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Mapping of major tectonic lineaments across Cameroon using potential field data

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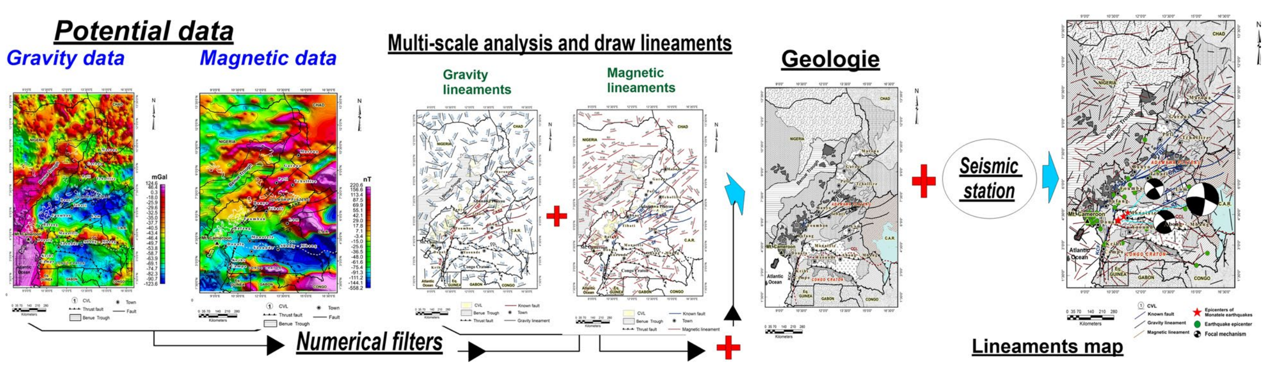
Abstract

The cartography of lineaments across a territory can be optimized using geophysical potential field data. In this study, land gravity and EMAG2 (Earth Magnetic Anomaly Grid) data were simultaneously used to identify and characterize the major lineaments that spread across Cameroon. The data were filtered using a multi-scale approach including horizontal and vertical gradient analyses. The Euler Deconvolution method was later applied to the filtered data to estimate the extension and depth of the identified lineaments. Results show that the main lineaments across Cameroon are laterally extended with a dominant N45°E orientation. Some of these lineaments correlated well with the geographical location of some known major tectonic structures found across the country. The depth of these lineaments varies between 1 and 35 km. Some of the identified faults are still active as their location correlated with the location of some recent earthquakes that occurred in Cameroon. This work, therefore, highlights some hidden tectonic features which knowledge generally precedes exploration for subsurface resources.

Keywords: Gravity anomaly, Magnetic anomaly, Filter, Lineaments, Depth

Graphical Abstract



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Introduction

The presence of lineaments on the continental landscape is generally a surface expression of more complicated processes occurring under the subsurface. These processes can be triggered by convection in the Earth mantle or chemical and thermo-mechanical activities within the crust. The Precambrian rocks in Central Africa consist of geological structures whose ages range from Paleoarchean to Neoproterozoic. In Cameroon, the crust is characterized by two main geological structures, namely, the Pan-African Mobile Belt (PMB) in the north and the Congo Craton (CC) in the south (Poidevin 1983; Nzenti et al. 1988; Fig. 1). The PMB is affected by a certain structural features such as: the Sanaga Fault (SF), Central African Shear Zones (CASZ), the Tchollire Banyo Fault (TBF), the Cameroon Volcanic Line (CVL), the Kribi Campo Fault (KCF) and the Adamawa Plateau (Koch 1959; Le Fur 1971; Toteu et al. 1984). These main features have been partially modeled using gravity (Kamguia et al.2005; Tadjou et al. 2009; Koumetio et al. 2012; Owona Angue et al. 2013; Nguiya et al. 2018), magnetic (Ndougsa-Mbarga et al. 2011) and seismic (Fairhead and Okereke 1987; Reusch et al. 2010; Tokam et al. 2010). However, the extension and geometry of these tectonic features as well as the processes behind the setting of these structures are still to be fully investigated.

Magnetic and gravity data are commonly used in exploration geophysics as preliminary techniques for large scale cartography of contacts between rocks composing the basement of the crust. The land gravity or magnetic data usually provides the best resolution for mapping. However, with the advent of the airborne technology, large areas can be surveyed at lower cost. The cartography of the lineaments in Cameroon is in progress with several projects conducted around mineral wealth potential areas. In this study, we use the available gravity and magnetic data to provide at regional scales, the cartography of the major lineaments that can be recovered in the potential field data. By simultaneously analyzing both gravity and magnetic data, we expect to reduce the non-uniqueness of solutions inherent for each method and,

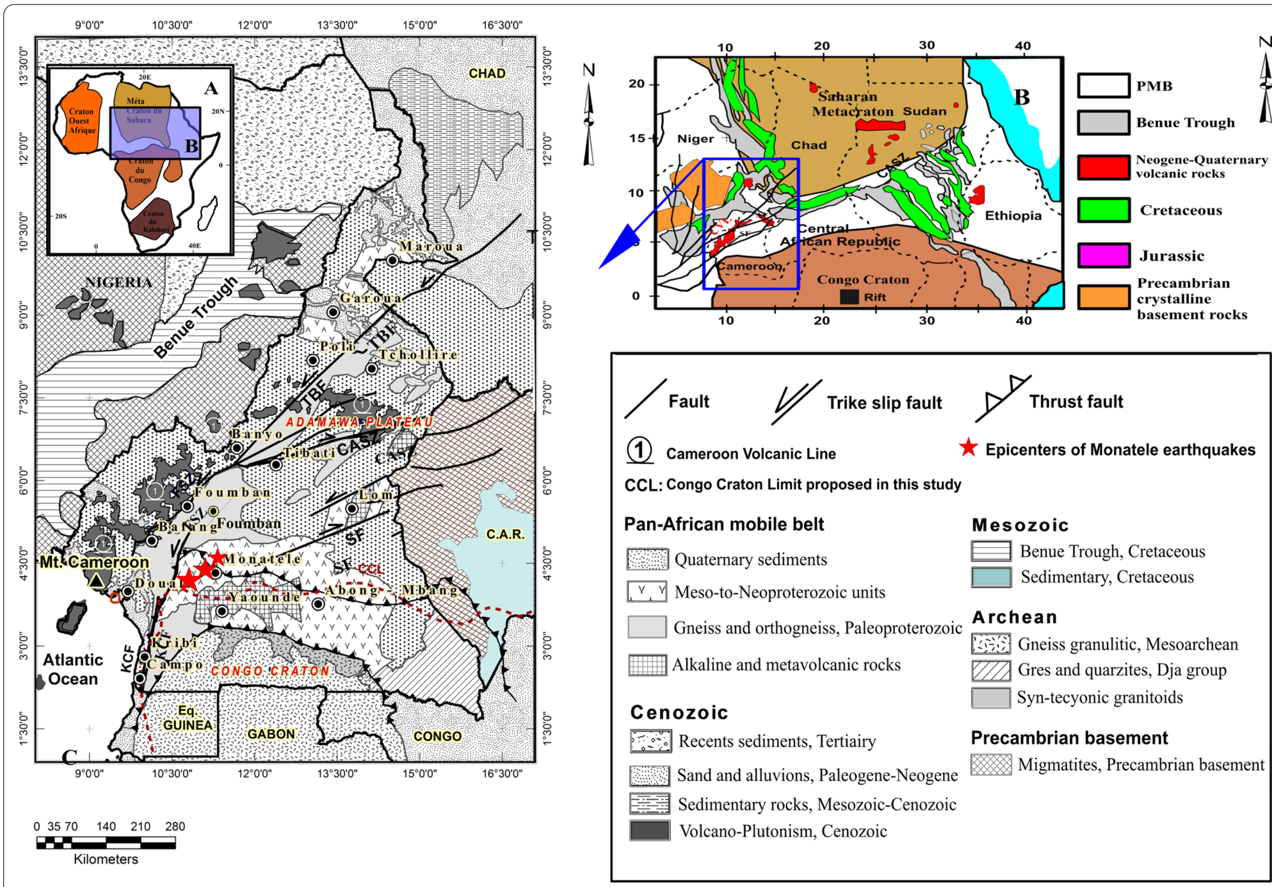

Fig. 1 **A** African Precambrian Cratons, metacratons and Orogenic belts (modified after Meert and Lieberman 2007). **B** Tectonic map of the Central Africa Orogenic Belt (CAOB) and the surrounding tectonic elements [modified from the Tectonic map of Africa by Commission for the Geological Map of the World (CGMW)]. **C** Geological map of Cameroon and surrounding countries modified from (Toteu et al. 2008)

therefore, provide more details on the structure of the lithosphere and its related tectonics.

Background

The geology of Cameroon is mainly characterized by the following structures: the Cameroon Volcanic Line (CVL) of about 1600 km long; the sedimentary basins in the northern part; the Adamawa Plateau; the Central African Shear Zone (CASZ); the northern boundary between the Congo Craton and the Pan-African Mobile belt (PMB) (Fig. 1). In the southern part of the country, the major tectonic units are the Congo Craton margin and the Sanaga Fault. The active boundary between the PMB and the Congo Craton occupies part of southern Cameroon and progresses towards the Central African Republic (Tadjou et al. 2009). The Congo Craton consists predominantly of Archean rocks with some resedimented materials formed in the Paleoproterozoic (Tchameni et al. 2001). In this region (Fig. 1), the Congo Craton underthrusts the PMB in the North. At depth, there is E–W striking dense bodies corresponding to lower crustal and/or upper mantle rock setting by tectonic compression (Boukeke 1994). The main Precambrian boundary between the Congo Craton and the PMB consists of meta-sedimentary rocks (Nzenti et al. 1994). These are presumed to have been deposited in a continental rift environment, based on the presence of alkaline and metavolcanic rocks of the Yaoundé and Lom successions (Nzenti et al. 1988). Further north, the Adamawa Plateau is surrounded by the CASZ which is parallel to the Sanaga Fault (SF), extending from the Cameroon coast to the Central African Republic and beyond (Dumont 1986). The Sanaga Fault has been characterized as a left-lateral deformation (Dumont 1986).

Several earthquakes of low to moderate magnitudes have been reported in Cameroon since the seventeenth century (Ambraseys and Adams 1986). In the southern part, three moderate earthquakes with a maximum intensity of IV were felt in the Kribi region in September 1987 (Ateba et al. 1992). Though there were no major damages reported, 2 years later, in July 1989 another moderate earthquake was felt in the area (Ateba et al. 1992). Two high-seismicity areas were identified from the past studies: (1) A seismic zone associated with the CVL and the CASZ. In this zone, the predominant and recent activities are located around Mt. Cameroon. (2) A seismic zone associated with the Foumbam Shear Zone (FSZ) and the northern margin of the Congo Craton. The Monatele earthquake of magnitude 4.5, occurred within this zone and was felt in Yaounde the nation's Capital (Ngatchou et al. 2018). In general, Cameroon can be considered as aseismic on a global scale (Tabod et al. 1992). However, with the occurrence of earthquakes, the identification and mapping of lineaments appear as a necessity in mitigating future catastrophe. It is also a necessity in understanding the general tectonics governing the setting of the Cameroon crust.

Data and methods

Gravity data

The gravity data used in this work consists of 15,742 irregularly spaced gravity stations (Fig. 2) collected between longitudes 8° and 17° East, and latitudes 1° and 14° North by many organizations and researchers during various field experiments (see Tadjou et al. 2009; Ngatchou et al. 2014; and references therein). We analyzed the data from irregularly distributed stations. Some remote areas are lacking data due to difficulty to access. They were collected at ~ 4 to 5 km intervals between gravity stations including base stations, along available roads and tracks using Worden gravimeters (n° 313, 600, 69 and 135) and the Lacoste and Romberg (model G, n° 471 and 828). The gravimeters readings were corrected for drift and the gravity anomalies were computed assuming mean crustal density of 2.67 g/cm^3. The accuracy of the gravity measurement is about 0.2 mGal. After interpolation with a kriging method developed in Surfer software for a 4 km grid (0.036°), the Bouguer anomaly map was created. The final Bouguer anomalies vary from − 123.6 to 124.6 mGal, with computed uncertainties of roughly 2 mGal and between 3 and 4 mGal in the worst cases (Poudjom-Djomani et al. 1996) (Fig. 3). Previous estimation of gravity anomalies using IGSN71 reference revealed maximum errors from merged data across Cameroon to 1.3 mGal (Fairhead and Binks 1991) or 2.52 mGal (Fairhead and Okereke 1987). The Kriging method has been proven efficient in predicting Bouguer anomalies in areas with low coverage of data (Kamguia et al. 2007).

Earth magnetic Anomalies Grid (EMAG2)

The second set of data consists of the Earth magnetic Anomalies Grid EMAG2 with a grid resolution of 2-arc-minute (~ 3.7 km) at the reference altitude above the geoid which was released following an international collaboration between various organizations including NOAA (National Oceanic and Atmospheric Administration) and CIRES (Cooperative Institute for Research in Environment Science). The original data set is a compilation of data from satellite, ship and airborne magnetic measurements (Maus et al. 2009). Some sections of the study area were lacking data in the original data set, since no data were collected there (Fig. 4a). These gaps were filled by interpolating the original data using Kriging method.

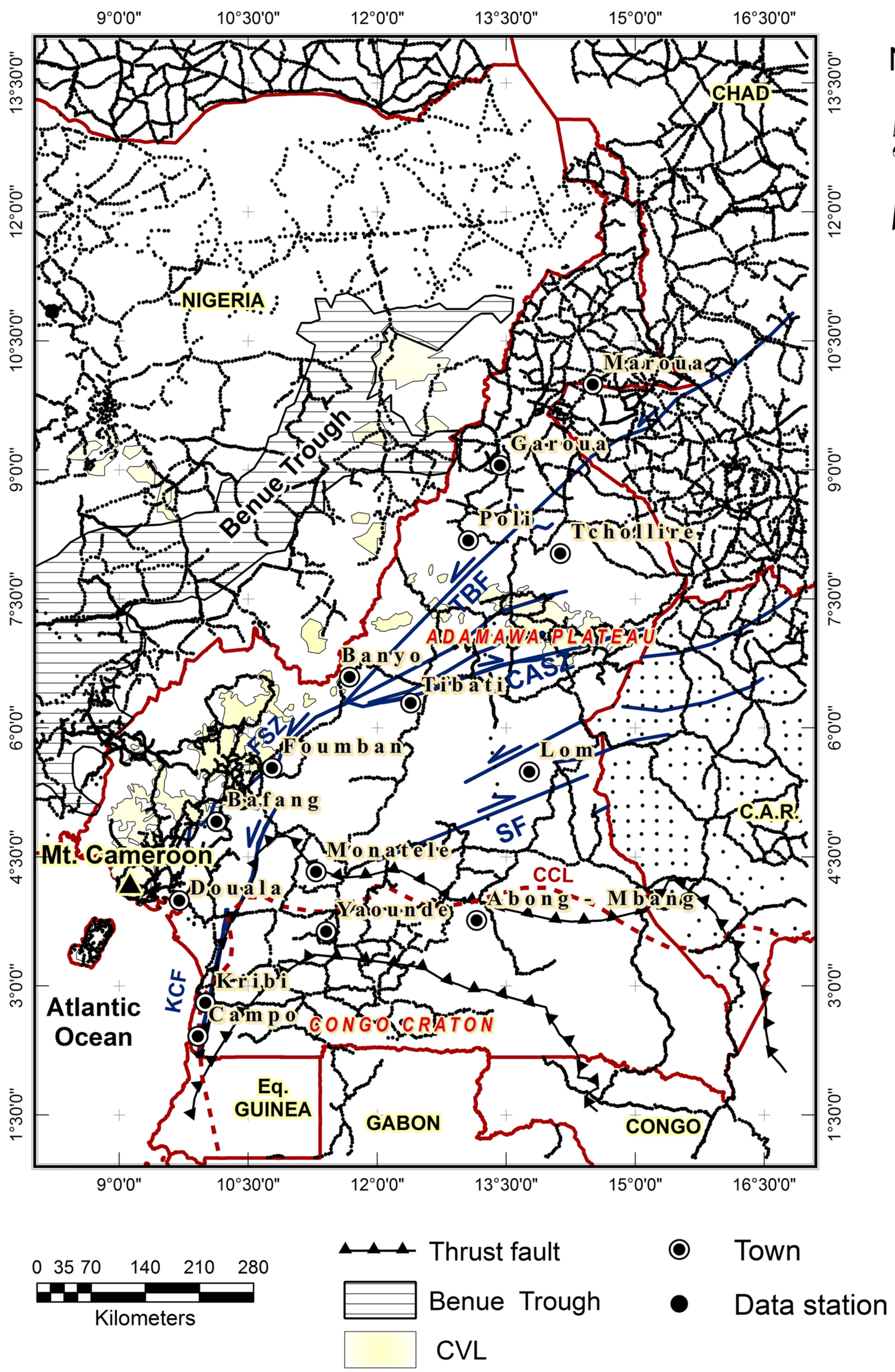

Fig. 2 Gravity data station map of the area (Collignon 1968)

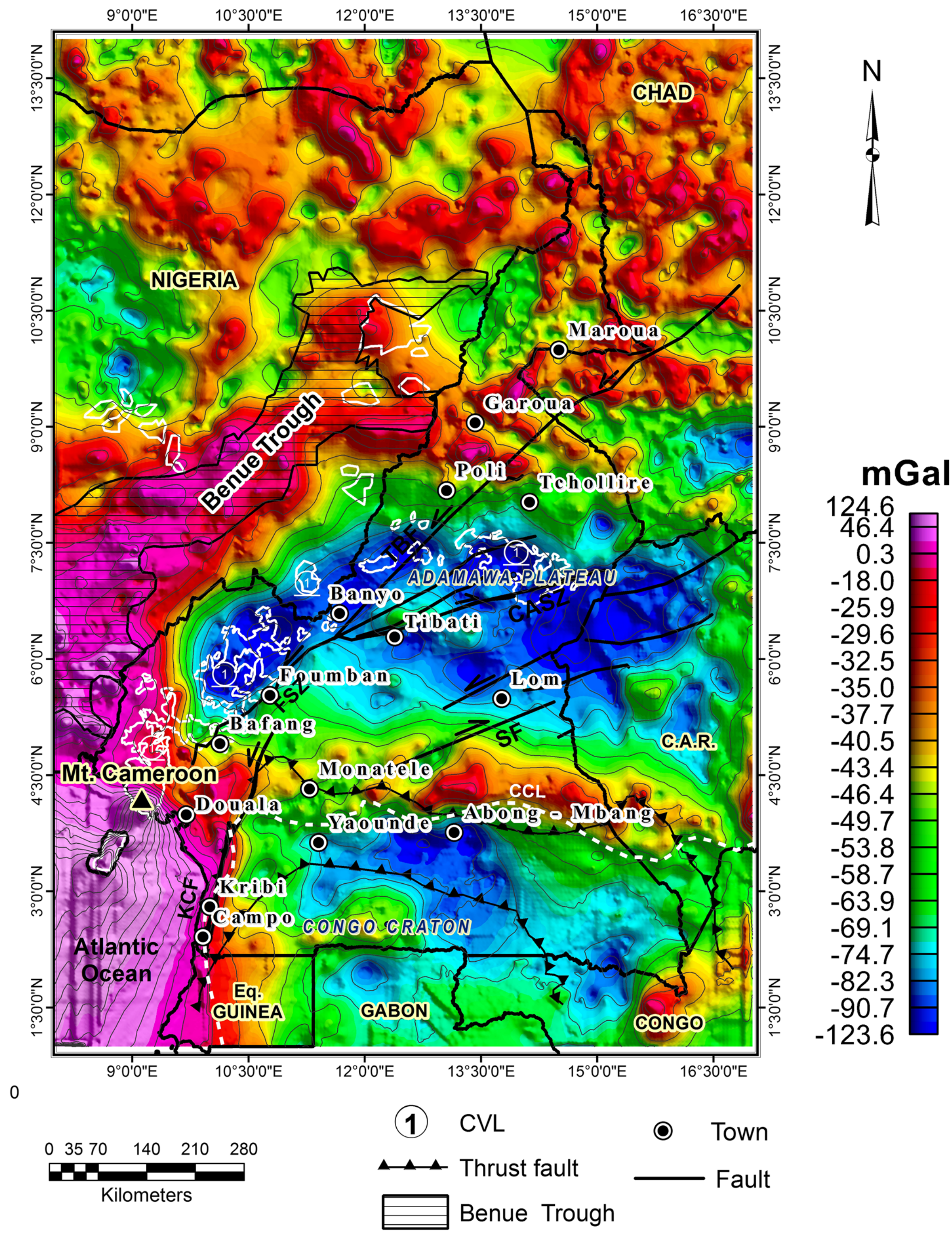

Fig. 3 Bouguer anomaly map of the study area interpolated using data from Fig. 2

Methods

The data used for this study are derived from potential fields; therefore, most of the various processing techniques can be applied simultaneously on both data sets to reduce the non-uniqueness of solutions inherent to each method taken apart.

The methodology used in this work involves a combination of techniques comprising upward continuation, horizontal derivative, maxima of horizontal gradient coupled to upward continuation technique and Euler Deconvolution. This combination of techniques has

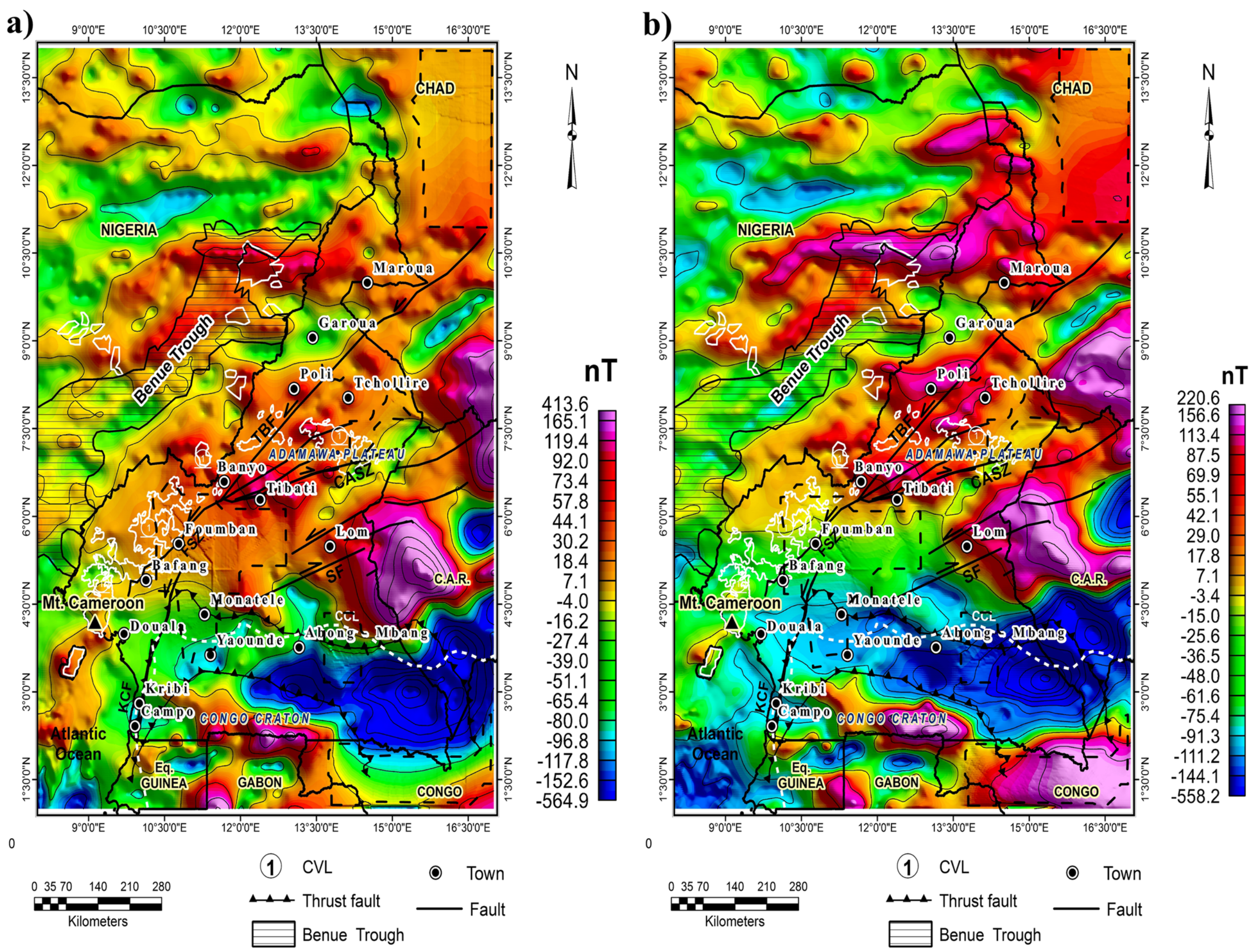

Fig. 4 **a** Total magnetic intensity map (TMI); **b** reduced to the equator of total magnetic intensity map (RTE–TMI). Black dashed contours are the areas lacking experimental data and filled by interpolation using the kriging method

the particularity in studying gravity signatures of subsurface geological features (Marcel et al. 2018).

Reduction to the Equator (RTE) of total magnetic intensity data.

The Reduction to the Equator is the operation which consists of enhancing the signal of the observed magnetic anomalies around the equator. This can be done using an algorithm that has been proven to be stable at low latitudes (Macleod et al. 1993). The RTE is efficient in correcting the asymmetry and lateral shift of measured total magnetic field (Aina 1986).

In this study, the following average values were used for inclination and magnetic declination, $I = -19.3°$ and $D = -1.34°$, respectively. The RTE data are further interpolated using kriging method to produce the magnetic RTE map (Fig. 4b).

Upward continuation

The upward continuation consists of artificially displacing the observation plane and calculating the field that would be observed at these new points from the data collected in the field (Jacobsen 1987). This operator was, therefore, applied in this work on the Bouguer and total magnetic intensity field reduce to equator anomaly map to observe the variation of the strong densities and susceptibilities contrasts with depth. These data were upward-continued at different levels 5 km, 10 km, 15 km, 20 km, 25 km, 30 km and 35 km to locate the anomalies of gravity and magnetic fields seen in these depths in the crust and understand the evolution of structure basement of Cameroon. The upward continuation is considerate as the low pass filter, because it attenuates the high frequencies due the sources of superficial anomalies. Thus, this method is suitable to study deeper and major crustal structure of the regions of interest for multi-scale analysis.

Horizontal derivative

The horizontal derivative (HD) or horizontal gradient is efficient for the location of lateral contacts between structures with different densities and susceptibilities (Cordell and Grauch 1985) and delineate subsurface geological features. One of the greatest advantages of this technique is that it is least susceptible to noise in potential field data (Phillips 1998). In the spatial domain, the amplitude of the Horizontal Derivative (HD) for a field $g(x, y)$ (resp. $H(x, y)$) at a point (x, y) is given by the below relations; Eqs. (1 and 2):

$$\mathrm{HD_g} = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + (\frac{\partial g}{\partial y})^2} \tag{1}$$

$$\mathrm{HD_H} = \sqrt{\left(\frac{\partial H}{\partial x}\right)^2 + \left(\frac{\partial H}{\partial y}\right)^2} \tag{2}$$

where $\frac{\partial g}{\partial x}$ and $\frac{\partial g}{\partial y}$ are the horizontal derivatives of the gravity field following x and y; $\frac{\partial H}{\partial x}$ and $\frac{\partial H}{\partial y}$ the horizontal derivatives of the magnetic field in the x and y directions, respectively.

First vertical derivative (VD)

The first vertical derivative applied to potential field data is useful in enhancing the effects of shallow features (Blakely and Simpson 1986; Jacobsen 1987). It is more responsive to local influences than to regional effects and is efficient in highlighting high frequency features that are sometimes shadowed by large amplitude anomalies.

Using upward continuation differences, the vertical derivative (VD) of a potential field at the height h is defined as Eq. (3):

$$VD_P = \left(\frac{\partial P}{\partial z}\right)_h = \frac{P^{up}_{h+\Delta h} - P^{up}_h}{\Delta h} \tag{3}$$

where P is the potential field (g or H), P^{up}_h is the field upward continued at the height h, $P^{up}_{h+\Delta h}$ is the field continued at the height $h + \Delta h$, and Δh is a small difference lying between 1/10 and 1/100 of the data sampling interval (Florio et al. 2006).

To obtain the first vertical derivative map, the Bouguer gravity and RTE magnetic data were gridded to about 4 km interval with a blanking radius of 20 km. The latter was converted to the frequency domain using a Fast Fourier Transform (FFT). The first vertical derivative operation was applied in the frequency domain following an upward continuation of the data by 2 km, and then returned to the spatial domain using inverse Fourier transform.

Edge detection using maxima on HD maps

To easily map lineaments, Blakely and Simpson (1986) developed an automated method based on the work of Cordell and Grauch (1985) which compare the value at a center point of a 3×3 grid window to the surrounding 8 points. Each of the four point triplets (central point + pair of points) is fitted with a parabola. This parabola's maximum is approved if it is inside the middle grid cell and has a value greater than the two outer points. Blakely and Simpson (1986) utilized a criterion based on the maximum value and an index I_d that depends on the number of legitimate maxima discovered in the 3×3 frame to qualify the various maxima employed. The index I_d ($1 \leq I_\mathrm{d} \leq 4$) gives an indication of the linearity of a maximum; when $I_\mathrm{d} = 1$, the horizontal gradient of anomalies is linear, when $I_\mathrm{d} = 4$ the maximum is a local peak. These authors discovered that indices 2 and 3 produced the greatest results when tested on maps at both local and regional scales. This method was successfully employed by Khattach et al. (2004, 2006) and Vanié et al. (2005, 2006) to classify several lineaments associated to important tectonic catastrophes in Morocco. We use it in our research area.

This method provides the maxima of horizontal gradient for each upward continued depth which are later plotted on a synthetic map (Blakely and Simpson 1986; Everaerts and Mansy 2001; Jafal et al. 2010; Hadhemi et al. 2016). Therefore, the dip orientation can be viewed as an alignment of maxima on the map, while a vertical dip is viewed as superimposed maxima from the different upward continued depths. Since gravity and magnetic data are considered to be potential field data, this method has also been applied to anomalies of the total magnetic intensity field reduced to the equator. The horizontal gradient method coupled to the upward continuation filter was used on both gravity and magnetic data at several upward continuation heights up to 35 km with 5 km steps. The overlay of the horizontal derivative maxima provides the location of the various contacts or faults, as well as their dips. In case the contacts are shown as circular shapes, it could indicate the presence of intrusive bodies.

Euler Deconvolution

Euler's Deconvolution filter is a method to estimate the depth of some linear subsurface structures from the gridded potential field data. It uses first-order derivatives x, y and z to determine the location and depth of various targets (sphere, cylinder, dyke and contact); each characterized by a specific structural index. The Euler homogeneity relationship for gravity or magnetic field data is defined by the following equation (Thompson, 1982; Reid et al.1990) shown for potential field g, Eq. (4):

$$(x - x_0)\frac{\partial P}{\partial x} + (y - y_0)\frac{\partial P}{\partial y} + (z - z_0)\frac{\partial P}{\partial z} = N(B - P) \tag{4}$$

where (x_0, y_0, z_0) the coordinates of the gravity or magnetic source, P is the field intensity measured at position (x, y, z), B the regional potential field, N is the structural index also refers to the geometry of the source and is the measure of the fall-off rate of the gravity field. (Thompson 1982; Reid et al. 1990; Ndougsa-Mbarga et al. 2011; Marcel et al. 2018). Another important parameter that follows when seeking for the appropriate solutions is the choice of window size; Marson and Klingele (1993) noted that the appropriate choice of the window size depends on the wavelength of the anomaly under investigation and the grid pitch. Good solutions are considered to be those that cluster well and have small standard deviations (Thompson 1982; Reid et al. 1990). Selection of the appropriate structural index is very important to obtain the correct depth solutions. However, the estimated horizontal location is independent of the structural index (Barbosa et al. 1999), which means that there is no ambiguity with regard to the structural location. In this paper, we applied the method using the structural index ($N \approx 0$) of contact or step (Thompson 1982; Reid et al. 1990), since the main objective is to map the faults and contacts. Despite generating scattered solutions, using a structural index very near to zero leads to a better estimation of depth and location of the contact/fault (Hatem and Mostafa 2013). The Euler deconvolution approach, which is applied to each solution, consists of defining an acceptable value of structural index N and then solving the equation for the initial parameters x_0, y_0, z_0, and the optimal regional B potential field using least squares inversion. A square window size which consists of the number of cells in the gridded data set to be used in the inversion for each selected solution location must also be specified. The window is centered on each of the solution slots. As a result, the points in this window are utilized to solve Euler's equation for the depth of the solution, with the distance from the window's center inversely weighted. In the gravity grid or magnetic field, the window should be big enough to include every solution anomaly of interest. Euler depths are the stratigraphic alterations of several formations of geological structures in terms of geology.

Results and discussion

Analysis and interpretation of gravity map

The Bouguer anomaly map of the study area (Fig. 3) shows the combined effects of shallower and deeper lithosphere structures, consequence of the difference in density and composition of the subsurface materials. Many zones of anomalies alternately positive or negative are observed, separated by areas of gradients that can be correlated to the main geologic features shown on the geologic map (Fig. 1). Previous studies generally associated the negative anomaly gradients along the latitude 4ºN to the transition zone between the CC and PMB, leading to the conclusion that CC disappear beneath PMB structures through a continental collision (Tadjou et al. 2009 and references therein). The large zone of negative anomalies north of latitude 4ºN is associated to the setting of the Adamawa Plateau. At the west, the Benue trough is linked to the large zone of positive anomalies. Further north, in the area surrounded by the cities Garoua, Poli and Tchollire, the anomalies are negative but with lower negative amplitude. This correlates well with the topography of the area which consists in general of plains and hills of altitude below 300 m. This explanation corroborates well with the isostasy theory that suggest elevated area are generally linked to the low anomaly sources constituting the crust. The zone of gradients between the Benue Trough (see Fig. 1) and the large anomalies can be associated to the setting of the CVL.

Analysis and Interpretation of magnetic map

The interpolated map obtained using RTE provides a more accurate estimate of the positions of the magnetic sources compared to the total magnetic intensity map (Fig. 4a). The RTE magnetic map (Fig. 4b) shows in the south of Cameroon, areas of low magnetic anomaly (less than − 15nT). The presence of some spots of high anomalies within the area can be associated to localized features within the CC or edge effects. Between latitudes 4°N and 7°N, there is large band of high magnetic anomalies (above 20 nT). It can be associated to the presence of the Adamawa Plateau. This band extends southeastwards to Central African Republic (CAR) with higher amplitude (up to 150 nT). This sector at the border of Cameroon-CAR is known as a potential mining area with several ongoing mining operations. Further north, the positive anomalies are dominant, with the presence of a maximum at the geological location of the Benue Trough. The alignment of spots of positive anomalies in the approximate N90°E direction is an indication that the magnetization is influenced potentially by the tectonics.

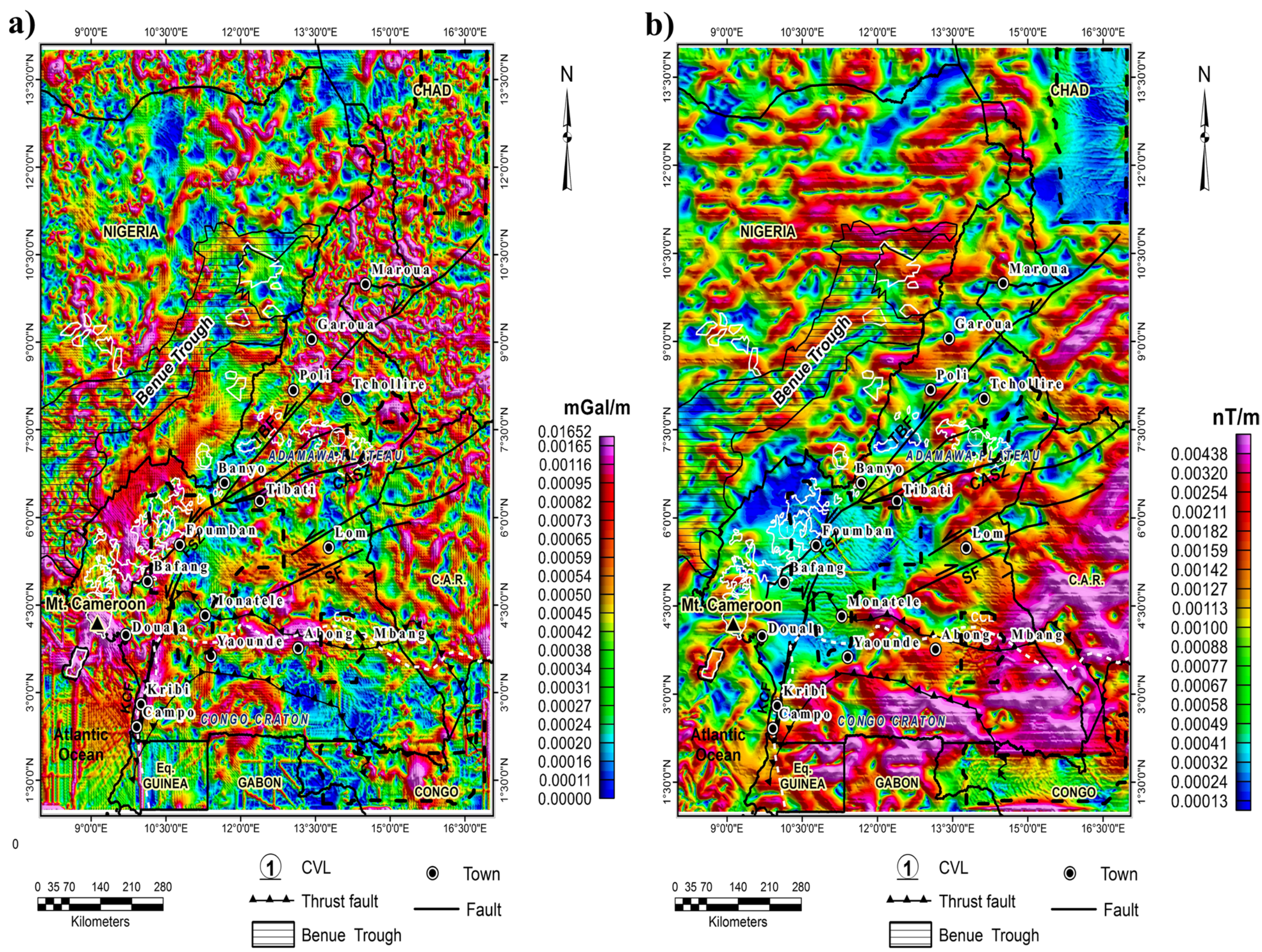

Fig. 5 Horizontal gradient map of: **a** Bouguer anomalies and **b** RTE–TMI

At first view, there is little similitude between gravity anomalies and magnetic anomalies in terms of shapes and locations of anomalous features (including gradients and concentric shapes). This suggests that magnetic method will provide additional resolution to the geologic features that could have been not identified from density contrasts.

Horizontal derivatives and lateral discontinuities

The HD map (Fig. 5a) for the Bouguer gravity data suggests that the Cameroon basement is globally affected by tectonic activities, since areas of high amplitude gradients are present all over the study area, assuming high amplitudes of HD are usually correlated to contacts or faults. This map also suggests that the most stable part of the crust can be found below latitude 4°N, where we can observer larger areas with lower amplitude of gradients. This is in agreement with the presence of the CC which is generally known as the most stable part of the crust. The high amplitude of gradient along the latitude 4°N, therefore, marks the northern limit of the CC, while high amplitude of gradient appearing as spots within the CC might be attributed to intracrustal discontinuities or intrusions. However, the fact that the high gradients are correlated to some of the main geologic units of the study area is an indication that the HD map can reveal the imprints of other hidden discontinuities within the crust.

The HD map from RTE magnetic anomalies (Fig. 5b) shows globally that the study area is divided into two areas: a zone of higher amplitudes of gradients located to the south and southeast characterized by large bands amplitude above 0.00438 nT/m which is adjacent to a much larger area in the north with gradient amplitude below 0.00438 nT/m. Assuming HD is the change of magnetization in the lateral direction, the high gradients observed in the areas suggested a concentration of magnetic rocks that could have been settled during the Pan-African orogeny by a volcano-plutonic process. Further north, the lines of gradients are observed in Nigeria can be linked to the setting of the Benue trough during

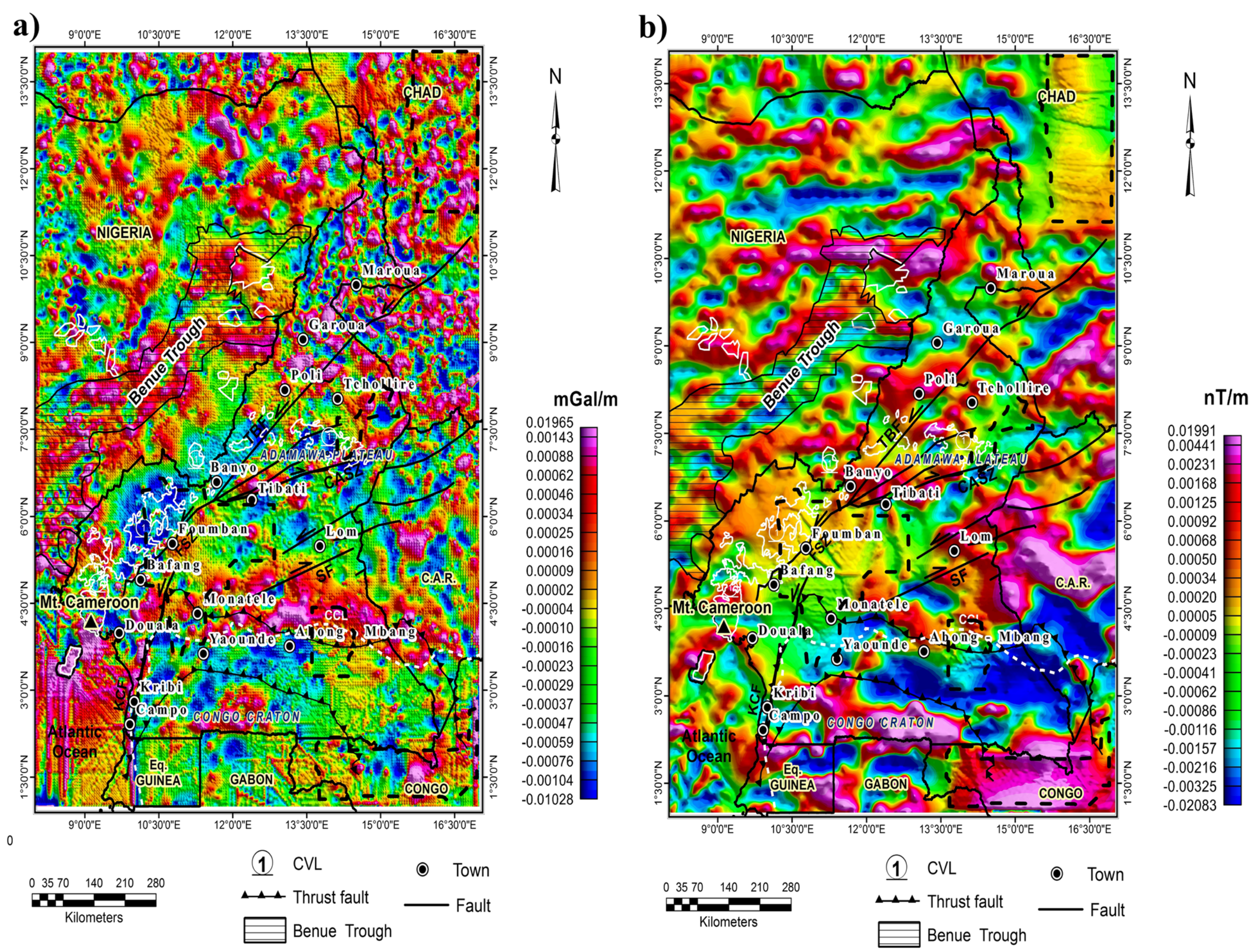

Fig. 6 Vertical gradient Map of: **a** Bouguer anomalies and **b** RTE–TMI

the Cenezoic resulting from some volcanic and plutonic activities. The linearity of the lineaments can be interpreted as dykes.

First vertical derivative and dipping layers

First vertical derivative of gravity data

The first vertical derivative of the gravity field (Fig. 6a) usually depicts high frequency anomalies caused by shallow structures (contacts of rocks) having significant difference in densities. In general, the shallow crust of Cameroon and neighboring countries consists of various rocks settled with various tectonic activities. The map of the first vertical reveals a vertical derivative high along the latitude 4°N which is known as the geophysical boundary between CC and PMB. At that boundary, higher density rocks of the CC are overlain by rocks of the PMB. Other areas associated with short wavelength anomalies could be interpreted as dipping contacts or dykes, while longer wavelength can be associated to the effect of variation in crustal thickness.

First vertical derivative of magnetic data

The first vertical derivative of the magnetic field (Fig. 6b) can be viewed as the rate of change of the magnetic field in the vertical direction. Unlike the vertical derivative of the gravity data, it can help to locate areas of potential magnetized mineral concentration within the shallower structures. In this perspective, the map suggests that part of the shallow structures in the south and southeastern part of the investigated areas have a high potential of magnetization. Several bands of high vertical magnetic gradients extending approximately in the N90°E direction can be observed in the northern part of the map (in Nigeria) right above the latitude 7°N. These lineaments can be interpreted as swarm of dykes. In fact, Ngoh et al. (2017) have identified similar lineament features in the northern

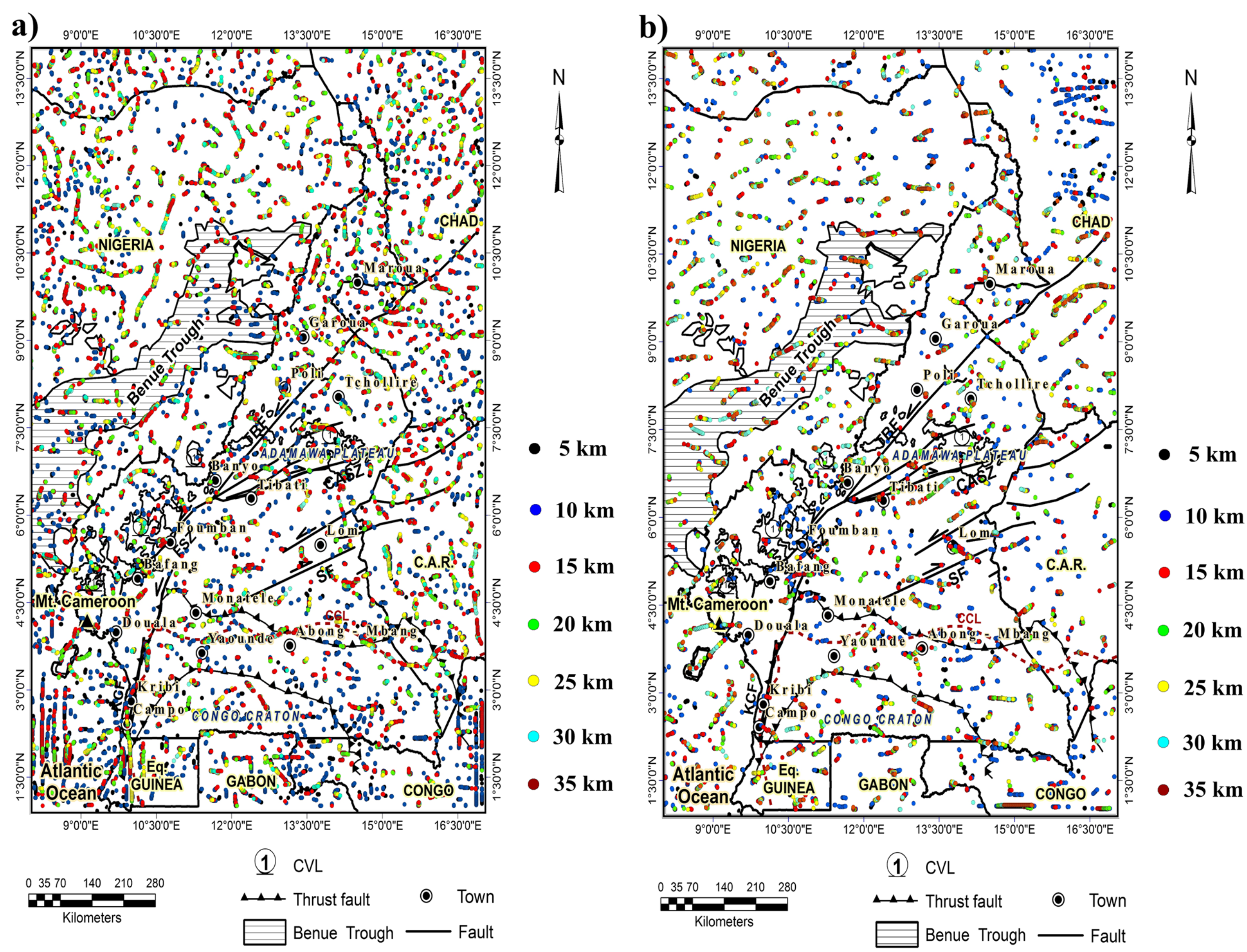

Fig. 7 Map of horizontal gradient maxima derived from upward continuation at different heights: **a** using Bouguer anomalies and **b** RTE–TMI

Cameroon using aeromagnetic data that have been interpreted as faults or dykes oriented roughly NE and NW.

Detection and mapping of lineaments

The maps obtained from the overlay of HD maxima computed on the various upward continued gravity and magnetic data at height 5 km to 35 km at steps of 5 km, are presented in Fig. 7a, b, respectively. The maps show in general that the maxima are distributed in a quasi-linear gradient shape that can be interpreted as the change in the density and magnetization within the crust. These changes were found to occur on the upward continued maps up to depth of 35 km. Therefore, lineaments can be viewed as a succession of linear features (HD maxima) that can be related to the trend of the existing faults in the study area as suggested by Koumetio et al. (2012) and Shandini et al. (2018). The gravity and magnetic lineaments detected here are traced out in Figs. 8 and 9, respectively. The tracing and highlighting of its lineaments is based on the multi-scale analysis of horizontal gradients maps of the anomalies (Blakely and Simpson 1986) (Fig. 5). These gradients are exploited to calculate and automatically detect the maxima for different depths (Fig. 7). The detected maxima are then superimposed to identify their directions and orientations (Fig. 7). Finally, the lineaments are plotted by following the spatial behavior of the superimposed maxima with depth.

Thus, the lineaments brought to light bear witness to the extent to which intracrustal basement of Cameroon is strongly characterized by major tectonic accidents. In addition to localized structural features, this study allowed us to highlight the lineaments which coincide with those located by geological work, namely: the Adamawa Fault (AF), the Tchollire-Banyo Fault (TBF), the Sanaga (SF) and Kribi-Campo Fault (KCF) and Northern of Congo Craton limit (CCL). Lineaments associated to gravity can be interpreted as known or

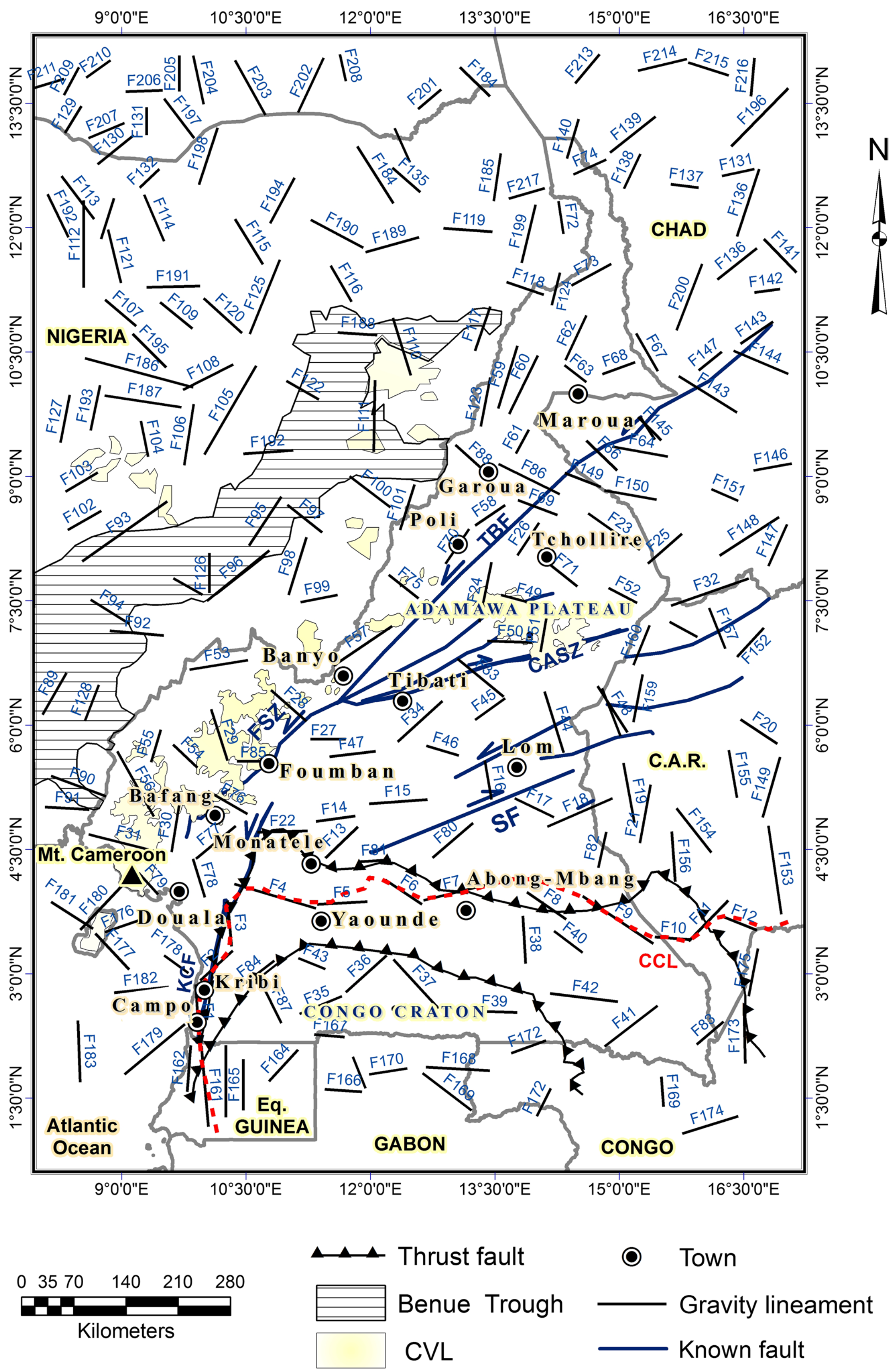

Fig. 8 Lineaments map derived from the Bouguer anomalies

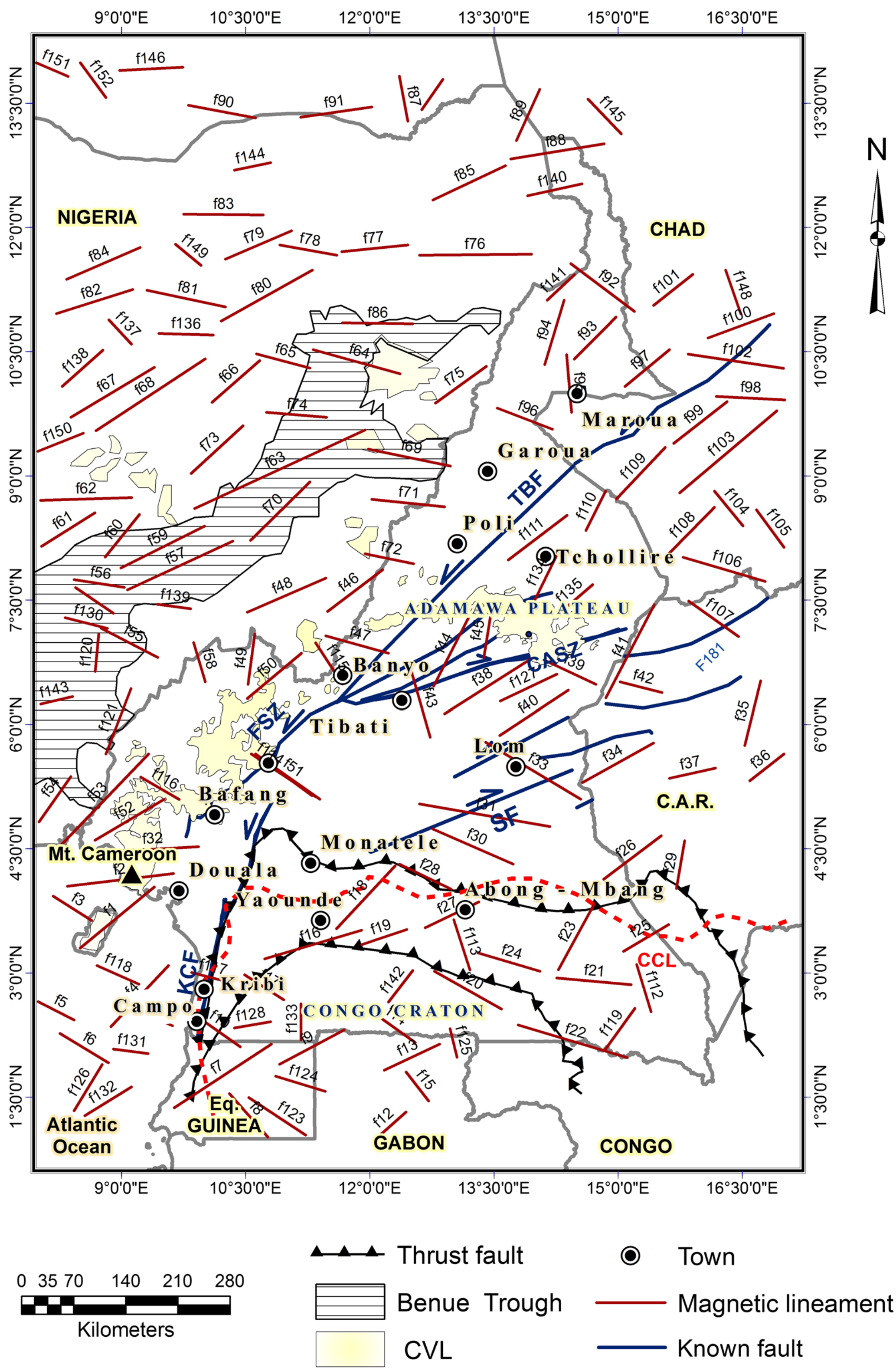

Fig. 9 Lineaments map derived from the RTE–TMI

hidden geologic contacts or existing faults in the study area, while those associated to magnetic anomalies can in addition be viewed as dykes or intrusions.

Estimation of depths of lineaments using Euler deconvolution

The Euler Deconvolution method was applied successively on both gravity and RTE magnetic data. The method is based around three parameters: (1) the structural index (N), who takes values ranging (from 0 to 3) depending on the structures considered and characterizes the rate of variation of the anomaly intensity with the distance, so the optimal value corresponds to a grouping of solutions obtained for different values (Thompson 1982 and Reid et al. 1990). However, low structural index ranging from (0 to 1) provide the best depth estimates (Reid et al. 1990); (2) the size of the window, so its size depends on the wavelength of the anomaly examined and the pitch of the grid (Marson and Klingele (1993); (3) and the tolerance (Z) defined as the acceptance rate of Euler solutions for geological structures. It representing the error on the depth. The tests carried out on the tolerance show that a level of estimation error on the depth between 5 and 15% ($0.05 \leq Z \leq 0.15$) depending on the geological structures gives the best results (Thompson 1982). As part of this study, the structural index ($N = 0$) was adopted with a window of 20 km × 20 km. The Euler solution calculated with a tolerance Z = 10% error on the depth and more, shows no overload on the solutions, which makes interpretation unnecessary. The Euler solution for a tolerance Z = 4% and less shows an insufficiency explained by the solutions absence at the level of the majority anomalies related to the different geological structures

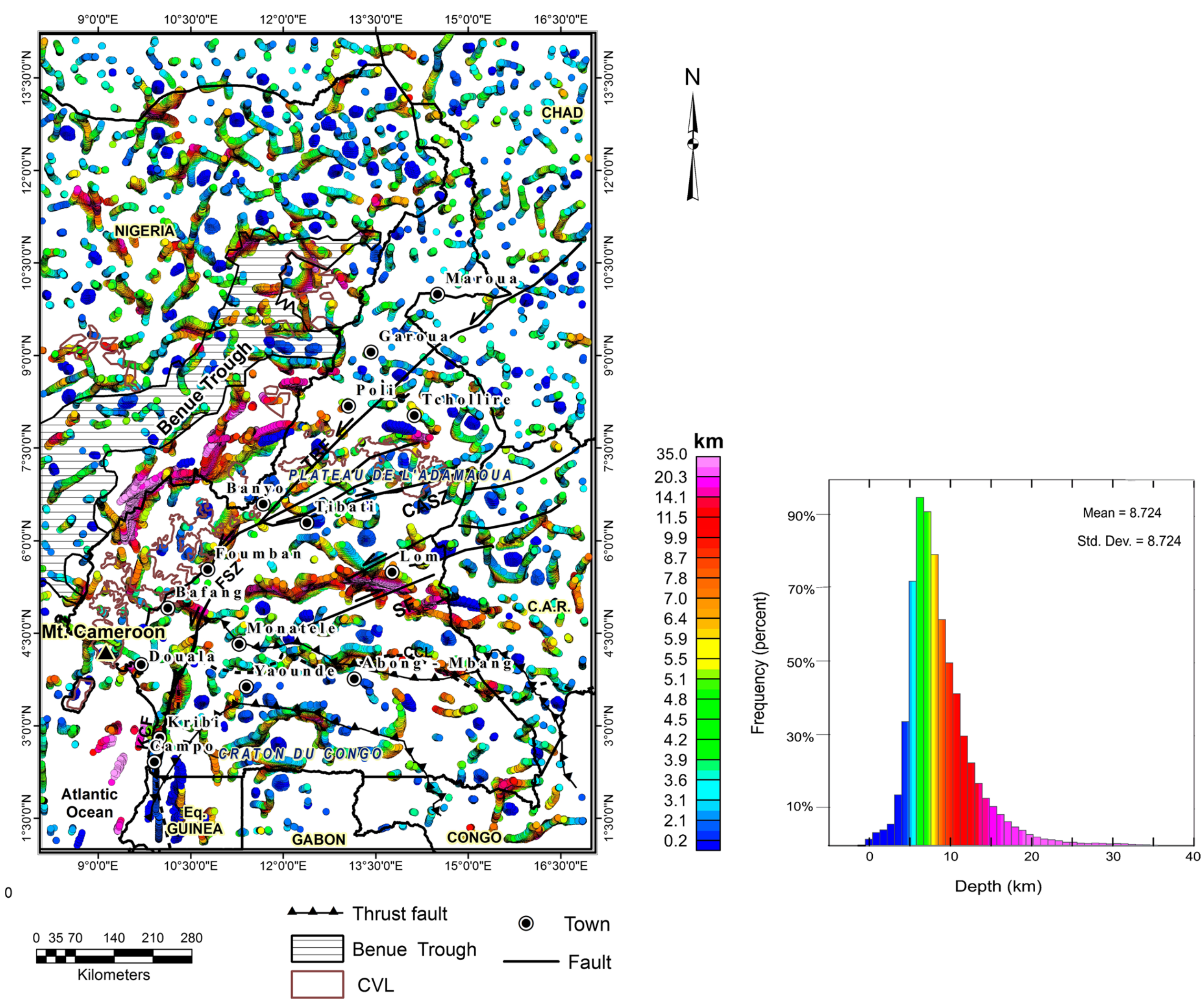

Fig. 10 Euler deconvolution map for the Land gravity data with a structural index of 0

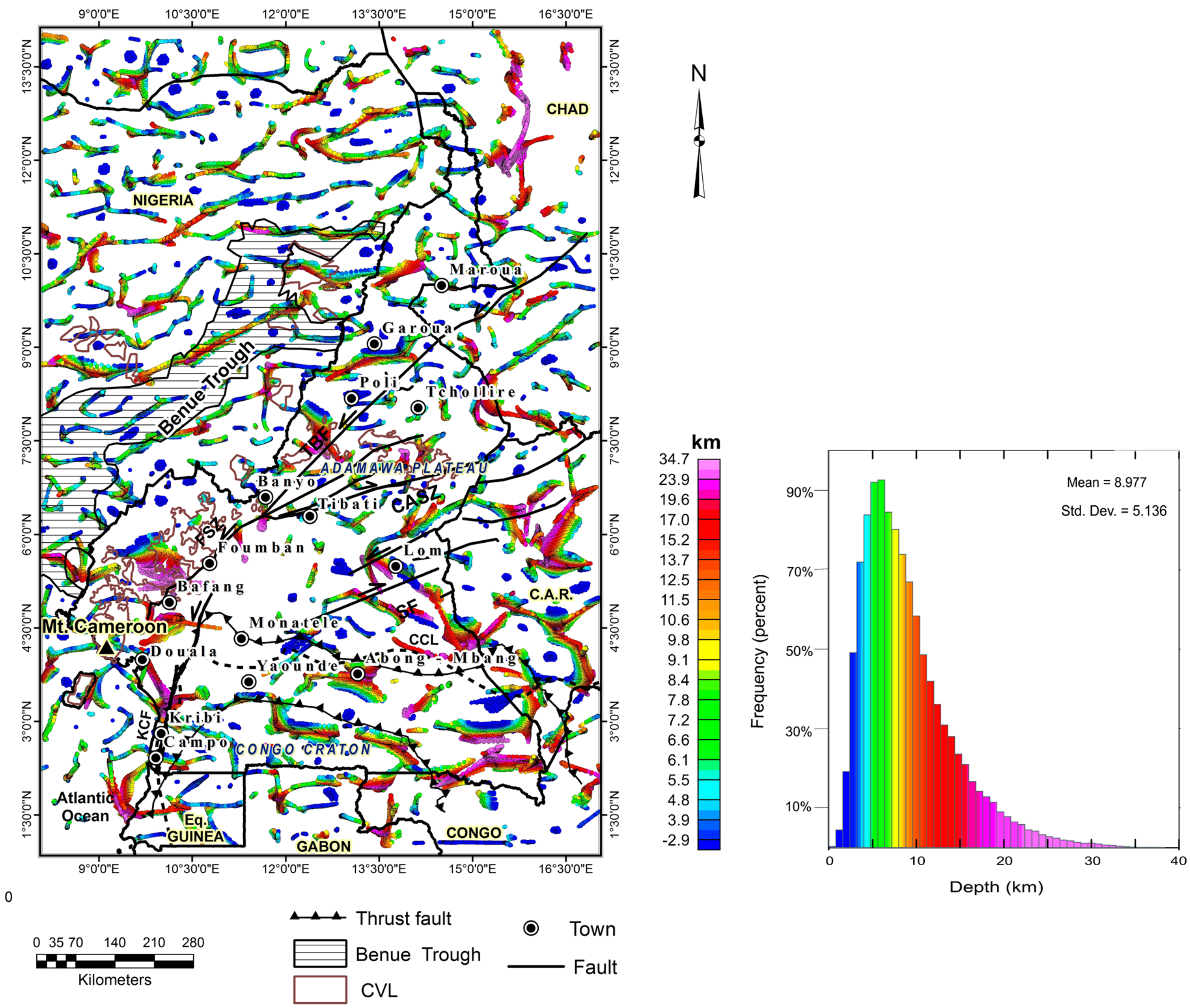

Fig. 11 Euler deconvolution for the Earth Magnetic Anomaly Grid with a structural index of 0

of this study area. With a tolerance of 5%, we observe a strong agreement of positions of the solutions and their depths with the majority of the anomalies of short and long wavelengths. Which coincides with those of the horizontal gradients.

The best solutions were obtained for the structural index $N=0$, since the data are unevenly distributed all over the study area using a window of 20 * 20 km. 217 and 152 lineaments were identified using gravity and magnetic anomalies data, respectively. Subsequently, we extracted the set of all depths values for each structural feature and then statistically calculated the average from a series of depth values extracted on each lineament. the principle consists of summing the values of the Euler depths over which each lineament passes and dividing by the number of depth points in the data series. (Additional file 1: Tables S1 and S2).

Figures 10 and 11 show a summary of depths estimated from the Euler's method. For both data sets, the solutions show that the depths of the source of the linear features are located between 1 and 35 km. These depths fall in the similar range as the epicenters of most recorded earthquakes in Cameroon. In fact, most of the recent activities were qualified as shallow earthquakes (Tabod et al. 1992; Ateba et al. 2009), since their epicenters are generally located at depth < 50 km.

The statistical analysis using the Rose Diagram indicates that the lineaments are mainly oriented in the N67.5°E (26%), N45°E (24%) N112.5°E (15%), N157.5°E (11%), N0°E (10%), N135°E (7%) and N90°E (6%)

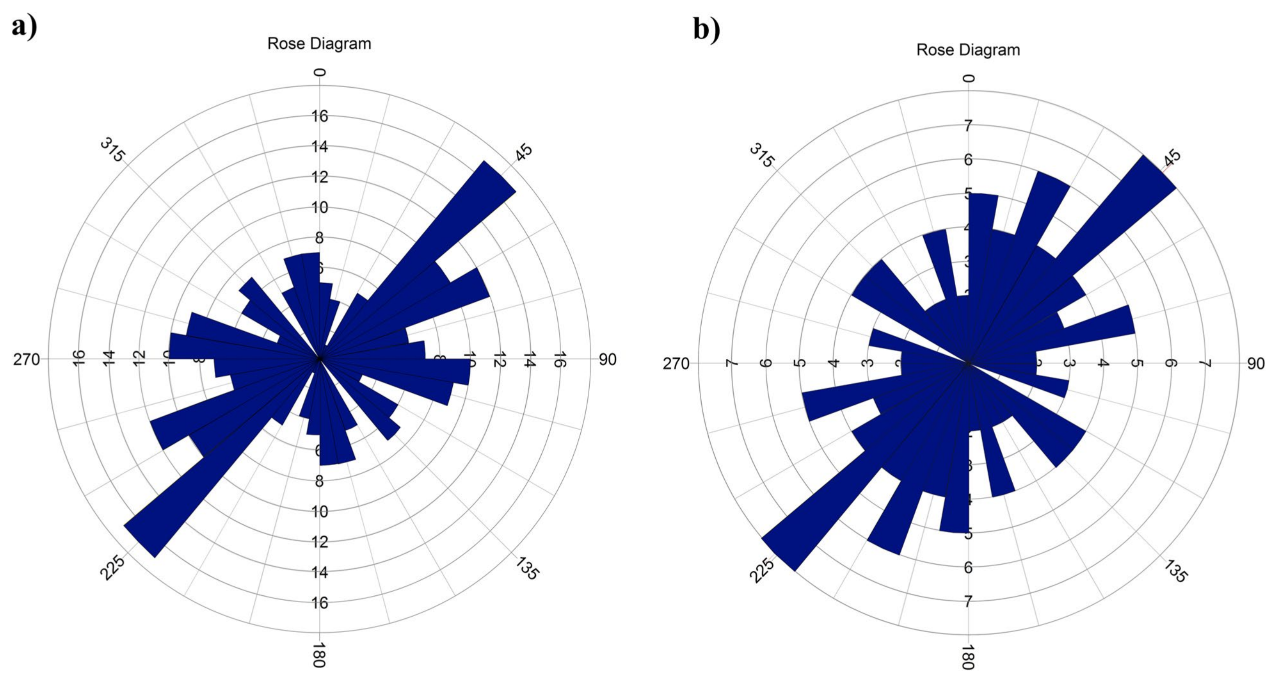

Fig. 12 Rose diagram of lineaments revealed by this work for: **a** gravity lineaments and **b** magnetic lineaments

directions (Fig. 12). The lineaments highlighted in this study show that the study area is very fractured. For gravity and magnetic anomalies, they also reveal that structural features in Cameroon have a strong dominance along the NE–SW direction. The results of this study provide an opportunity for more research on the characteristic tectonic accidents of the basement in Cameroon. Some of the previous lineaments were not highlighted in this study. This may be due to the pitch and the resolution of the data of around 4 km which may not be suitable for locating and detecting more detailed information on the basement; requiring in-depth investigation.

Conclusions and discussion

The derivative methods applied to potential field data have shown in previous studies their capacities in detecting some geologic features as well as their geometrical parameters (Cordell and Grauch, 1985; Koumetio et al. 2012). In this study, the derivative methods have allowed to identify several lineaments across the whole study area. Few of the identified lineaments are both resolved simultaneously by gravity and magnetic anomalies data. The two data sets are, therefore, complementary. The results are consistent with the location of some recent earthquakes recorded, by a network of temporary broadband stations in 2005–2007 (Tokam et al. 2010; Ngatchou et al. 2018). It can be noted that all the recorded seismic events are located within the vicinity of detected lineaments from this study (Fig. 13). Therefore, in areas, where geology is poorly known, using both gravity and magnetic data can be a first step settling target for future exploration as generally indicate in mining exploration.

Figure 13 also provides a synthesis of identified lineaments associated to the existing geology map. Compared to Fig. 1 which is the synthesis of known geology (Toteu et al. 2008), it can be inferred that most of the lineaments are related to geologic contacts within the Cameroon territory. In this work, the gravity and magnetic lineaments are located under the basis of the multi-scale analysis of the gradient maxima of Bouguer anomalies and the total magnetic field reduced to the equator. All the same, the spatial distribution of the depths for geological structures that can be associated with these lineaments are also highlighted from the Euler deconvolution. In addition, the Euler deconvolution method also provides a spatial distribution of depths for geological structures beyond the areas of contrasting gradients of gravity and magnetic anomalies. Furthermore, Euler deconvolution and horizontal gradient maxima derived from upward continuation at different heights enable to characterize some structural linear features. Therefore, these estimated of lineaments depth do not necessarily correspond to the lineaments which may be due to the different filters used for the transformation of data anomalies. However, this work present approximately similar limit depth of features at 35 km for this two last techniques.

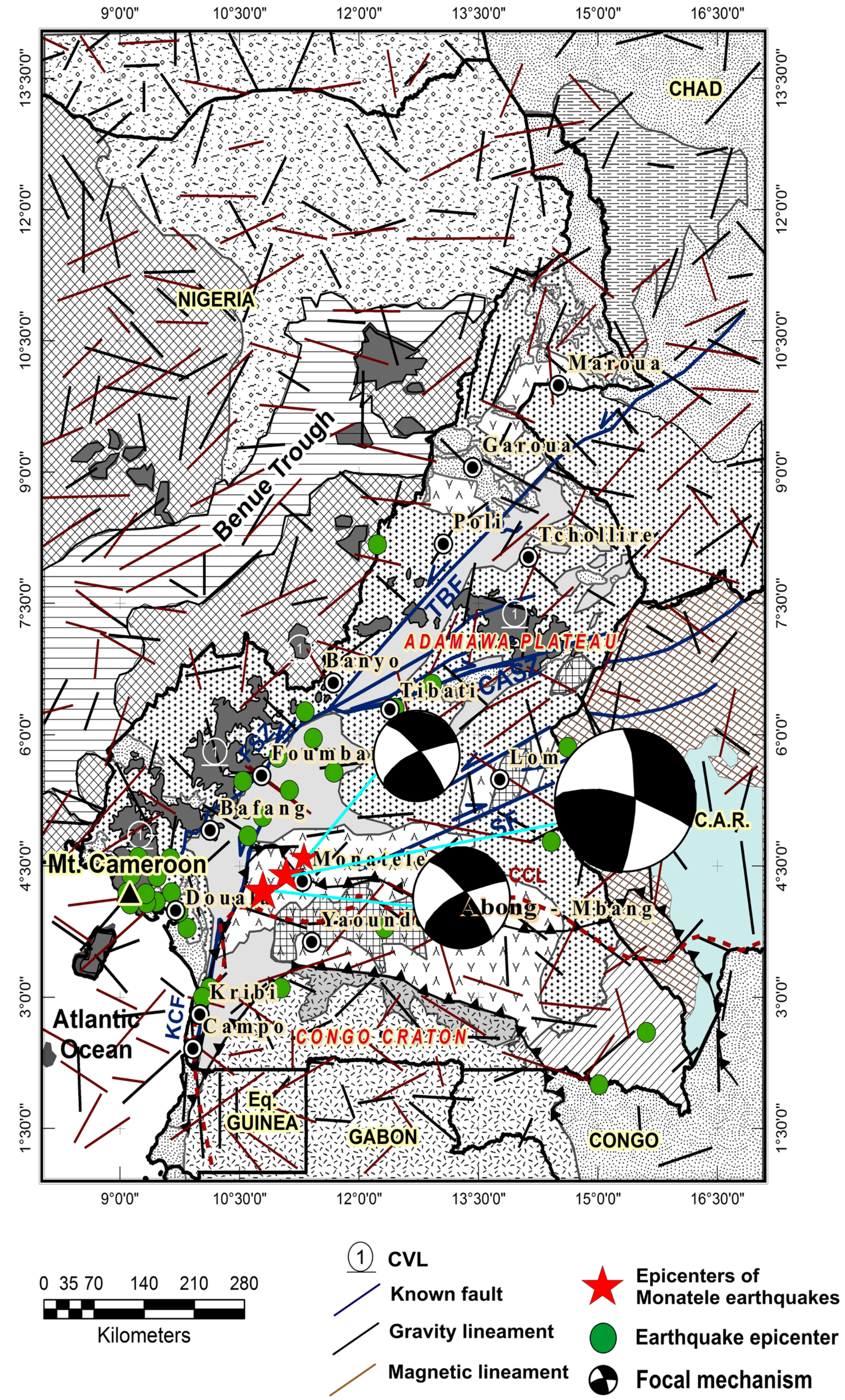

Fig. 13 Cartography of lineaments correlated to some tectonic earthquakes that occurred recently in Cameroon; Green circles are the earthquakes recorded by the network of temporary broadband stations; Red stars represent the epicenters of the Monatele event. Spheres are the focal mechanism for main and aftershocks. Black and white quadrants represent the compression and dilatation, respectively

The orientations of lineaments vary with approximately 50% of lineaments following roughly the directions N90°E and N67.5°E which is quite parallel to the direction N30°E generally pointed in geology as the direction of the lineaments of Cenezoic volcanism extended from the Gulf of Guinea to Benue through in Nigeria (Deruelle et al. 2007). This suggests the setting of the CVL has probably played a major role in the development of other tectonic activity during the Cenezoic.

Assuming that most of the lineaments can be related to faults, some of these major faults if not all might be still active, since earthquakes have been recorded in most part of the country, the quiet places being quiet because of the lack of a monitoring system.

Abbreviations
EMAG2: Earth Magnetic Anomaly Grid; PMB: The Pan-African Mobile Belt; CC: Congo Craton; CASZ: Central African Shear Zones; TBF: Tchollire Banyo Fault; KCF: Kribi Campo Fault; SF: Sanaga Fault; FSZ: Foumbam Shear Zone; CVL: Cameroon Volcanic Line; CCL: Congo Craton limit; CIRES: Cooperative Institute for Research in Environment Science; NOAA: National Oceanic and Atmospheric Administration; TMI: Total Magnetic Intensity anomalies; RTE: Reduce to equator; HD: Horizontal Derivative; VD: Vertical Derivative; FFT: Fast Fourier Transform; CAR: Central Africa Republic; NS: North–South; E–W: East–West; SW–NE: South–West–North–East; NE and NW: North–East and North–West.

Supplementary Information
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Additional file 1: Table S1. Orientation and depths of the various segments of lineaments derived from gravity data. **Table S2.** Characteristic orientation and depths of different segments of magnetic lineaments.

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Author contributions
CACF established the objective, conceived of the methodology of gravity and magnetic data analyses and interpreted geophysical maps. SN and CACF contributed to the geological aspect of the paper and generated maps. APTK contributed by integrating the seismic analyses in relation to the tectonic lineaments highlighted. CACF and CAM wrote the first draft of the paper. MPM, APTK and SN performed critics and improved the interpretation of results. RN supervised the work and revised the paper. All authors read and approved the final manuscript.

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Availability of data and materials
The gravity and magnetic data use in this study are available, respectively, at the BGI (Bureau Gravimétrique International): https://bgi.obs-mip.fr/data-products/ and NOAA (National Oceanic and Atmospheric Administration): https://www.ngdc.noaa.gov/geomag/emag2.html.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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