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Crustal structure of Loum-Minta region derived from satellite gravity data and its tectonic implications

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--***ABSTRACT***--
The objective of this study is to improve the knowledge of the geological structures of the Loum-Minta area using satellite gravity data derived from the WGM2012 global geopotential model. The Bouguer anomaly map obtained shows values ranging from 50.91 to 87.24 mGals. The map is characterized by elongated anomalies in a dominant NE-SW direction, influenced by the orientation of the geological formations of the region. Tilt angle, Center for Exploration Targeting (CET) and Euler deconvolution were applied to the Bouguer anomaly grid covering Loum-Minta. These two techniques revealed a series of lineaments with main orientations N-S, ENE-WSW, E-W and NE-SW. A strong correlation between the structures highlighted by tilt angle and CET was observed, confirming their accuracy. The Euler deconvolution method was also applied to the Bouguer anomaly grid, with a structural index SI = 0.2 and a window size of 10, where the depth of the source roofs exceeds 7 km. The structural map could help to update the geological map of our study area and be used in future hydrogeological or mining work.

Key-words: *Satellite gravity, WGM2012, CET, Euler deconvolution*

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I. INTRODUCTION

Our work concerns a strictly continental domain located east of central Cameroon, precisely in the transition zone between the Congo Craton and the Pan-African chain. This zone presents a variety of evolutionary and age structures, divided into a Cratonic domain and a Pan-African domain. For several years it has been the focus of a series of geophysical studies (Amougou et al., 2020; Diallo et al., 2023; Mono et al., 2019; Mono, Ndougsa-Mbarga, Bi-Alou, et al., 2018; Mono, Ndougsa-Mbarga, Tarek, et al., 2018; Ndougsa-Mbarga et al., 2014; Ndougsa-Mbarga et al., 2011; Zanga-Amougou et al., 2013). The results of this work suggest that this region is characterized by a continental collision with the thrusting of the Pan-African craton (Mvondo et al., 2007; Ngako et al., 2008; Tchakounté et al., 2017; Toteu et al., 2004). A recent study conducted to the north of the study area by Salimatou Dialo et al. (2023), which combined magnetic and geological data, highlighted certain geological structures, in particular magnetite quartzites, which are considered potential sources of primary rutile mineralization. The work of Mono et al. (2018, 2019), using aeromagnetic data, highlighted a series of geological accidents organized along the main directions E-W, ENE-WSW, NE-SW.

The gravimetric method uses the correlation between variations in the gravity field and the density of the subsurface rocks to infer and identify crustal structures. In Cameroon, this method has been widely used to characterize surface and deep structures (Apollinaire et al., 2017; Fantah et al., 2024; Nana et al., 2021; Saidou et al., 2024; Shandini & Tadjou, 2012; Tadjou et al., 2009; Yandjimain et al., 2024; Zanga-Amougou et al., 2013). It should be noted, however, that the accuracy of the results obtained with this method may depend on whether terrestrial or satellite gravity data are used. In reality, gravimetric data in Cameroon are very scarce and have low spatial resolution due to the inaccessibility of the areas. To compensate for the lack and scarcity of terrestrial and airborne gravity data, several authors suggest that gravity data derived from the gravity model can be used effectively. They are less costly and allow rapid, general coverage of large exploration areas in less time. In Cameroon, interesting results have been obtained using satellite gravity data (Anaba Fotze et al., 2021; Fantah et al., 2024; Nana et al., 2021; Yandjimain et al., 2024; Zanga-Amougou et al., 2013).

The combined global gravity field model based on the World Gravity Map (WGM2012) satellite (Bonvalot et al. 2012; Förste et al. 2014; Gilardoni et al. 2016) was used in this work. The consistent coverage of the entire study area provided by the WGM2012 gravity data will allow geological and geophysical interpretations that are currently not possible with the available airborne and ground-based data. The objective of this study is to improve the knowledge of the geological structures of the Loum-Minta area by applying the Tilt Angle Method, Center for Exploration Targeting (CET) and Euler deconvolution to satellite gravity data from the WGM2012 global geopotential model.

II. GRAVITY DATA GEOLOGIC AND TECTONIC SETTING OF STUDY AREA

The study area (Figure 1) is part of the North Equatorial Pan-African Range (Nzenti et al., 1988; Nzenti et al., 1998). This chain is considered to be the result of convergence and collision between the Congo craton and the mobile belt (Abdelsalam et al., 2002; Penaye et al., 1993; Toteu et al., 2001). Cameroon is characterized by: (i) Paleoproterozoic migmatitic gneisses and granulites (Penaye et al., 1989); (ii) Meso- to Neoproterozoic metamorphosed and deformed volcanosedimentary sequences (Nzenti et al, 1988) and (iii) syn-tectonic granitoids with calc-alkaline affinity intruded into gneisses (Kwékam et al., 2010; Njanko et al., 2006).

Structurally, this area has recorded numerous shear zones such as the Central Cameroon Shear Zone (CCSZ) and the Sanaga Fault (SF) (Dumont, 1986). Three phases of deformation have been highlighted in this area by (Nzenti et al., 1998; Nzenti et al., 2007; Tchakounté et al., 2017). The D1 tectonic event is associated with high-grade amphibolite facies metamorphism and develops S1 schistosity, while the D2 phase is associated with medium-grade amphibolite facies metamorphism (Nzenti et al., 1998). The essentially brittle D3 phase is characterized by the emplacement of diaclases and veins. However, this phase is associated with the development of major regional structures such as the Central Cameroon Shear (CCC) and the Sanaga Fault (SF).

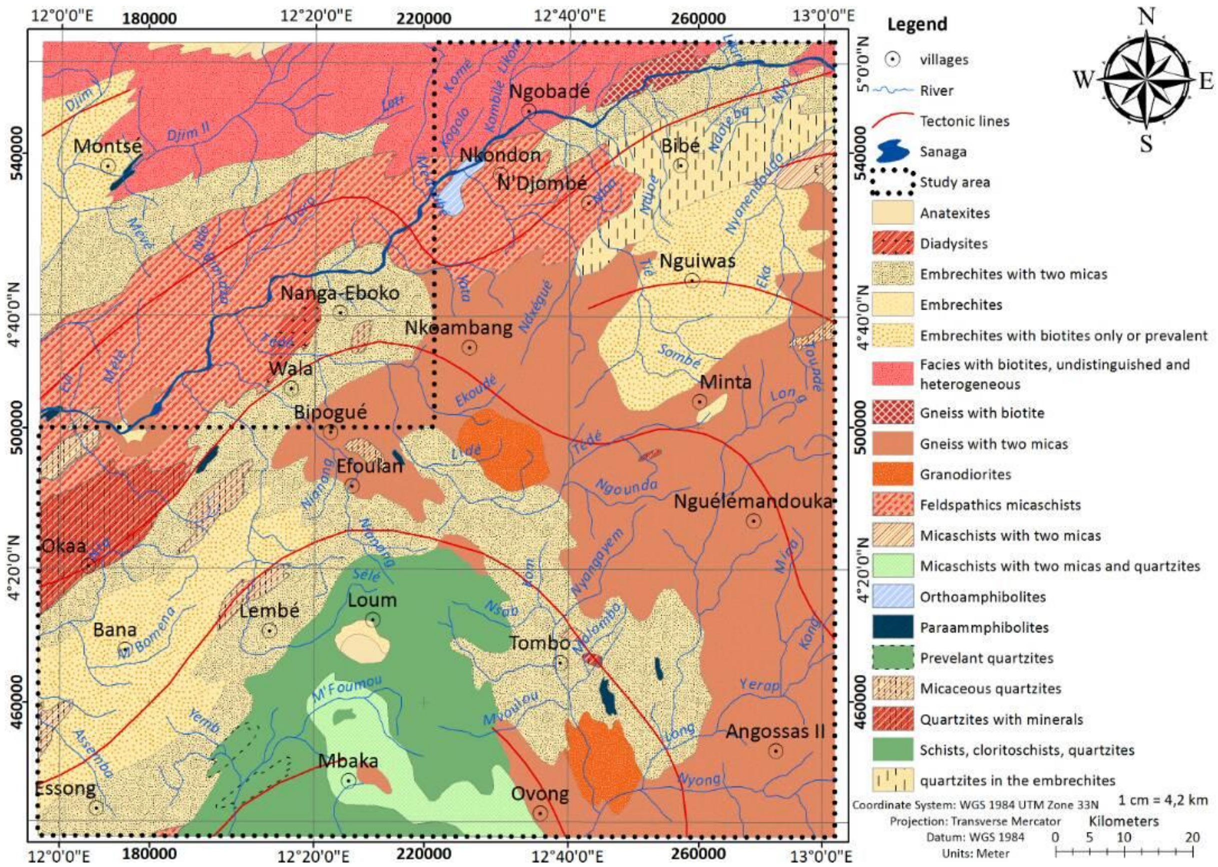

Figure 1: Geological map of the study area ((Gazel & Gérard, 1954), modified as a document available in the public domain).

III. MATERIALS AND METHOD

Gravity Data

The Bouguer gravity anomaly data for Loum-Minta (Figure 2) were obtained from the database of the World Gravity Map (WGM2012), which was released by the Commission for the Geological Map of the World (Balmino et al., 2012), with a latitude and longitude range of 4° - 5°E and 12°–13°N, and a grid spacing of 0.1°, respectively. The International Bureau of Gravity Survey built the WGM2012 database based on the high-resolution global Earth gravity models EGM2008 and Technical University of Denmark (DTU10) global gravity field using the spherical harmonic approach. Terrain corrections were derived from the ETOPO1 model, which considers the contribution of most surface masses (atmosphere, land, oceans, inland seas, lakes, ice caps, and ice shelves).

The tilt angle derivative (TDR)

The tilt angle method (Miller & Singh, 1994; Salem et al., 2008; Verduzco et al., 2004) is the calculation of the inverse tangent of the ratio of the modulus of the horizontal partial derivatives to the vertical derivative of the magnetic field, which is written according to the equations:

$$\theta = tan^{-1}\frac{\frac{\partial M}{\partial z}}{\sqrt{\left(\frac{\partial M}{\partial x}\right)^2+\left(\frac{\partial M}{\partial y}\right)^2}} \qquad (1)$$

where M is the magnetic field or anomaly map. The advantage of the transformation is that by calculating an angle, all shapes are represented similarly, whether the anomalies are of low or high amplitude. According to (Salem et al., 2007), the zero value of the angle corresponds to the structure boundary (h = 0) and the distance between the ± 45° value and the zero value corresponds to the structure depth. In this way, we can observe the boundaries of tabular structures and their depths directly on the transformed map.

CET method

The Centre for Exploration Targeting (CET) is a suite of algorithms that provides functionalities for the enhancement, lineament detection, and structural complexity analysis of potential field data (Holden et al., 2008). This technique employs a series of automated steps to delineate lineaments and identify promising areas of ore deposits. These steps include the outlining of regions of convergence and divergence of structural elements, as well as texture analysis, lineation delineation and vectorization, and complexity analysis, which collectively generate a contact occurrence density map.

Euler Deconvolution

Euler deconvolution is a method used to obtain position and apparent depth of gravimetric or magnetic anomalies sources (Reid et al., 1990; Thompson, 1982). This method consists in making the link between the components of a gravity field and the position of anomalies sources with a degree of homogeneity called "structural index". Euler's deconvolution equation (Thompson, 1982) is written as follows:

$$\frac{\partial M}{\partial x}(x-x_0)+\frac{\partial M}{\partial y}(y-y_0)+\frac{\partial M}{\partial z}(z-z_0)=SI(B-M) \qquad (2)$$

Where (xo, yo, zo): position of the magnetic source; (x, y, z): position of the observer; M: total magnetic field detected at (x, y, z); B: regional value of the total field; SI: degree of homogeneity, often called structural index. In geology, the depths obtained by Euler deconvolution represent the stratigraphic or structural transitions found in geological formations. Thus, these Euler solutions appear where there are lithological discontinuities.

IV. RESULTS AND INTERPRETATION

Bouguer

Figure 2 shows the Bouguer anomaly map covering the study area with positive and negative anomalies of varying size and amplitude ranging from 50.91 to 87.24 mGals. This map reflects lateral variations in the density of the Loum-Minta shallow and deep geological units and is characterized by elongated anomalies following the dominant NE-SW direction. An overview of the configuration of these anomalies shows that they are strongly influenced by the orientation of the geological formations of the region. The brightest anomalies are located to the south at the Mbaka prospect, with an amplitude of 50 mGal, and are also found at the Nguiwas and Minta prospects, which are characterized by a NE-SW orientation. The Bouguer anomaly map of the study area is also characterized by the presence of significant anomalies around the Angossas 2 and Nguelemendouka localities. These anomalies are thought to be the result of bedrock uplift due to magmatic intrusions of dense rock. There are zones of strong anomalies (anomalies above the average of -68 mGal) and zones of weak anomalies (anomalies below the average), sometimes separated from the former by gradients of varying magnitude. Gravimetry plays an important role in identifying deep faults, their boundaries and their branches (Everaerts & Mansy, 2001). The strong contrasts (gradients) shown on the gravity map are the result of discontinuities or interfaces such as faults, flexures and intrusive contacts.

The main immediate information provided by the Bouguer anomaly map is the distribution of density heterogeneities. This map does not provide sufficient information, but it does contain information such as the amplitude of horizontal gradients between anomalies, or low amplitude anomalies that are often masked by regional anomalies. Three tools proved useful in processing this map: tilt angle, CET, and Euler deconvolution..

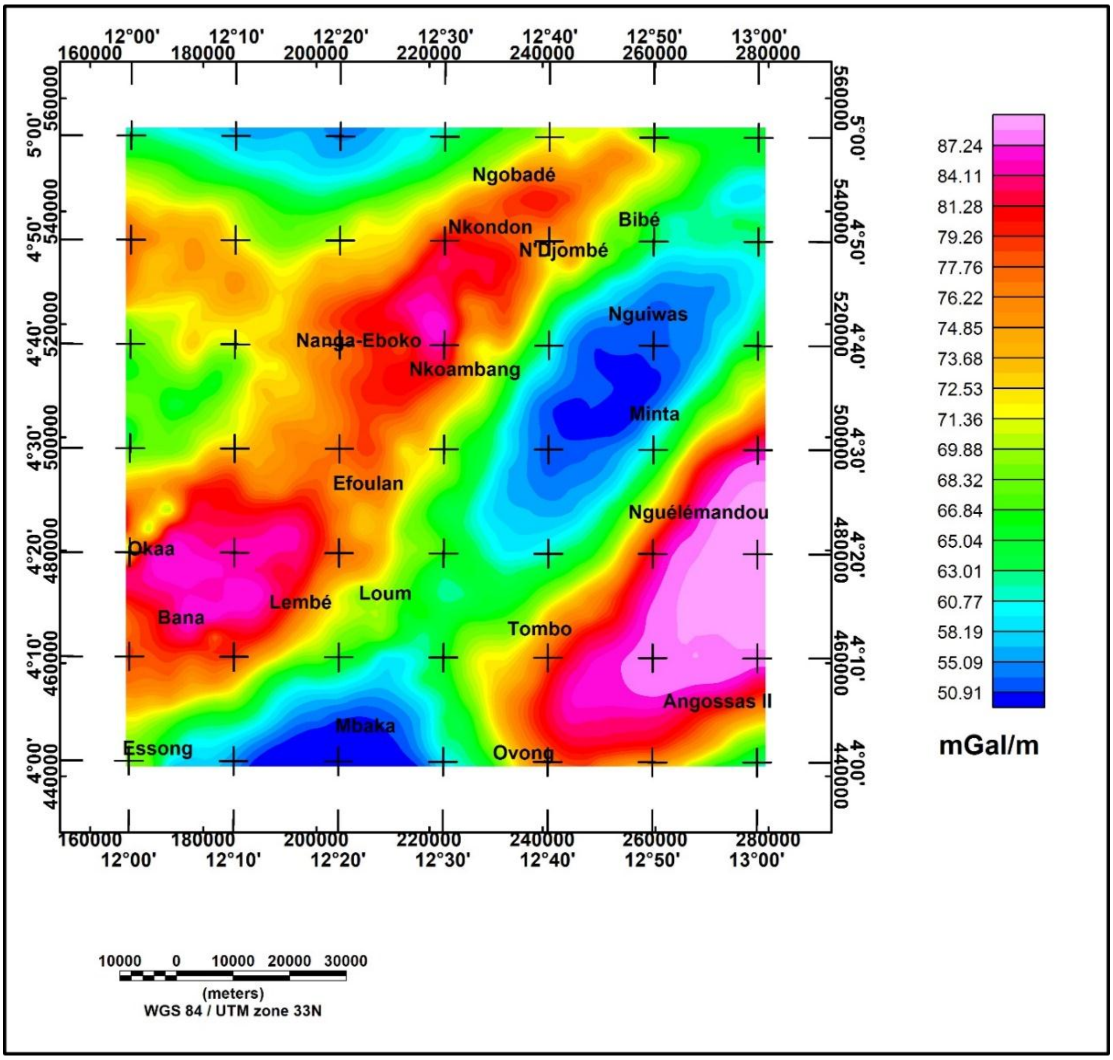

Figure 2: Bouguer anomaly map of the study area.

Tilt angle map

To identify structure boundaries, the TDR method was applied to the Bouguer anomaly data grid covering the study area. The TDR map (Figure 4) of the study area shows a range of values from -1.32 to 1.29 radians. Geological contacts are represented by black lines corresponding to zero Tilt angle. Figure 5 shows a summary of the various contacts obtained using this technique, highlighting the main boundaries between zones with significant density contrasts. At first glance, Figure 5 shows that the shape of the highlighted structures suggests: (1) linear contacts corresponding to faults or (2) circular contacts corresponding to the horizontal contours of the boundaries of intrusive bodies or diapirs. Thus, linear contacts would refer to faults or fractures located at variable depths and oriented along the following preferred directions: E-W, ENE-WSW, NE-SW. Linear pseudocircular or curvilinear structures with closed contours refer to cavities. This is the case for the cavities in and around the Nanga-Eboko area. These lithological contacts, which are clearly visible in the southwestern part of the study area, indicate that we are dealing with intrusions of low density compared to the density of the host structure, or with infill.

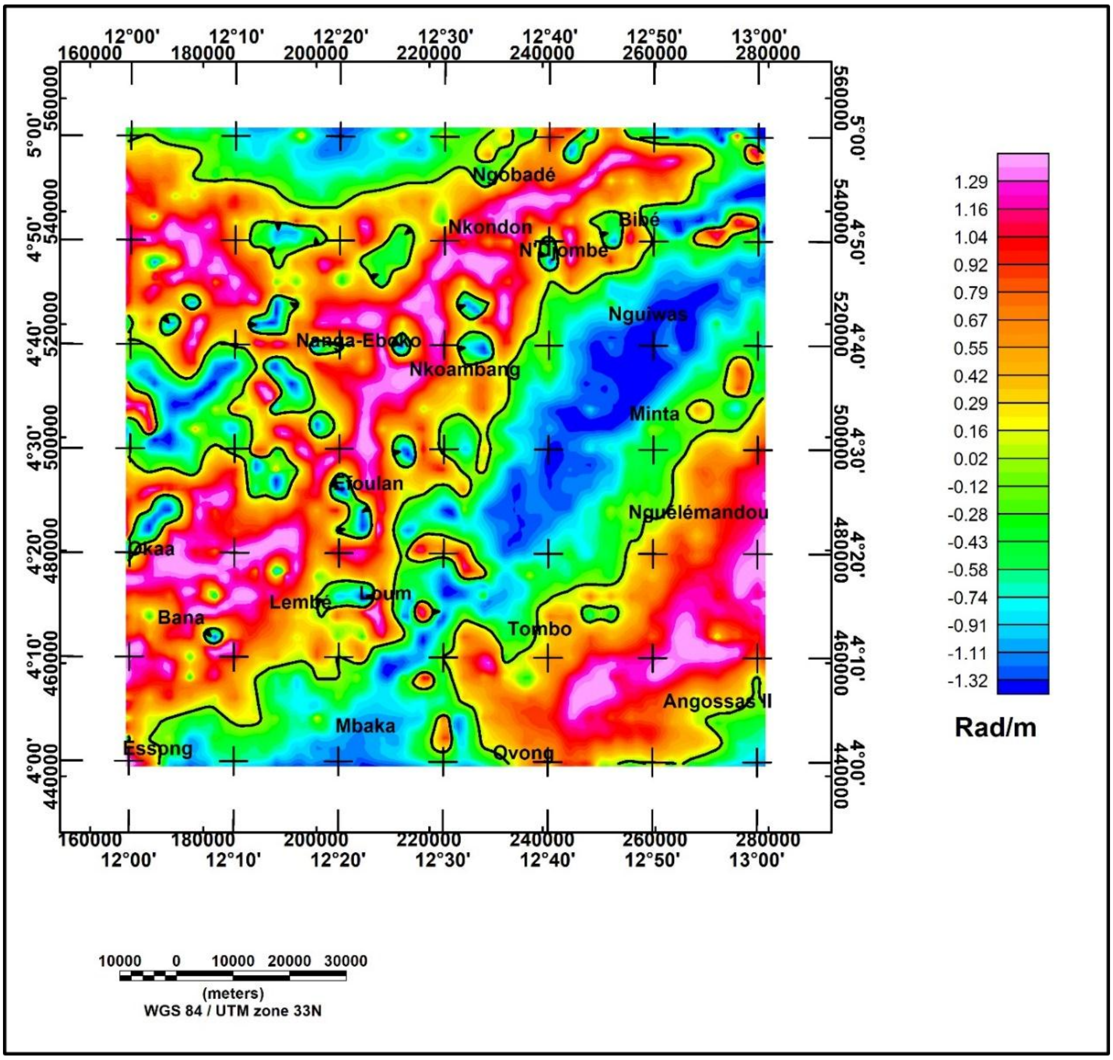

Figure 3: TDR map, the black lines show the 0 radian contour of the tilt angle.

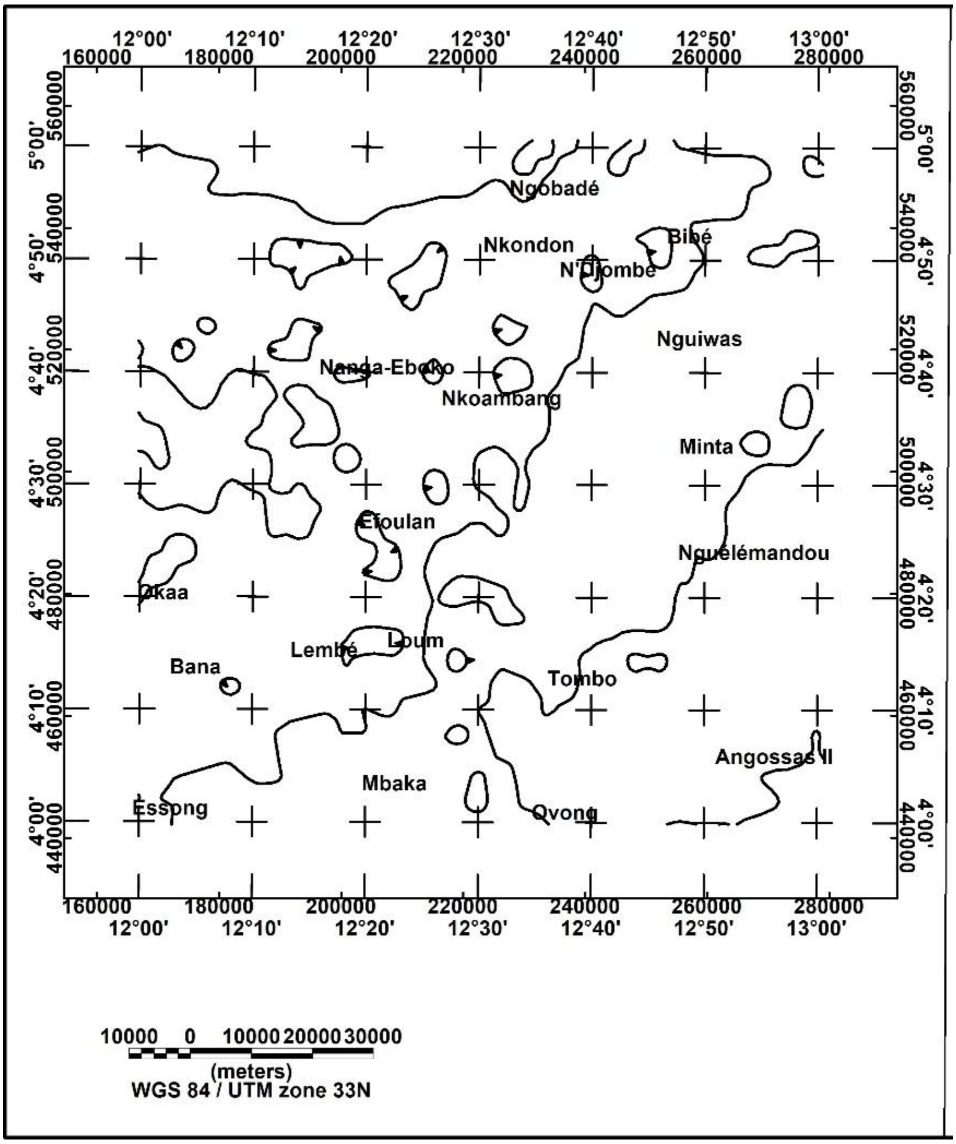

Figure 4: Lineaments of Tilt angle derivative (TDR).

CET lineament analysis of gravity data

The approach involved the identification of linear structures within the gravimetric data through the use of consecutive map byproduct forms, including standard deviation, which estimates density variations, and phase symmetry, which is employed to separate laterally continuous lines. Subsequently, the resulting lineaments were enhanced by suppressing noise and background signals using an amplitude thresholding technique The outcome of the CET lineament extraction is illustrated in Figure 5. In general, the traces are oriented in the N-S direction, although some are oriented in the E-W direction.

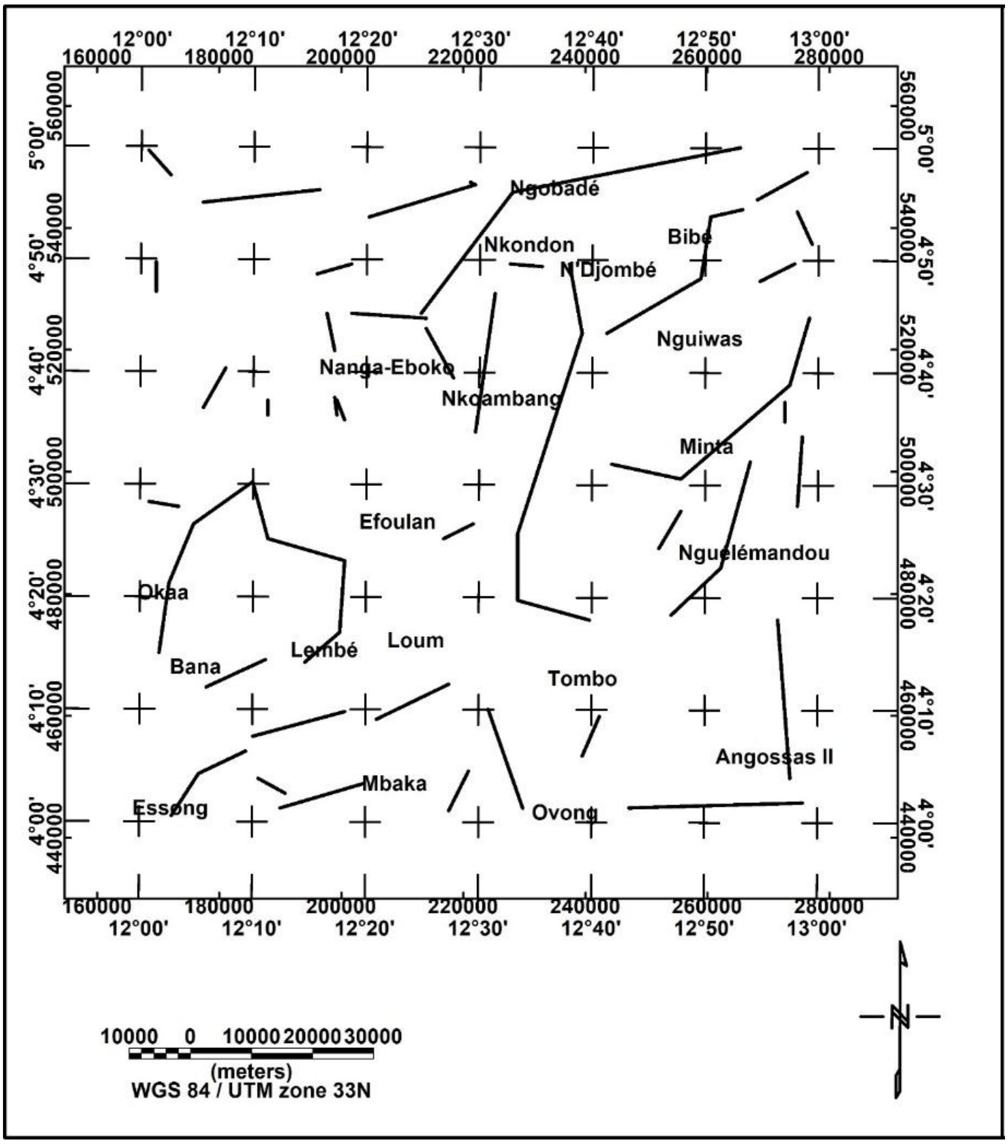

Figure 5 : Vectorisation lineaments map

V. STRUCTURAL INTERPRETATIVE MAP AND EULER DECONVOLUTION

In order to better illustrate the results obtained from the tilt angle and CET methods, we have summarized all these observations in an interpretative map of gravimetric lineaments. This document integrates (i) structures previously recognized by direct geological mapping of outcrops and (ii) others newly highlighted in the present study. Examination of Figure 6 shows good agreement between the structures highlighted by the two techniques. Together, these structures form a network of faults preferentially oriented in N-S, ENE-WSW, E-W and NE-SW directions, with N-S directions dominating according to the directional rosette (Figure 6B). These observed directions are consistent with those highlighted by several geophysical studies in the vicinity of the study area (Amougou et al., 2020; Apollinaire et al., 2017; Basseka et al., 2011; Diallo et al., 2023; Ndougsa-Mbarga et al., 2014; Yandjimain et al., 2017). The Euler deconvolution method was applied to Bouguer anomalies with a 10 × 10 window, a maximum tolerance of 7% and a structural index of 0.2. This structural index was chosen because it better distinguishes the various contact zones and subsurface faults. Figure 7 shows the structural solutions obtained by applying Euler's method to the Bouguer anomalies. The solutions (faults and fractures) are grouped into six depth ranges from shallow to deep subsurface at [0; 2 km [, [2; 4 km [, [4; 6 km [, [6; 8 km [, [8; 10 km [and over 10 km intervals, respectively. This explains why the origins of lineaments and faults in the study area are diverse. The calculated depth ranges place these features in the brittle zone of the upper crust. This is consistent with studies by Mono et al. (2018, 2019) and Amougou et al. (2020).

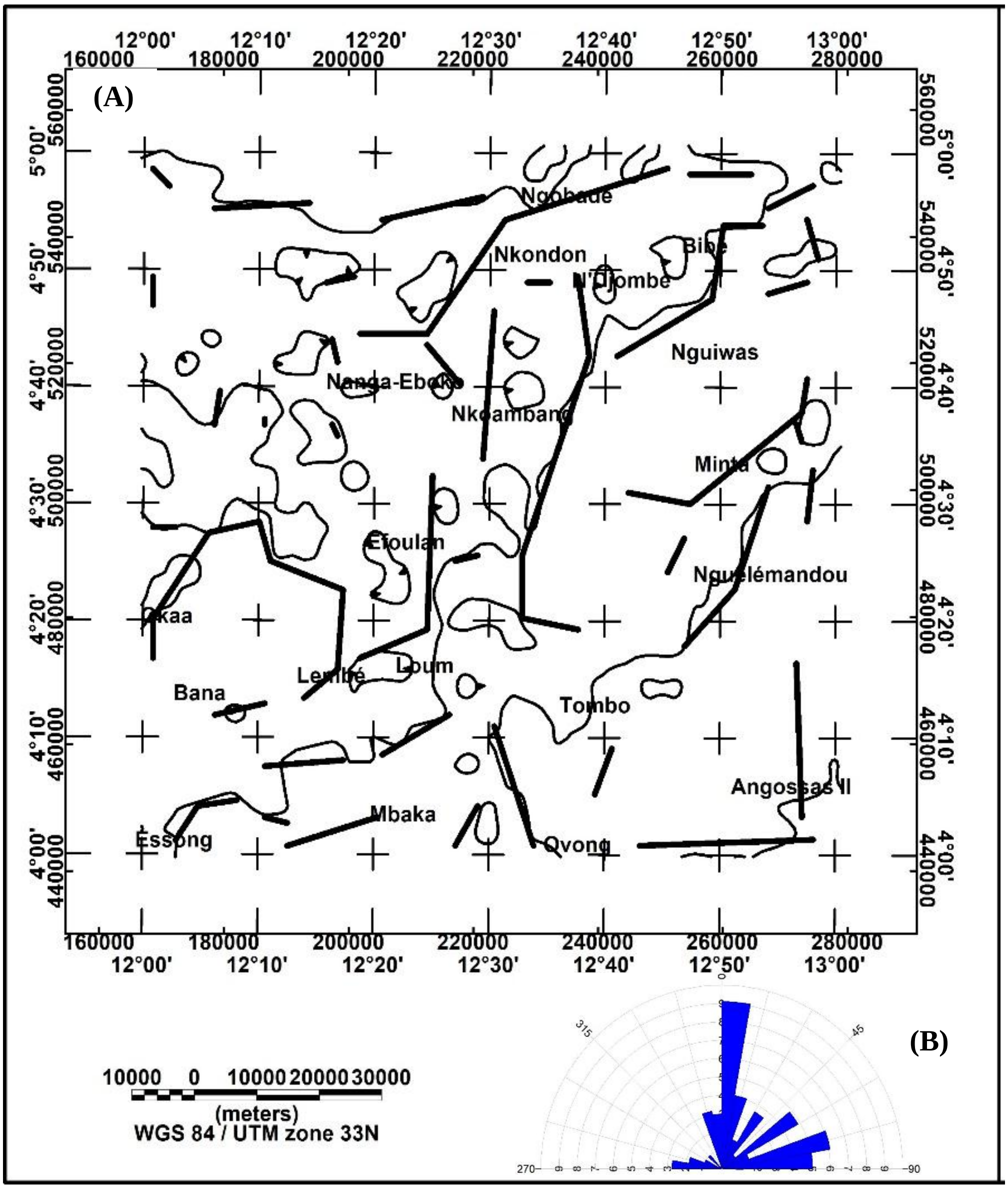

Figure: A Structural map of study area; B: rose diagram

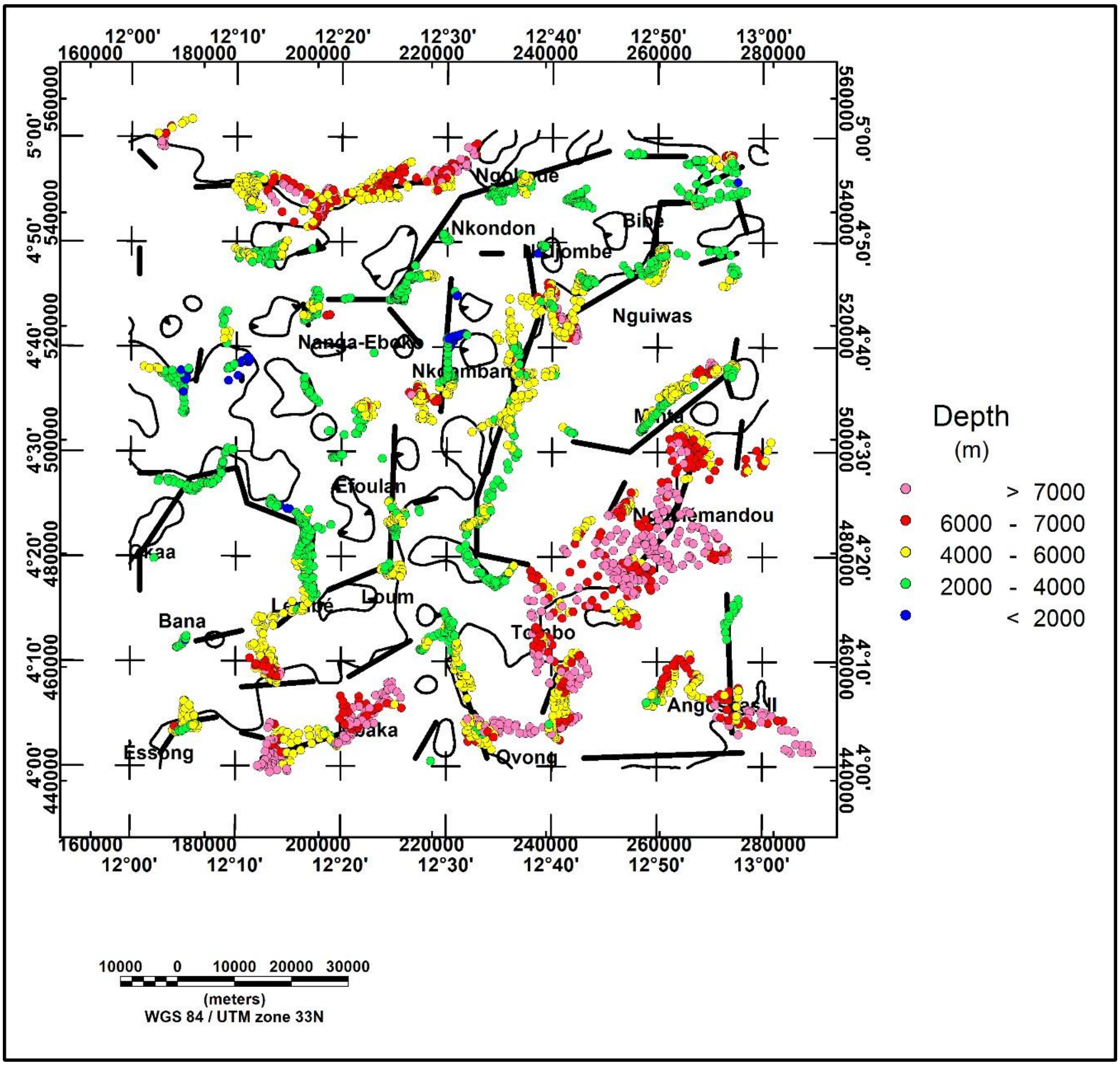

Figure 7 : Structural interpretation map of Euler solutions for N = 0.2.

VI. CONCLUSION

The present work, based on the analysis of satellite gravity data, has highlighted the various geological structures present in the region. Calculated and interpolated Bouguer anomalies have revealed gravity signatures that correlate well with previous work in the study area. Tilt angle and CET were used to highlight the lineaments of the study area. A structural map of the study area was produced, confirming the existence of faults recognized or inferred by previous studies, specifying their orientation, and highlighting new, previously unknown faults. The Euler deconvolution method was also applied to the Bouguer anomaly map to highlight other features and to estimate the depth of the source roofs of the various structures to depths of over 7 km. The information provided by this study should guide future hydrogeological and mining exploration campaigns in the region. It is recommended that prospecting efforts be focused on areas with the strongest gravity anomalies. However, further studies combining multiple geophysical and geological methods would be required to further the understanding of this complex area.

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