sedimentary basin. Likewise, Sanaga River flows on fractured zones, deeper in the delta than in the inner continent. Fractures of the CVL distinguish themselves

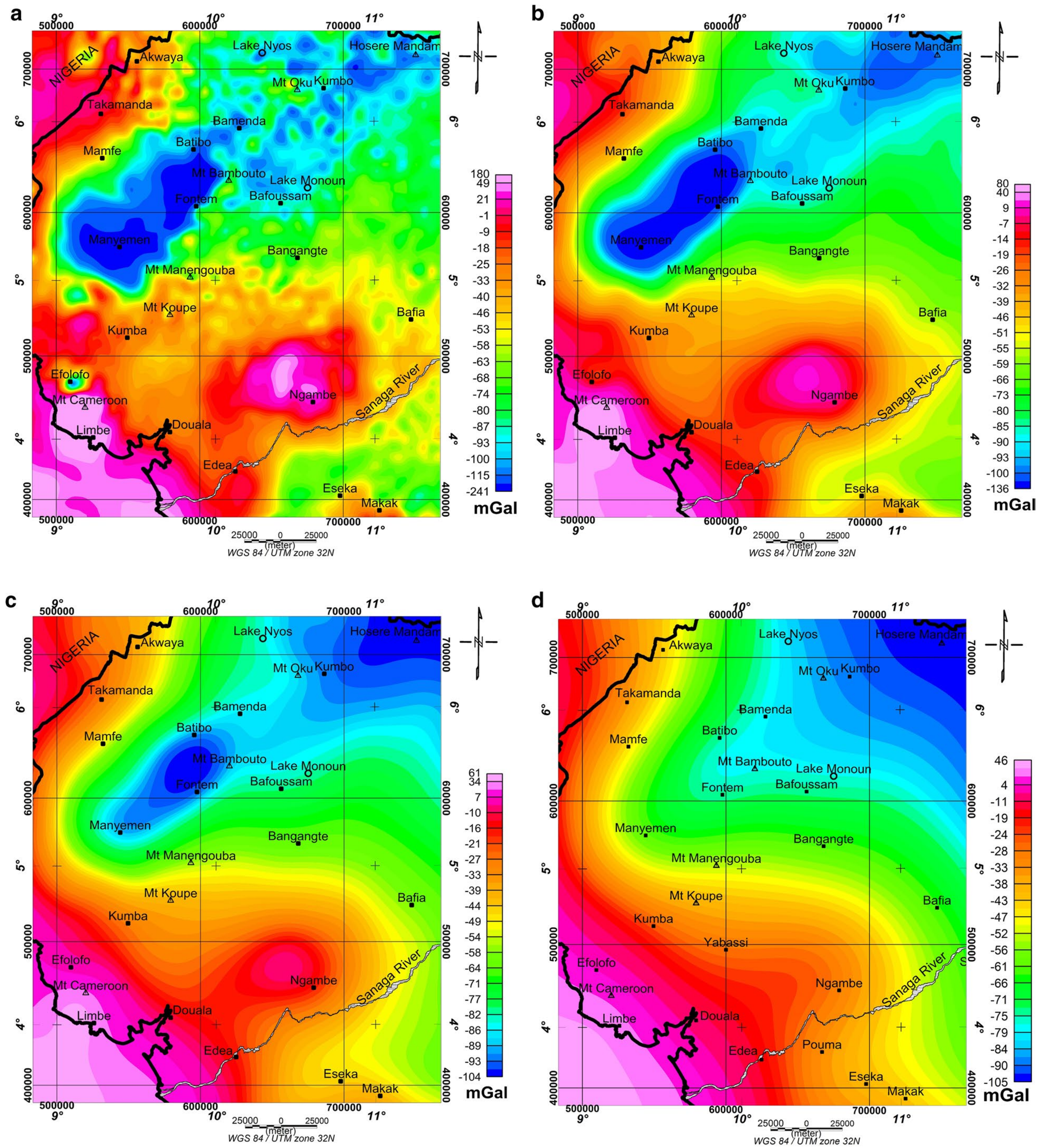

Fig. 6 Upward continued map at 5 (**a**), 10 (**b**), 20 (**c**) and 40 km (**d**)

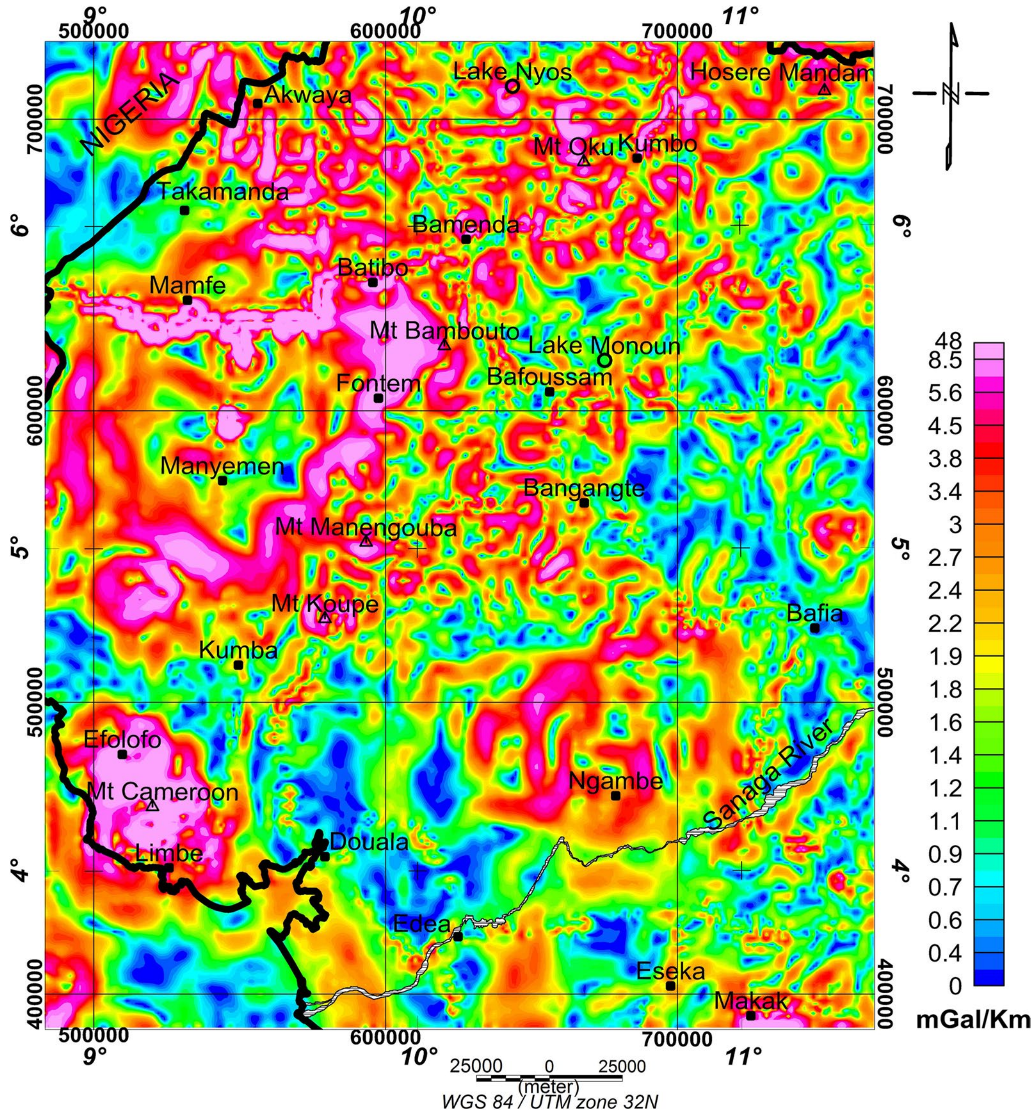

Fig. 7 Horizontal gradient map of the study area

in Limbe, Mount Cameroon, Fontem and Mount Bamboutos localities. On the western side of the CVL, deed fractures trending N–S and covered by Benue Trough sediments are highlighted.

Discussion

Validation of results

This work was carried out in an area where volcanic activities are still active (materialized by gas emissions in lakes Nyos and Monoun, and eruptions in Mount Cameroon). Based on the identification of known geological features, the main findings demonstrate the reliability of the gravity data derived from the Earth Gravitational Model EGM2008. Ground gravity data are usual tools to study the subsurface of terrestrial crust (Poudjom-Djomani 1993; Marcel et al. 2010; Jaffal et al. 2010; Hadhemi et al. 2016). The study area comprises volcanic mountains which are hardly surveyed by ground gravity campaigns. It presents therefore an actual challenge for a continuous spatial investigation. The Earth gravitational Model EGM2008 which integrates terrestrial and satellite gravity data enables to overcome the sparseness in gravity maps due to lack of data.

Upward continued maps highlighted a NE–SW trending regional structure which corresponds to the CVL direction (Le Maréchal 1976). Besides, subsurface formations of previous geological studies are well expressed through residual anomaly map. Gravity data derived from

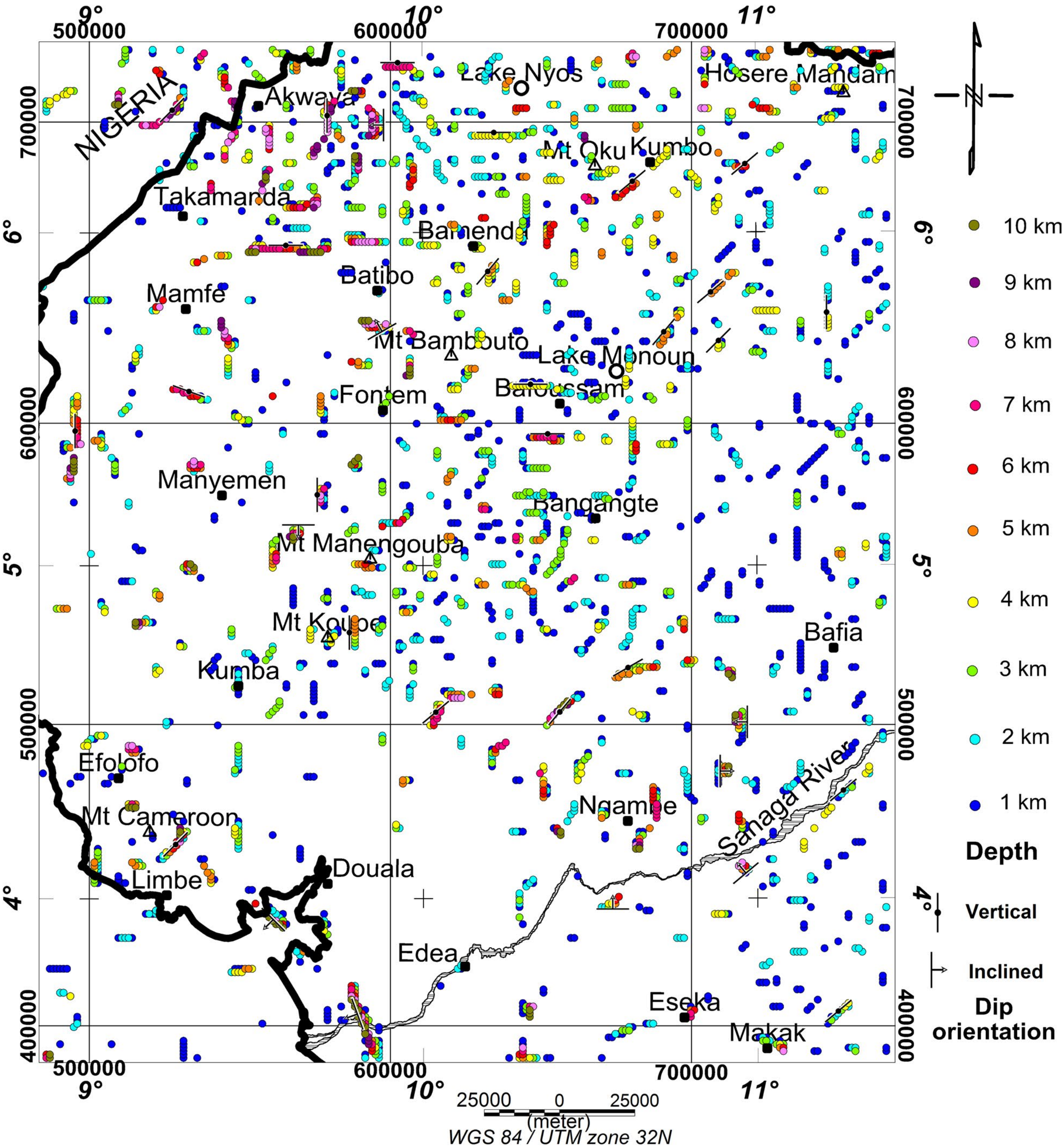

Fig. 8 Map of horizontal gradient maxima derived from upward continuation at different heights

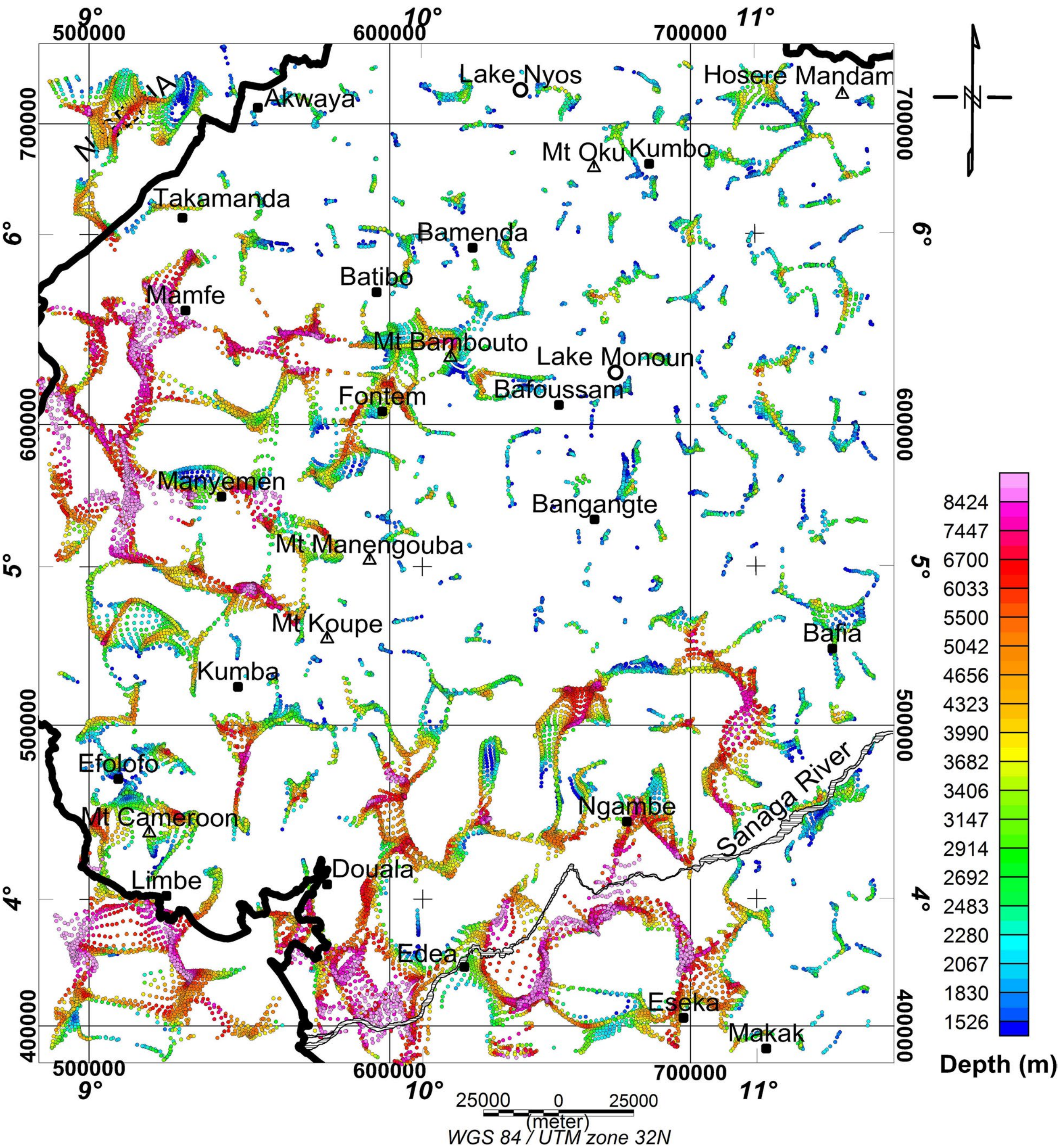

Fig. 9 Deconvolution Euler map with a structural index of 0.1

EGM2008 expose efficiently the geophysical response of the geology in the area of study. Located dense materials of volcanic formations like basalts (Telford et al. 1990) are aligned in the same direction with the CVL (N30°). This residual anomaly map presents obviously sedimentary basin characterized by low amplitude anomaly such as Douala basin filled by cretaceous deposits (Regnoult 1986; Nguene et al. 1992) and the cretaceous Benue

Trough. Positive residual anomaly of Ngambe exposes the garnetiferous gneiss. Abate Essi (2010) studied the density of diverse geological formations of Pan-African Fold Belt and showed that garnetiferous gneiss of Yaoundé Group and especially where there is intense accumulation of garnet called garnetite or garnet rock has high density above 3 g/cm^3. EGM2008 is therefore useful for geological investigation based on rock density variation. Furthermore, horizontal gradient maxima derived from upward continuation at different heights and deconvolution of Euler enable to characterize some structural linear features. These two last techniques present approximately similar limit depth of features at 10 km. The lineaments highlighted in this work are discussed in the next section.

Structural contribution

Previous works on the CVL put in evidence lineaments (Fig. 2) like faults using geological surveys (Ngako et al. 2006; Nkouathio et al. 2008; Nsifa et al. 2013) and remote sensing interpretation (Moreau et al. 1986; Nkono et al. 2014). The CVL is made of Cenozoic to recent volcanic lavas that assuredly buried fractures. Geopotential field data especially gravity data derived from EGM2008 (Pavlis et al. 2012) in our case enable to delineate some shallow structures based on density variations of geological bodies within the crust. Figure 10 presents lineaments deduced from the combination of different techniques used in this work (horizontal gradient, horizontal gradient maxima coupled with the upward continuation, Euler deconvolution). This map brings out well-known lineaments and reveals new ones. The confirmation of known lineaments demonstrates the efficiency of the geopotential model EGM2008 to highlight subsurface linear features interpreted as faults or geological contacts. Consequently, regional structural analysis in mountainous zones can be performed with the help of gravity data derived from EGM2008. Hence, a synoptic table (Table 2) summarizes interesting lineaments in accordance with previous works.

Lineaments L2 and L3 follow an ENE–WSW and NE–SW directions, respectively. They tally the Foumban shear zone representing the ending of Central Africa shear zone CASZ (Ngako et al. 1991, Njonfang et al. 2008). Sanaga River is delineated by lineaments L11- and L16-oriented NE–SW. Lineament L18 trending N–S superimposes the South-Western Cameroon shear zone (SWCSZ) and corresponds to a deep fault (Euler deconvolution displayed approximatively 8 km of depth). Besides, another deep fracture trending NW–SE is detected at the contact ocean-continent (lineament L20); therein, the maxima of horizontal gradient coupled with upward continuation method reveal its westward dip. At the east side of L20, the contact between sedimentary basin of Douala and Pan-African Fold Belt is put in evidence under L24. L22 is oriented NE–SW and represents a lineament crossing the Bioko volcanic island. The northern edge of Congo craton in contact with Pan-African Fold Belt describes a thrust front (Ngako et al. 2008; Toteu et al. 2001) whither L15, L17, L19 are highlighted with a NE–SW orientation. In the Pan-African Fold Belt around Hosere Mandam, the geological contact between granite and high-grade gneiss, put in evidence by Koch (1953), is confirmed in this study with lineament L1 trending NE–SW. In addition, NE–SW Benekuma fault, N–S Mundemba anticlinal, Bikoki anticlinal as well as anticlinal in Takamanda granite are identified in this work by L39, L34, L33 and L37, respectively. Sedimentary basin of Mamfe, the southern part of Benue Trough, underlines lineament L40.

The statistical analysis is performed in the rose diagram (Fig. 11). This diagram includes confirmed and revealed lineaments. It translates widely the CVL direction as the major tectonic feature of the study area trending NE–SW.

The new lineaments revealed in this study added to the previous ones show that the study area is very fractured. The findings of this study provide an opportunity for more research on the CVL. Some of the previous lineaments (Fig. 3) have not been highlighted in this study. This may be due to the resolution of EGM2008 (5 arcminutes) which may not be suitable to locate and detect more detailed information of the subsurface. Other techniques such as seismic, aeromagnetic investigations, satellite imagery, ground geological verification, etc. can be integrated for more efficient results. However, this statistical result of lineaments (Fig. 11) confirms the reliability of EGM2008.

Geohazard and land-use: development planning implications

Numerous lineaments are highlighted in this continental part of the CVL. Many of them confirm earlier studies while other ones are revealed. They generally refer to faults or geological contacts as described above. These lineaments express locally weakness zones of the subsurface in the terrestrial crust. Tamen et al. (2007) suggest that lineaments in the basement rocks work as pathways for magma ascent. In the study area, two different types of volcanic activities still occur: volcanic eruptions in Mount Cameroon (latest eruptions in 2000, 1999, 1982) and the famous deadly gas emissions from maar lakes of Monoun (in 1984) and Nyos (in 1986). It is also important to point here that several other maars are numbered in this volcanic sector. Maar defines shallow volcanic craters with steep sides. Some of the CVL maars have been studied: Nyos (Lockwood and Rubin 1989), Barombi

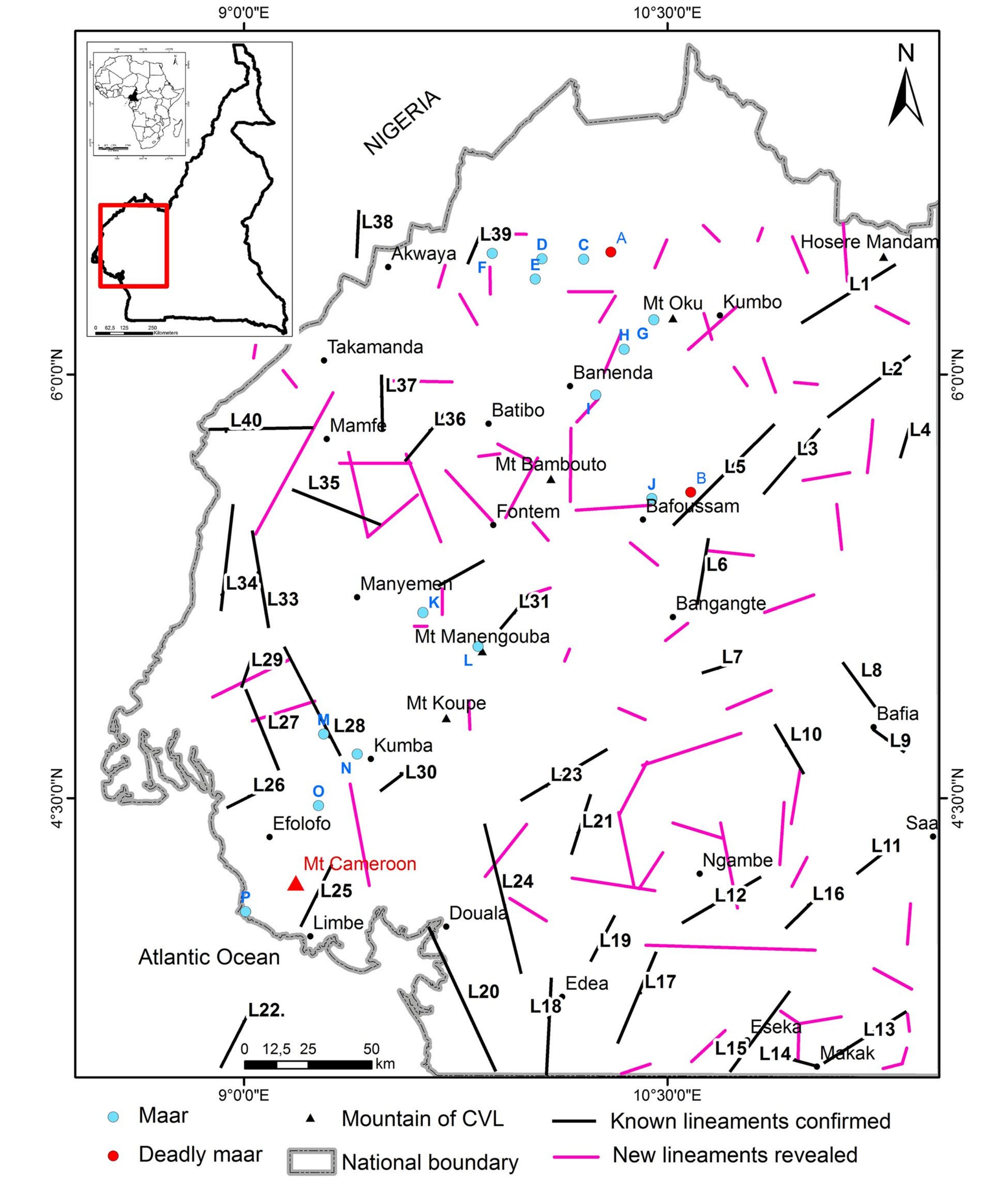

Fig. 10 Lineaments extracted from gravity data derived from EGM2008. Maars of study area (*A* Nyos maars, *B* Monoun, *C* Mbulom, *D* Wum maar, *E* Mbellifang maar, *F* Benakuma, *G* Oku maar, *H* Sabga maar, *I* Bambili maar, *J* Baleng, *K* Beme, *L* Manengouba maar, *M* Bikoki maar, *N* Barombi maar, *O* Barombi Koto maar, *P* Debunscha) The deadly maar lakes and Mount Cameroon are highlighted in red

Table 2 Summary of main lineaments identified in the study area

Lineaments	Trend	Significance
L20	NW–SE	Boundary fault continent—ocean
L24	N–S	Limit Douala sedimentary basin—Pan-African belt
L15, L17, L19	NE–SW	Contact Pan-African Belt—Congo craton
L11, L16	NE–SW	Sanaga River fault
L18	N–S	SW Cameroon SZ
L22	NE–SW	Lineament of Bioko island
L34	N–S	Mundemba synclinal
L33	N–S	Bikoki Anticlinal
L40	E–W	Mamfé lineament
L37	N–S	Granit anticlinal of SE Takamanda
L39	NE–SW	Benekuma fault
L1	NE–SW	Geological contact granite—high-grade gneiss
L2, L3	ENE–WSW to NE–SW	Foumban SZ (CASZ)

Koto (Tamen et al. 2007), Debunschar (Ngwa et al. 2017). The multitude of lineaments puts in evidence in this work attest of the vulnerability of this sector. Thus, special attention should be paid on this zone for geohazard prevention.

Conclusion

The filtering of gravity data derived from EGM2008 is efficient to explore the Cameroon Volcanic Line. Its NE–SW direction is the main structural feature revealed as confirmed by the rose diagram. In addition, important faults like Foumban (Central Africa) and SW Cameroon shear zones or the contact between Pan-African Fold Belt and Congo craton provide the reliability of this methodological approach. A correspondence is found between gravity anomalies and geological formations. This work corroborates once more the vulnerability of the CVL zone. The distribution of faults and maar lakes shows that special attention should be paid in this sector to prevent

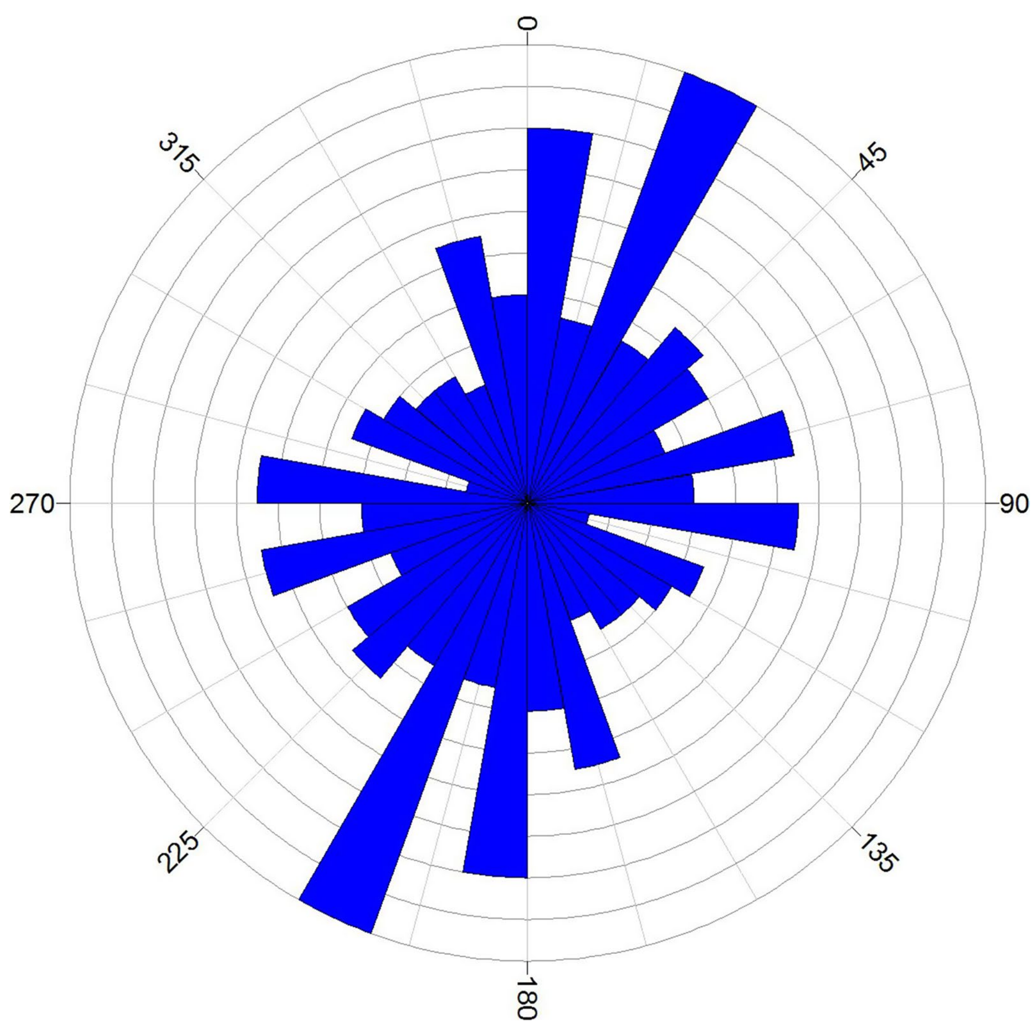

Fig. 11 Rose diagram of lineaments revealed by this work

natural disasters such as gas emissions of “asleep” maars. The earth gravity model EGM2008 resulting of the combination of terrestrial and altimetry-derived gravity data is therefore advantageous for subsurface investigations in volcanic mountainous areas as the CVL where terrestrial gravity surveys cannot easily reach.

Authors’ contributions

JM conceived of the methodology of data analyses and interpreted geophysical maps. JMAE contributed to the geological aspect of the paper and generated maps. JM and JMAE wrote the first draft of the paper. PN performed critics and improved the interpretation of results. OS participated in designing this study. EM supervised the work and revised the paper. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Ethics approval and consent to participate

Not applicable.

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