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Structural Setting of the South-West Cameroon Using Satellite Potential Field Derived from SGG-UGM-2 Gravity Data

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Abstract

This study aims to improve knowledge of the structure of southwest Cameroon based on the analysis and interpretation of gravity data derived from the SGG-UGM-2 model. A residual anomaly map was first calculated from the Bouguer anomaly map, which is strongly affected by a regional gradient. The residual anomaly map generated provides information on the variation in subsurface density, but does not provide sufficient information, hence the interest in using filtering with the aim of highlighting the structures affecting the area of south-west Cameroon. Three interpretation methods were used: vertical gradient, horizontal gradient coupled with upward continuation and Euler deconvolution. The application of these treatments enabled us to map a large number of gravimetric lineaments materializing density discontinuities. These lineaments are organized along main preferential directions: NW-SE, NNE-SSW, ENE-WSW and secondary directions: NNW-SSE, NE-SW, NS and E-W. Euler solutions indicate depths of up to 7337 m. Thanks to the results of this research, significant information has been acquired, contributing to a deeper understanding of the structural composition of the study area. The resulting structural map vividly illustrates the major tectonic events that shaped the geological framework of the study area. It also serves as a guide for prospecting subsurface resources (water and hydrocarbons).

Keywords

SGG-UGM-2 Model, Horizontal Gradient, Bouguer Anomalies, Potential Field Data

1. Introduction

The study area, located in Central Africa, lies in southwest Cameroon between latitudes 2˚24'N - 4˚39'N and longitudes 9˚59'E - 11˚31'E (**Figure 1**). This area bears the traces of the various tectonic events that have marked the African continent over geological time. It straddles the northern margin of the Congo Craton and the North Equatorial Pan-African Range. The area is marked by a continent-to-continent collision involving compressional and extensional movements giving rise to major faults. Tectonic movements continue to have an impact in the area, and a series of earthquakes ranging from 3.4 to 5.7 on the Richter scale have been reported (Ateba et al., 1992; Nfomou et al., 2004; Tabod et al., 1992; Tadjou et al., 2009). For several decades, on the basis of terrestrial gravimetric data carried out over the whole of Cameroon between 1962 and 1967 by ORSTOM, and a few one-off campaigns carried out along roads, the South-West Cameroon region has been the subject of several gravimetric investigations (Angue et al., 2011; Clotilde et al., 2016; Clotilde et al., 2013; Kamto et al., 2021; Koumetio et al., 2012; Koumetio et al., 2014; Malquaire et al., 2020; Ndongmo et al., 2023b; Yandjimain et al., 2023) with a view to improving geological knowledge of the area. The main results of this work suggest that the basin basement is cut by a massive block of gneiss and granodiorite some 4.5 km thick (Malquaire et al., 2020). Numerous deeply rooted structural features oriented in NE, NNE, NS, NNW, NW and EW directions have been highlighted in this region (Angue et al., 2011; Clotilde et al., 2016; Clotilde et al., 2013; Kamto et al., 2021; Ndongmo et al., 2023a). Fractures and faults NNE-SSW to NS would be local relays of the Kribi-Campo fault are related to the Kribi shear zone (Clotilde et al., 2013). Two south-southwest to north-northeast (SSW-NNE) normal faults with an average vertical displacement of 20 km have also been identified, one along the Eseka-Akom II axis and the other along the Edea-Kribi axis (faults F1 and F31 in **Figure 2**) (Koumetio, 2004).

Although this work has succeeded in highlighting discontinuity zones and underground structures at relatively great depths in the study area, the low spatial resolution of the ground gravity data in the ORSTOM database in the study area (because it only follows roads according to Djomani et al. (1995)) makes the results of the said work more or less reliable. To address gaps in coverage and the lack of data acquisition over large areas, global gravity field models are of great importance (Hirt et al., 2013; Sobh et al., 2018). Several global gravity field models integrate data from satellite gravimetry, satellite gradiometry, satellite altimetry and terrestrial gravimetry. In this study, we used gravity data derived from the SGG-UGM-2 model of the Earth's gravity field. The SGG-UGM-2 model showed the best performance in GPS/levelling validation. This model provided high-resolution data compared with all GRACE mission models such as GGM02, EGM2008, etc. The National Geospatial-Intelligence Agency (NGIA) provides gravity data frequently used to study surface and deep crustal structures and analyze tectonic and dynamic processes. Gravity data derived from the SGG-UGM-2 model are successfully used for tectonic and crustal studies (El-Raouf et al., 2023), or to estimate the Moho gravity model (Sahoo & Pal, 2022).

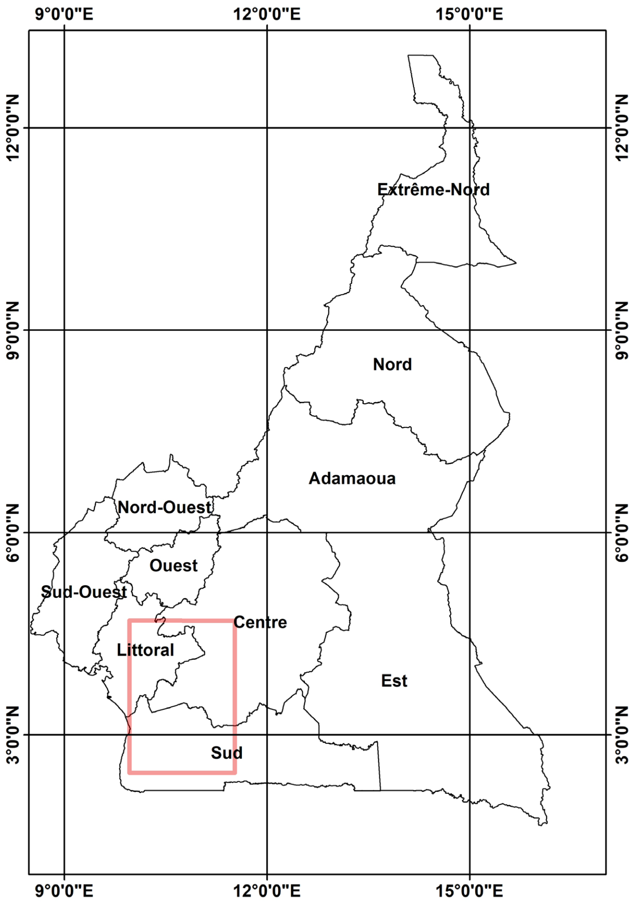

Figure 1. Location map of the study area.

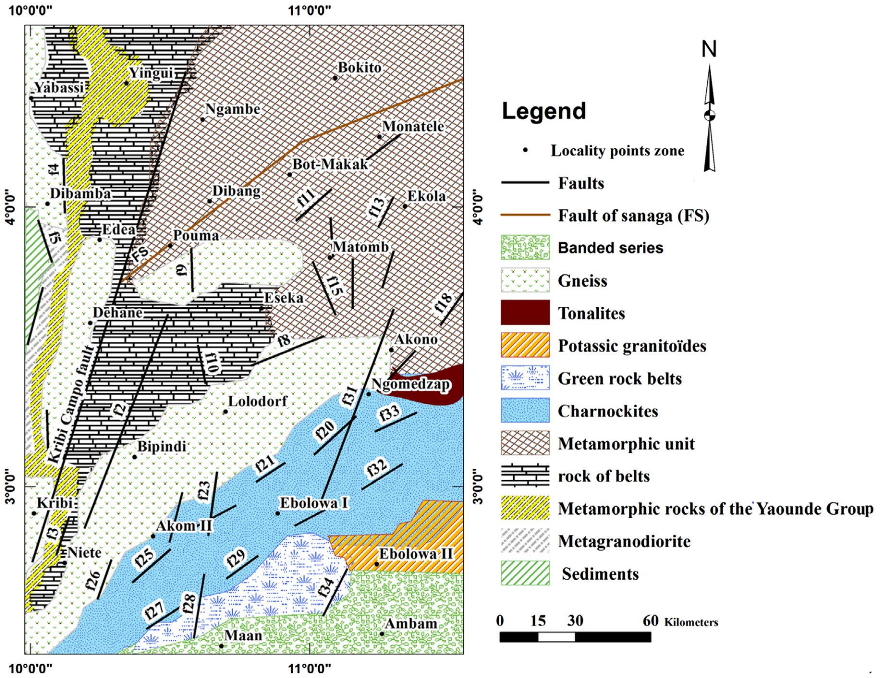

Figure 2. Geological map of south-west Cameroon based on (Feybesse et al., 1998; Koumetio et al., 2014; Ndongmo et al., 2023a) modified.

In this study, using gravimetric data derived from the SGG-UGM-2 model, we aim to highlight structural elements that could contribute to a better geological understanding of the South-West Cameroon zone, since knowledge of deep-seated faults in this region, where the seismic risk is not negligible, is important. To achieve this objective, the methods of vertical gradient, horizontal gradient coupled with upward continuation and Euler deconvolution were used. The efficiency of these techniques has been substantiated by a multitude of empirical studies, including those conducted in the context of southern Cameroon (e.g., Koumetio et al., 2012; Basseka et al., 2011; Shandini et al., 2010; Clotilde et al., 2016). Furthermore, the enhanced interpretation of Bouguer anomaly maps can facilitate the identification of structures of regional significance. The combination of these methods therefore serves to reinforce the validity of the results presented in this article.

2. Geological and Tectonic Context

The study area (**Figure 2**) is entirely underlain by the formations of the Ntem complex and the presence of Pan-African terrains evolving at the northwestern margin of the Congo Craton, known here as the Yaoundé Group. The Ntem complex is divided into two units: the Ntem unit of Archean age and the Nyong unit of Paleoproterozoic age (Lerouge et al., 2006; Penaye et al., 2004; Pouclet et al., 2007; Toteu et al., 1994). The Archean basement of the basin is composed mainly of greenstone belt rocks, charnockites and potassic granitoids (Nzenti et al., 1998). The Nyong unit comprises metasedimentary and metavolcanic rocks, granitoids and syn-tectonic to late-tectonic syenites (Ndema Mbongue et al., 2014; Pouclet et al., 2007). Recent work reveals that the area has mainly undergone brittle deformation linked to multi-stage compressional and extensional tectonics that give rise to major faults. These are mainly characterized by the Kribi-Campo Fault (KCF) system, which is defined here as a continuation of the Sanaga Fault (Claude et al., 2014; Tadjou et al., 2009). Cheunteu Fantah et al. (2022) estimated the depth of the lineaments highlighted in the study area from gravity and magnetic data, this depth varies between 1 and 35 km. It should be noted that some of the faults identified in this study remain active, as their positions correspond to the occurrence of recent earthquakes in Cameroon. Several authors (Koumetio et al., 2012; Koumetio et al., 2014; Yandjimain et al., 2023) have applied the multi-scale gradient analysis method to the Bouguer anomaly in order to highlight lineaments and intrusive bodies in southwest Cameroon. Work carried out by Tabod (1991) on the continental volcanic line of Cameroon shows that the earthquakes that occurred in the vicinity of Kribi had foci located at a depth of around 30 km.

3. Data and Method

3.1. Satellite Gravity Data (SGG-UGM-2)

This study used a high-resolution terrestrial gravity field model SGG-UGM-2, as the Bouguer gravity anomaly. Combining observations from the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE), the Gravity Recovery and Climate Experiment (GRACE) normal equation, marine gravity data derived from satellite altimetry, and continental gravity data derived from EGM2008, this model is built up to degree 2190 and order 2159. It is derived from the theory behind the Ellipsoidal Harmonic Analysis and Coefficient Transformation (EHA-CT) method for calculating spherical harmonic coefficients from averaged grid areas and point gravity anomalies on the ellipsoid (Liang et al., 2020; Liang et al., 2018). The Bouguer anomaly map of the SGG-UGM-2 model is shown in **Figure 3**, reflecting the effect of all density heterogeneities beneath the topographic surface.

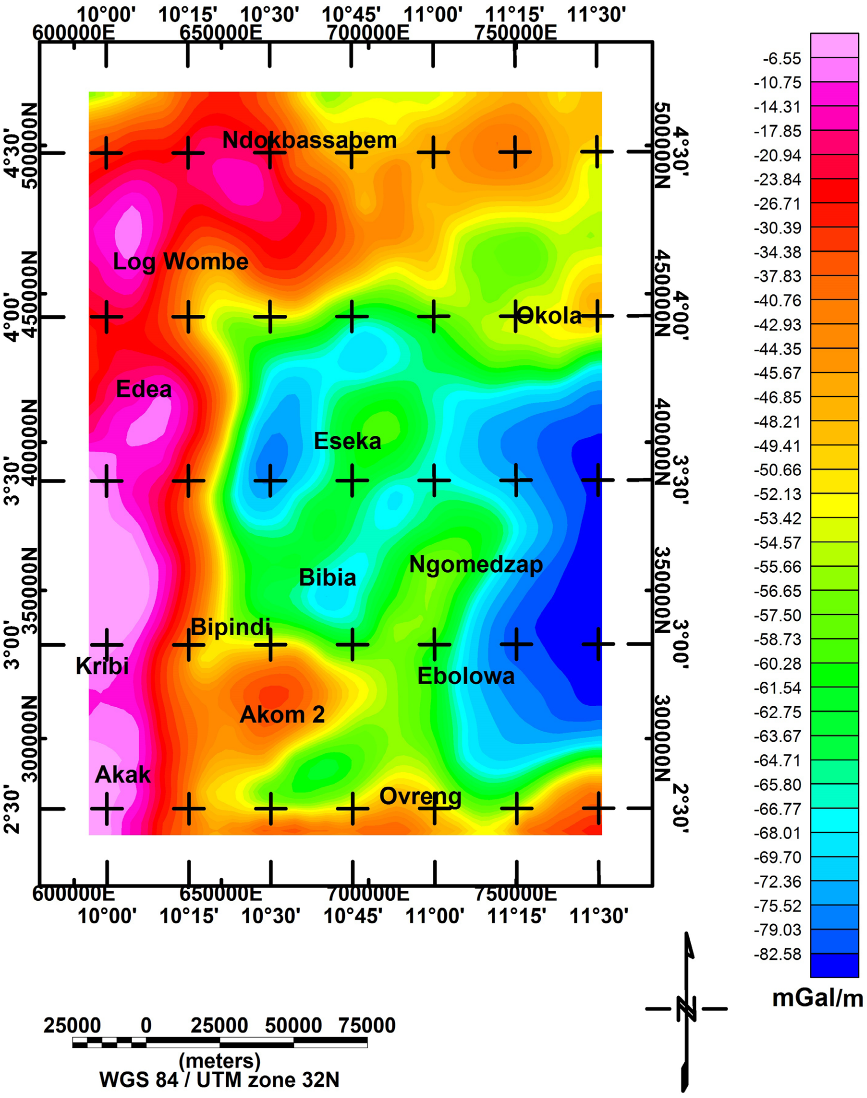

Figure 3. Bouguer gravity anomalies map.

3.2. Method

Various methods were applied to the Bouguer Anomaly of the SGG-UGM-2 model, in order to highlight the main structural features and the delineation of the various characteristic lineaments. The Bouguer anomaly is caused by geological structures of different dimensions and/or located at different depths. In an attempt to isolate the long-wave phenomena responsible for the regional anomaly, we perform a regional/residual separation using a polynomial fit (Radhakrishna Murthy & Krishnamacharyulu, 1990). This procedure highlights the role of shallow geological structures.

To better exploit these data and bring out new elements in relation to the information provided by the residual map, we applied a series of mathematical treatments. These involve filtering the gravimetric signal in the frequency domain. The vertical gradient was applied to the residual map to highlight shallow lithologies. It is obtained using the following expression:

$$\frac{\partial F}{\partial z} \tag{1}$$

where F is the gravity field.

According to Dobrin & Savit (1988) and Telford et al. (1990), this transformation should attenuate, if not eliminate, the regional component that distorts and sometimes masks the relationship between shallow basement geology and anomaly shape. The vertical gradient acts as an amplifier for high frequencies, i.e. for anomalies of small extension, at least in one direction.

According to Nabighian (1984), the analytical signal is the three-dimensional (3D) vector, where the absolute value of this signal is defined as the square root of the sum of the vertical and the two horizontal derivatives of the magnetic field. If F is the gravimetric field, then the absolute value of this signal is given by:

$$AS = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2 + \left(\frac{\partial F}{\partial z}\right)^2} \tag{2}$$

where $\frac{\partial F}{\partial x}, \frac{\partial F}{\partial y}$ and $\frac{\partial F}{\partial z}$ represent the gravity data gradients F.

Calculating the horizontal gradient from the residual anomaly is very useful for locating geological contacts, as the boundary between two blocks of different densities corresponds to the maximum of this gradient (Blakely, 1995; Blakely & Simpson, 1986; Cordell & Grauch, 1985; Khattach et al., 2004). The *THG* formula is given by Cordell & Grauch (1985):

$$THG = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2} \tag{3}$$

where $\frac{\partial F}{\partial x}$ and $\frac{\partial F}{\partial y}$ represent the gravity data gradients F.

Coupled with upward continuation, the horizontal gradient enables faults to be located and their dip determined (Archibald et al., 1999; Khattach et al., 2004). Linear contacts correspond to faults, while circular contacts are the limits of diapirs or intrusive bodies.

The Euler deconvolution method, applied to potential field data, enables us not only to locate contacts in the horizontal plane, but also to estimate their depth (Nabighian & Hansen, 2001). It is based on a mathematical procedure represented by the Euler homogeneity equation (Thompson, 1982):

$$\frac{\partial M}{\partial x}\left(x-x_0\right)+\frac{\partial M}{\partial y}\left(y-y_0\right)+\frac{\partial M}{\partial z}\left(z-z_0\right)=SI\left(B-M\right) \qquad (4)$$

where (x_0, y_0, z_0) is the position of the source the effect is detected in (x, y, z).

Thompson (1982) and Reid et al. (1990) point out that the choice of structural index appears to be very important; for a number of structures, they have established a structural index (N) that can take values from 0 to 3, corresponding to whole numbers for certain simple structures. Thus, they consider that an N = 1 index is best suited for thin veins, dykes and faults with low vertical rejection, and an N = 0 index for faults with high rejection, and an N = 0.5 index for intermediate cases.

4. Results and Discussion

4.1. Bouguer Anomaly Map

Analysis of the Bouguer map in the study area enables us to identify the main features of the anomalies observed and to establish the links between these anomalies and the geological and tectonic contexts of the region. The Bouguer anomaly map (**Figure 3**) shows the existence of several anomalies of different shapes and signs, with values ranging from −82 to −6 mGal. These different gravity anomalies are separated by zones of strong gradients, indicating the presence of density discontinuities, generally materializing tectonic faults. A visual analysis of this map (**Figure 3**) shows that the study area is characterized by elongated anomalies following dominant directions SSW-NNE to North-South (N-S) and secondary directions South-West to North-East (SW-NE), East to West (E-W), South-East to North-West (SE-NW) to South-South-East to North-North-West (SSE-NNW). **Figure 3** shows, on the one hand, areas with dense anomaly sources (above-average anomalies of −42 mGal), and on the other, areas with less dense anomaly sources (below-average anomalies). Superimposing these anomalies on the major geological and structural features of the study area reveals the lack of correlation between the various gravity anomalies and the surface geology, suggesting structural complexity.

4.2. Residual Anomaly Map

Implementing the separation technique introduced by Radhakrishna Murthy and Krishnamacharyulu (1990), the residual anomaly map (**Figure 4**) is derived from the Bouguer anomalies by subtraction of a second-order regional polynomial surface. The selection of the regional second-order surface was based on a careful examination of terrestrial gravity data, with the aim of effectively distinguishing deep and shallow structural anomalies in the South-Western region of Cameroon.

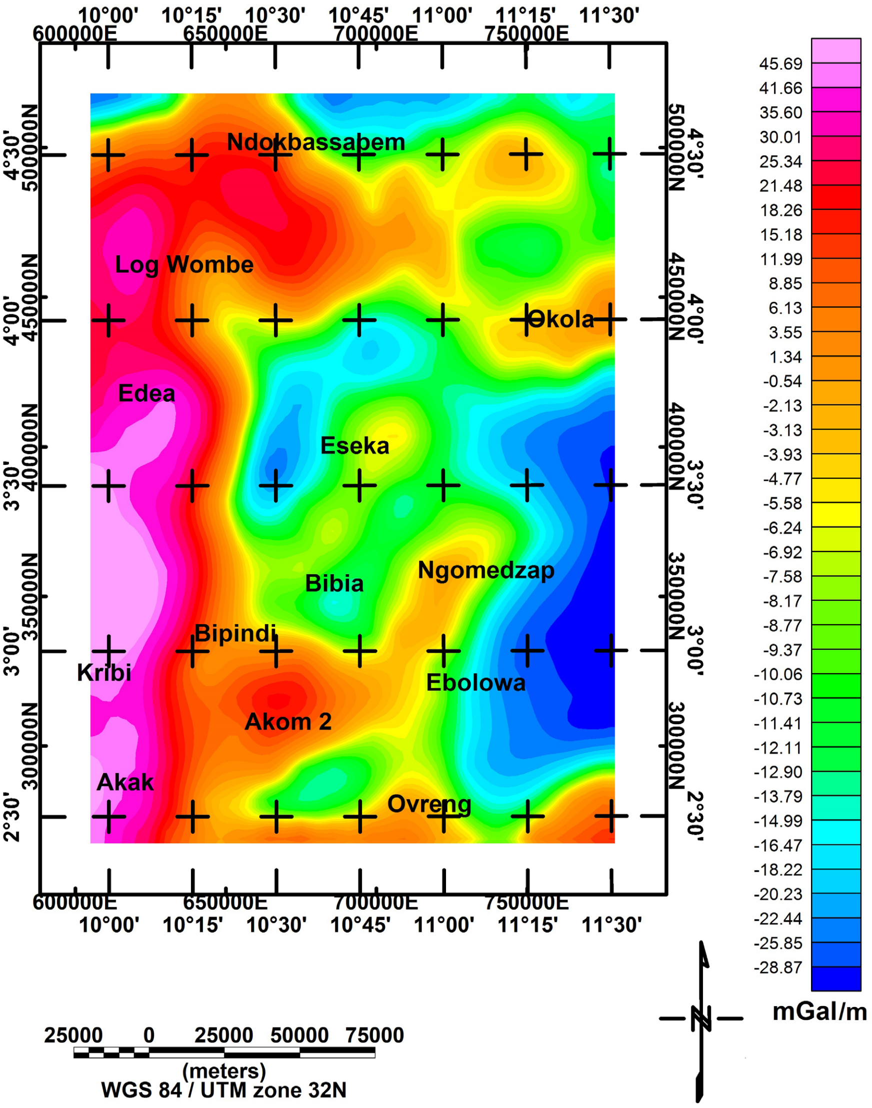

Figure 4. Residual gravity anomalies map.

The residual anomaly map (Figure 4) highlights anomalies related to shallower crustal structures than most of those observed on the Bouguer map. From a general point of view, we note that the residual anomaly map (Figure 4) shows the same characteristics as those of the Bouguer anomaly. Like the Bouguer anomaly map, the residual anomaly map shows areas of positive and negative anomalies, separated by zones of significant gradients. The map shows anomalies with amplitudes ranging from −28 to +45 mGal. From west to east, the study area is characterized by:

- At the western edge, a major positive anomaly trending South-North to East-West, with a maximum amplitude of 45 mGal in the Akak locality, and between the area between Kribi and Edea. The linear shape of this anomaly suggests that it marks the boundary of a large structure to the left of the study area. This major anomaly is located on top of Archean and Paleoproterozoic formations. Its position close to the sea suggests that the source of this anomaly consists of very dense rocks.

- The central part of the study area is characterized by anomalies of intermediate values, ranging from −17 mGal to −6 mGal. This area is separated from the area described above by a westward-trending N-S gravity gradient.
- The eastern boundary is characterized by a large negative anomaly located between Ebolowa and Okola. This anomaly is thought to be the gravimetric signature of reworked Craton formations. This zone is separated from the central part by a N-S gradient.

The residual anomaly map shows several zones of strong gravimetric gradients that may correspond to contacts or discontinuities (faults, flexures, etc.). To study these zones of particular interest for structural characterization of the study area, we applied the analysis methods described above.

4.3. First Vertical Dérivative Map

The purpose of the first vertical derivative is to highlight anomalies associated with shallow structures at the expense of those associated with deep structures. Illustrated in this study by Figure 5, the first derivative map shows a lateral separation of anomalies and an amplification of the gravimetric effect of superficial

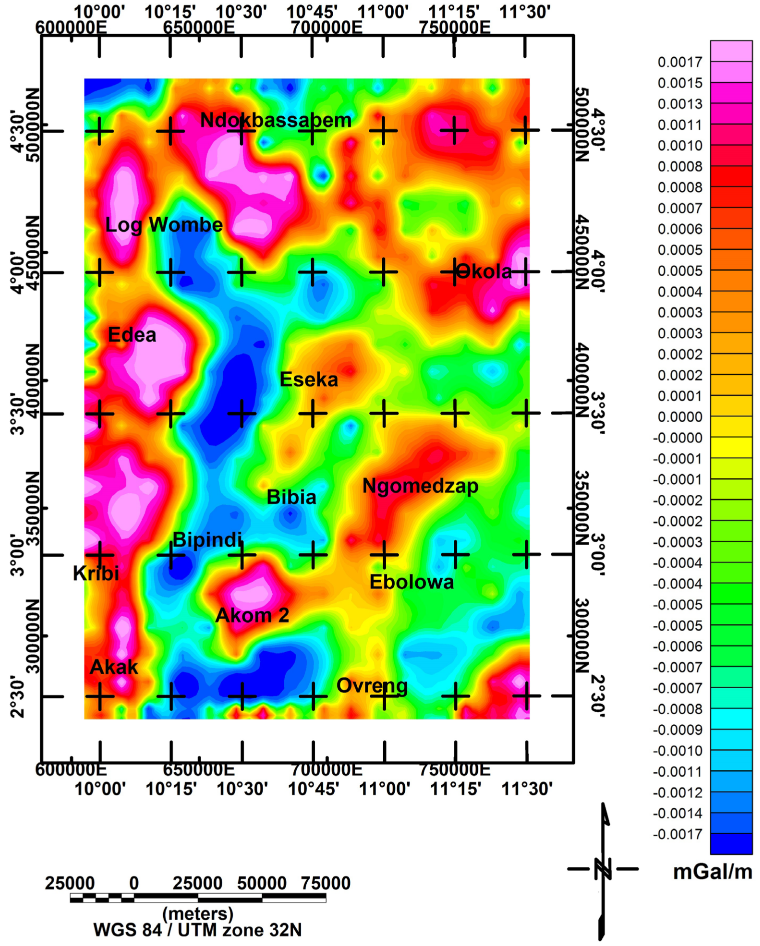

Figure 5. First Vertical Derivative (FVD) of the residual gravity anomalies map.

density contrasts to the detriment of deep density contrasts. A phenomenon of decoalescence can be observed here, with certain long-wavelength anomalies identified on the residual anomaly map being decomposed into two or more other short-wavelength anomalies. This phenomenon is clearly visible at the western edge of the study area, where the large anomaly that used to occupy this zone has broken up into short-wavelength anomalies of varying shape and size. A similar phenomenon was observed in the Ebolowa zone, at the western edge of the study area. The large negative anomaly that was present in this area has disappeared to the detriment of new anomalies of more restricted extension associated with superficial sources, which clearly confirms that it is of deep-seated origin. The new anomalies highlighted on the first derivative map are probably due to the presence of tectonic faults, intrusions and very significant superficial geological contacts in the subsurface of the study area. The presence on this map of the vertical gradient oriented ENE-SSW observed between the localities of Kribi and Edea could materialize the Kribi-Campo Fault observed on the geological map (**Figure 2**).

4.4. Horizontal Gradient Map

The horizontal gradient map of the Bouguer residual anomalies shown here in **Figure 6** highlights zones of horizontal gradients of varying amplitude, shape

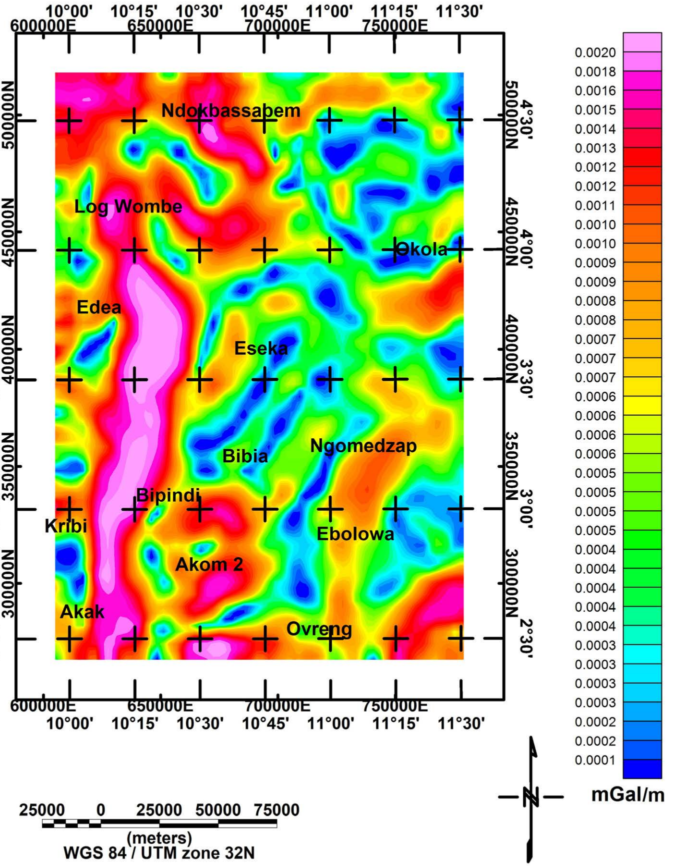

Figure 6. Total horizontal gradient of the residual gravity anomalies map.

and orientation. The diversity of anomalies observed on the map reflects the complexity of the geological structures in the area under investigation. Gradient zones can be easily distinguished in areas such as Aka, Bipindi, Kribi, Ebolowa, Eseka and Ndokbassaben. The trends of these high-amplitude horizontal gradients are approximately NNE, NNW to NS in some places. These gradients probably correspond to contact/fault-type structures (high-gradient zone) and intrusive structures. The presence of these lineaments, although widely spaced due to the resolution limitations of the SGUGM-2 global gravity model data, serves as evidence that the subsurface of the study area is significantly influenced by geodynamic phenomena.

4.5. Multiscale Analysis of Gradient Maxima and Lineaments Map of the Studied Area

To highlight the geological contacts associated with the faults or fractures suspected on the previous maps, we applied the multi-scale horizontal gradient analysis method described above to the Bouguer residual anomalies. The map below (**Figure 7**) is an overlay of the horizontal gradient maxima maps of the

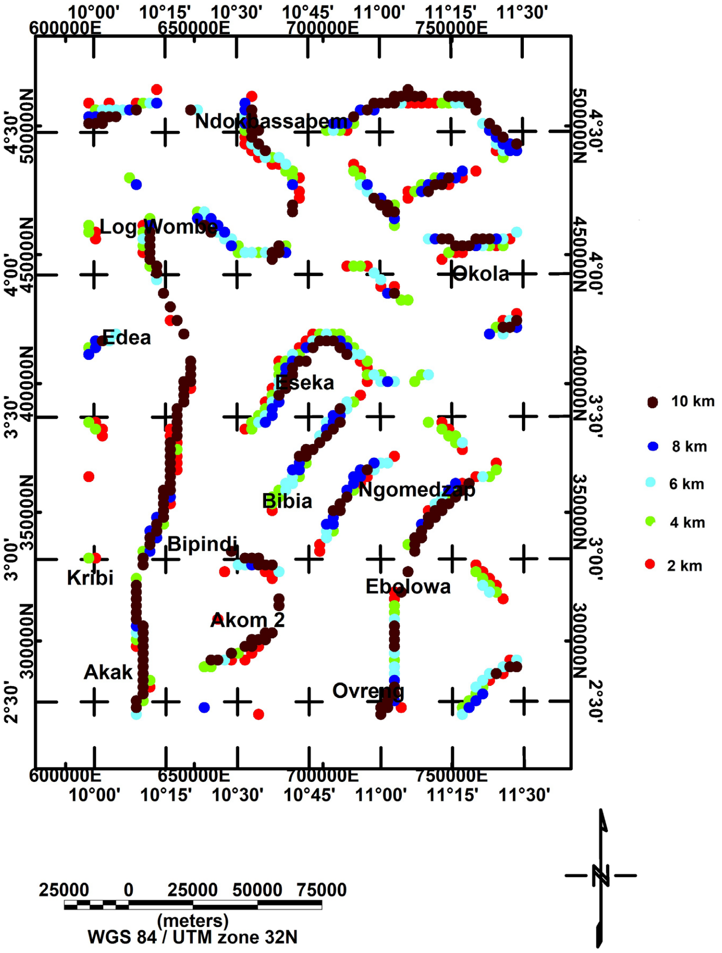

Figure 7. Superposition map of maxima of the horizontal gradient of the residual gravity anomalies.

Bouguer residual anomalies extended upwards at 2 km, 4 km, 6 km, 8 km and 10 km. These maxima highlight areas of abrupt density change, interpreted either by faults or geological contact, as intrusive information (Jilali & Khattach, 2023; Souga Kassia et al., 2020). The behavior and directions of superimposed maxima provide information on the orientation and dip of localized lineaments (**Figure 7**). The degree of importance (at depth) of a fault is determined by the persistence of the presence of local maxima at increasingly higher extension altitudes. In the context of this study, it would appear at first glance that the maxima of the various extension levels are superimposed over almost the entire map, which implies that most of the structures in the study area are vertical structures, highlighting (1) linear contacts corresponding to faults or (2) circular contacts corresponding to the horizontal contours of the boundaries of intrusive bodies or diapirs. These include:

- A family of N-S, ENE-WSW-trending accidents in the Akak and Kibi localities, materialized by the superposition of maxima resembling linear structures. The same is true for those passing to the south-east and north of the study area, with multiple directions, north of Okola, between Oveng and Ebolowa. The quasi-vertical dip of these families of faults suggests that they are deep, non-outcropping faults associated with lithospheric extension.
- Circular or curvilinear lineamentary structures with closed contours in the Akom 2, Eseka and Bibia localities, based on the superposition of maxima, refer to cavities.

The map of local maxima of horizontal gradients calculated at different altitudes (**Figure 7**) has enabled us to construct a synthetic structural map highlighting accidents (faults numbered 1 to 17) and the contours of intrusive formations in the bedrock (1 to 4) (**Figure 8**). This map is a valuable tool for hydrogeological and mining research, providing essential information on flow directions, drainage axes and recharge zones. Statistical analysis reveals the presence of 21 gravitational structural features, ranging in size from 0.21 km to 62.81 km, with an average of 17.12 km. The rosette of mapped fracture directions highlights the main preferential directions: NW-SE, NNE-SSW, ENE-WSW and secondary directions: NNW-SSE, NE-SW, NS and E-W. This interpretation validates the interpretations already made on the residual and derived maps of the study area. These different structural directions all belong to the Pan-African domain. The deep basement faults observed in this area concur with the findings of Shandini et al. (2010) and Basseka et al. (2011), who confirmed the CC/NEFB collision and identified NE-SW and NW-SE lineaments within the area. The ENE-WSW orientation, characteristic of Pan-African tectonics on a regional scale, has also been noted in the study area by Feumoe et al. (2012) and Noutchogwe et al. (2010). This is also the direction of major Pan-African structures in Cameroon, such as the Cameroon Shear Center and the Sanaga Fault. Analysis of gravity data revealed numerous NNE-SSW to NS fractures and faults, acting as local connections with the Kribi-Campo fault associated with the Kribi Shear Zone. This fault is recognized as the southern extension of the

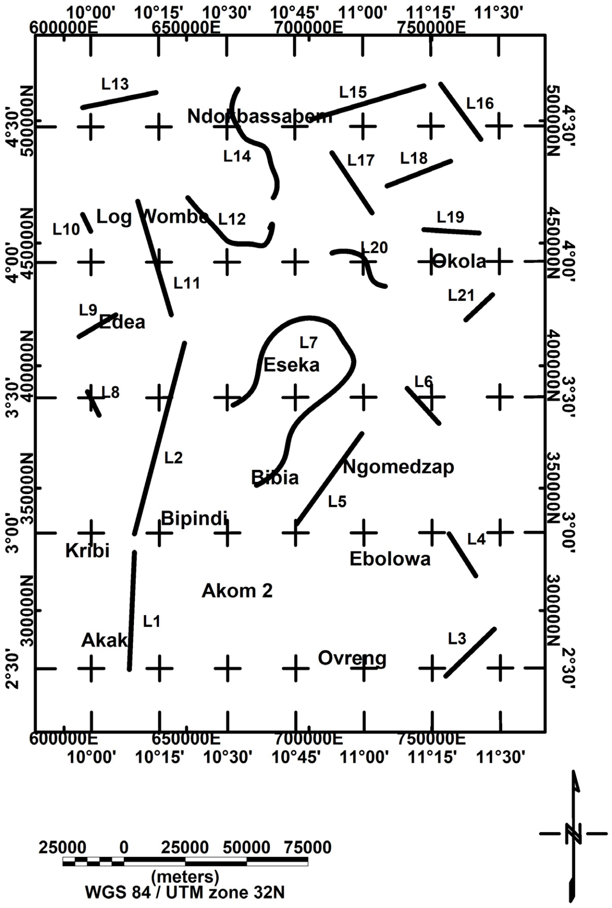

Figure 8. Structural map of the Bouguer gravity anomalies data.

Eseka-Dja fault by Angue et al. (2011). The EW, NS, NE-SW and NW-SE trending faults identified in this investigation, align with faults observed in previous aeromagnetic studies conducted in southern Cameroon by Feumoe et al. (2012) and Ndougsa-Mbarga et al. (2012). The presence of these lineaments, although widely spaced due to data resolution limitations of the SGG-UGM-2 global gravity model, serves as evidence that the subsurface of the study area is significantly influenced by geodynamic phenomena (**Figure 9**).

4.6. Euler Deconvolution Map

In this work, to improve the estimation of depth-to-basement solutions, Euler's 3D deconvolution technique was performed on Bouguer data with the aim of finding the depth-to-basement of lineaments. The procedure is carried out with a 10 × 10 moving window, a depth tolerance of 15% and structural indices 0.5 to effectively locate contact boundaries, faults and dykes. The Euler solution map reveals new deep contacts and clearly defines that the solution for depth ranges from 2.7 km to 11.2 km. Contact depths in the zone are not uniform, suggesting that not all lineaments have the same origin. These Euler depths seem to detect the edges of geological formations, as well as fractures or fault patterns (**Figure 10**).

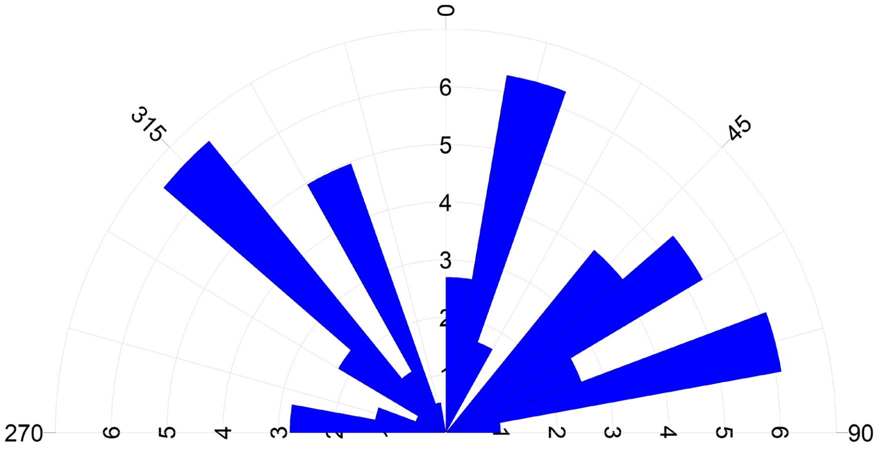

Figure 9. Rose diagram that shows the fault orientations within Southeast Cameroon.

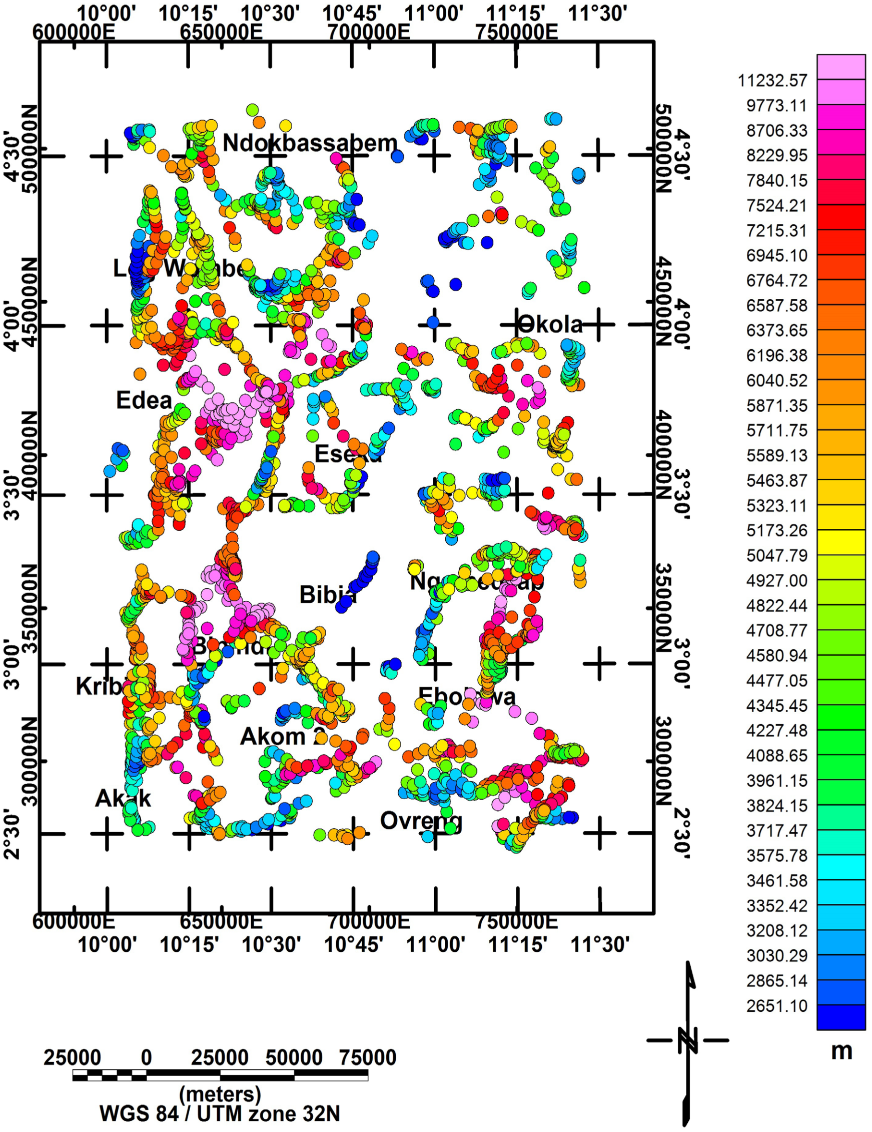

Figure 10. Euler solutions of the residual gravity anomalies. Structural index: 0.5 depth tolerance: 15%; Nyquist window 7 km × 7 km.

5. Conclusion

This study investigated the structural characteristics of the South-West region of Cameroon, using gravity data derived from the SGG-UGM-2 model. At the end of this investigation, a structural diagram of the South-West Cameroon region was drawn up. This document incorporates structures previously recognized by direct geological mapping of outcrops or interpreted taking into account geological and topographical considerations. In addition to the major faults highlighted in this study, indications have been obtained of their dip and depth. Together, these structures form a network of faults preferentially oriented along the following directions: NW-SE, NNE-SSW, ENE-WSW NNW-SSE, NE-SW, NS and E-W. These directions are generally well correlated with pan-African geological structures. The NNE-SSW and N-S directions are probably related to the Kribi shear zone. The Euler deconvolution method was applied to the Bouguer anomaly map to highlight the various surface faults in the study area and their depths. In view of the geological structures highlighted in this study, it is clear that tectonic activity continues in the region. Although this study has established a structural scheme for the south-west region of Cameroon, further research is needed to refine our understanding of the geology of this area. An in-depth analysis of the physical properties of the rocks, such as density, porosity and permeability, would help to better constrain the geological models and improve the interpretation of the gravity data. The integration of drilling data would provide valuable information on the lithology, stratigraphy and structure of the subsoil. This would help refine interpretations and validate geological hypotheses. Finally, the use of other geophysical methods, such as seismic or magnetometry, could provide additional information on the structure of the subsoil and enable tectonic discontinuities to be better characterized.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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