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Magnitude Of The Southern Spill Of Pan-African Formations On The Congo Craton: Implication On The Northern Tectonic Limit Of The Congo Craton In Southern Cameroon With Extension In The Central African Republic From Spectral Analysis And 3d Modeling

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Abstract:
A gravimetric study is being conducted in Cameroon and the Central African Republic with the aim of determining the extent of the southern spillover of the formations of the Central African Pan-African Belt (CAPB) onto the Congo Craton (CC). To achieve this, we first determined the geophysical boundary (Tectonic Boundary) of the Congo Craton (TBCC) in the study area, which extends from South to North between latitudes 3°00'N and 5°00'N and from West to East between longitudes 10°00'E and 16°00'E. Knowledge of the geological boundary of the Congo Craton (GBCC) has shown that the tectonic boundary is situated further north than the geological outcrop boundary. The data used in this work are derived from the EIGEN-CG03C gravity model. The data grid of this gravity model was extracted from ICGEM with a resolution of 0.01° 0.01°. Spectral analysis performed on six (06) profiles allowed us to assess the depths of investigation to a little over 14 km. The 3D modeling showed not only that the TBCC has a deep origin, but also that the granulites are a suture formation between the CC and the CAPB; this metamorphic formation was established after the collision between the CC and the CAPB. The Tilt Angle method enabled us to delineate the sought tectonic boundary on the anomaly maps and to accurately evaluate the extent of the southern spillover of the Pan-African formations onto the CC. This work shows that the maximum spillover amplitude (~83.5 km) is observed in the west of the study area between Mpem and Yaoundé in Cameroon, while the minimum amplitude (~18.5 km) is observed in the east of the southern area of Carnot in the Central African Republic. The central region is characterized by an amplitude that has a little variation, with an average amplitude of approximately 55.5 km.*
Key Word*: spillover amplitude; tectonic boundary; geological boundary; spectral analysis; tilt angle; 3D modeling.*

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I. Introduction

The term "geophysical boundary" was first introduced by Dumont (1986). Since then, the geophysical boundary between the Congo Craton (CC) and the Central African Pan-African Belt (CAPB) has been of significant geological and geophysical interest. This boundary, also referred to as the Tectonic Boundary of the Congo Craton (TBCC), marks the transition between two major lithospheric layers, offering valuable insights into the tectonic processes that have shaped the region throughout geological history. The transition zone between the CC and the CAPB is particularly important for understanding the evolution of crustal density variations, the collision and orogeny processes that have led to the juxtaposition of dense archean rocks and less dense pan-african rocks in this region [1]. Although the precise delineation of the northern boundary of the Congo Craton remains to be determined, geophysical studies highlight a network of faults traversing the study area. These studies reveal that this boundary is located between two linear sets of deep geological structures, continually subjected to compressive stresses [1], [2], [3]. A series of previous works, mostly conducted in neighboring regions, indicate that the area is characterized by a major E-W tectonic feature along the 4°N parallel, not identified by classical geology, likely due to its depth [3]. Previous geophysical studies, including gravimetric surveys [2],[5], seismology [6], magnetism [7], and aeromagnetics [8], have provided additional information on the complex tectonic structuring of the region. The objectives of the present study are to prove the existence of the northern tectonic boundary of the CC, to materialize it, to model the structures characterizing the transition zone between the CC and the CAPB, to demonstrate that this boundary has a deep origin, and to assess the extent of the southern spillover of pan-african formations onto the CC.

II. Material And Methods

Geology and tectonics of the study area

The geological map of the study area (Fig. 1) reveals that it straddles the Congo Craton (CC), which occupies its southern part, and the Central African Pan-African Belt (CAPB) located in its northern part. It extends from South to North between latitudes 3°00'N and 5°00'N, and from West to East between longitudes 10°00'E and 16°00'E. The pan-african tectonic events occurred in the mobile zone of Central Africa, located in the central and northern regions of Africa, and this mobile zone constitutes the main component of the pan-african orogeny around 530 Ma [9], [10], [11]. In Cameroon, this Central African mobile region is referred to as the Central African Pan-African Belt [12]. The basement of this region consists of a metamorphic complex, as well as platform formations that are structurally linked to the underlying complex, folded and slightly altered. The CC in Cameroon is represented by the Ntem complex, which mainly comprises crystalline and granular rocks (granodiorites) dating from the Archean era, which were reinforced during the Eburnean orogeny [13]. According to geological investigations, the study region was formed during the pan-african event at the end of the Proterozoic and the beginning of the Paleozoic, during the convergence and collision between the Congo Craton to the south and the Pan-African Mobile Belt to the north [8], [9], [14]. The lithological richness of the region is evident in the transition zone between the CC and the pan-african formations. The ancient geological formations of the Congo Craton, such as gneisses, granites, and schists, testify to an ancient geological history characterized by metamorphic and magmatic processes [10], [11]. Their increased density compared to the basement is due to their mineralogical composition and previous tectonic evolution [15]. The presence of metamorphic rocks such as granulites, migmatites, and schists in the Pan-African formations indicates more recent tectonic processes associated with the pan-african orogeny [1]. The metamorphic rocks, which have a lower density than the Archean rocks, result from metamorphic and deformation processes. The Central African Pan-African Belt, the main component of the northern zone, is characterized by intrusive rocks of basic magmatic origin such as basalts, granulites, gneisses, and granites, as suggested by studies [1], [15].

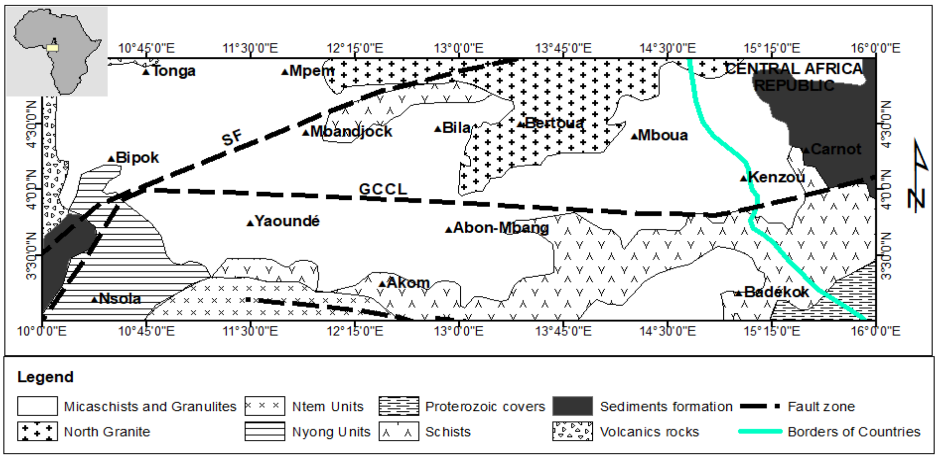

Figure. 1. Geological map of the study area, modified [2] (SF: Sanaga fault; GCCL: Geological Congo Craton Limit)

Origin of gravity data

The gravity model data from EIGEN-CG03C are used in this work. The data grid for this gravity model was extracted from ICGEM with a resolution of 0.01°* 0.01°. The EIGEN-CG03C combined gravity field model is an upgrade of EIGEN-CG01C [16]. This model offers high-resolution gravity data up to degree and order 360, with topographic heights calculated from the spherical harmonic model of topography (ETOPO1) using 2670 kg.m^{-3} as the density value for the continents. This means it can detect smaller and more precise gravity variations across the Earth's surface, allowing for better visualization and understanding of gravitational anomalies. The EIGEN-CG03C model combines gravity data from several sources, including the CHAMP and GRACE missions, as well as terrestrial gravity data. This multi-source approach enables better coverage and higher accuracy of the gravity data [17].

Methods

All the gravimetric data maps were modeled using the Geosoft Oasis Montaj v 8.4 software. This software allowed us to model the gravimetric data maps and perform various filtering processes to obtain other maps, such as the residual anomaly map and the tilt angle map. Using Matlab 2022, we determined the depth of the geological structures from the data collected on the profiles drawn on the residual map. ArcGIS 10.2.2 software enabled us to create the geological map of the study area, while Potent software version 4.17 allowed us to compare the experimental curve obtained from the anomalies observed on the residual anomaly map with the calculated curve, also known as the theoretical curve, in order to achieve a 3D modeling of the geological structures.

Isostatic separation

The concept of isostasy is based on the principle of gravitational equilibrium between the lithosphere and the asthenosphere. The Oasis Montaj software version 8.4 was used to perform this separation. The isostatic separation method, as implemented in Geosoft Oasis Montaj software, uses Bouguer data as well as topographic information to estimate regional and residual gravity. This approach relies on a modified version of the algorithm developed by the USGS to calculate the isostatic regional gravity of Airy from a topographic grid. It allows for determining the depth to the Mohorovičić discontinuity using the topographic grid, terrain density, Moho density contrast, and compensation depth relative to sea level. The topography is modeled assuming a continental crust density of 2670 kg/m³ and an upper mantle density of 3300 kg/m³. The results of this calculation are then combined with a solution beyond this depth to obtain a complete regional gravity according to the Airy model [18].

The tilt angle

The tilt angle method is an effective technique for detecting the edges of subsurface structures and estimating their depth using a tilt angle map derived from gravity gradient data. The tilt angle (TDR) is defined as follows [19],[20]:

$$TDR = tan^{-1}\left(\frac{\frac{\partial g}{\partial z}}{\sqrt{(\frac{\partial g}{\partial x})^2 + (\frac{\partial g}{\partial y})^2}}\right) \qquad \textit{Equation 1}$$

Where $\frac{\partial g}{\partial z}$ is the vertical gradient of gravity and $\sqrt{(\frac{\partial g}{\partial x})^2 + (\frac{\partial g}{\partial y})^2}$ is the magnitude of the horizontal gradient. The tilt angle (TDR) varies in the range: $-\frac{\pi}{4} < TDR < +\frac{\pi}{4}$. This angle is zero at the measurement point ($x = x_0$) indicating the horizontal location of the source. Furthermore, the depth of the source can be estimated because the tilt angle reaches $+\frac{\pi}{4}$ when $x - x_0 = z_0$ and $-\frac{\pi}{4}$ when $x - x_0 = z_0$.. Therefore, half of the horizontal distance between the $\pm\frac{\pi}{4}$ radians contours of the tilt angle correspond to the depth of the source. Additionally, the depth of the source can also be determined from the distance between the points where the tilt angle is zero and $\pm\frac{\pi}{4}$ radians, considering a vertical contact at the point ($x = x_0$).

Spectral analysis

Spectral analysis, as described by Spector and [21], is an interpretation technique based on the study of the energy spectrum properties of gravity or magnetic anomalies. Indeed, the average depth of the disturbing masses (responsible for the observed anomalies) can be estimated by studying the logarithm of the spectral power as a function of spatial frequency. Gravity varies with distance along an established profile, and spectral power is the amplitude of the discrete Fourier transform of gravity. The average depth of the sources responsible for the different observed anomalies can be evaluated using the following expression [22],[23]:

$$H = \frac{\Delta logP}{4\pi\Delta k} \qquad \textit{Equation2}$$

Where $\log(P)$ is the variation of the logarithm of the spectral power for a variation of spatial frequency, $k(1/km)$ and $H(km)$ is the average depth of the plane representing the density contrast. The underlying assumption is that shallow sources are represented by the high wavenumber portions of the entire spectrum, and only deep sources contribute to the low wavenumber portion [15].

III. Result

Topographic Map of the Study Area

Figure 2 presents the topographic map of the study area, highlighting the various altitude variations within the studied zone. This map reveals that the study area is quite rugged, especially in the vicinity of the 4°N parallel, around the geological boundary. Altitudes in this transition zone between the CC and the CAPB reach approximately 7500 m. This confirms that we are in an area that has been tectonically active and implies the presence of one or more faults in the study area. The topographic map has been obtained with the assistance of Oasis Montaj software version 8.4.

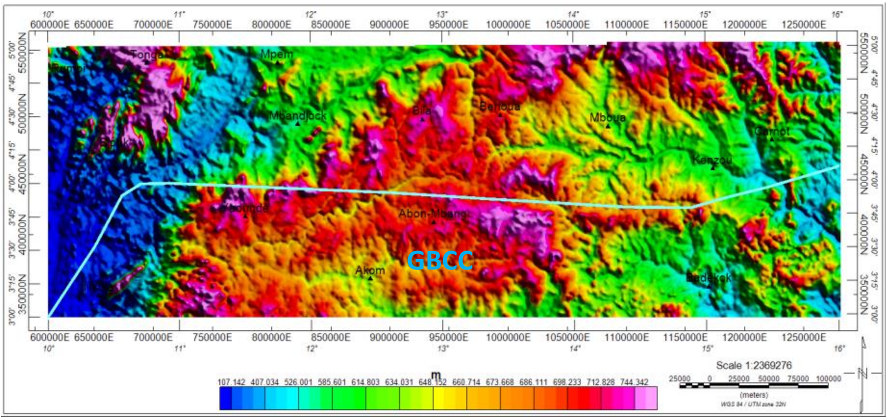

Figure. 2. Map of Topographic

Bouguer Anomaly Map

The Bouguer anomalies highlight the distribution of density anomalies of geological structures and contain information about subsurface discontinuities, which can be revealed by gradient filters. The map of Bouguer anomalies (Fig. 3) indicates that the area is generally covered by relatively weak anomalies ranging between -98 mgal and -60 mgal. However, the positive anomalies observed around the 4°30'E parallel could provide evidence of uplift of the Pan-African basement, responsible for nearly all significant gravimetric anomalies detected in the area. This large positive anomaly peaking at -28 mgal plunges into the locality of Nsola and could reveal the western margin of the Congo Craton. It attests to the existence of a significant tectonic structure situated beyond the geological boundary. There is a correlation between high elevations and strong anomalies observed around the cities of Bila and Bertoua in Cameroon. According to the geology of the study area, the negative anomalies around the locality of Akom in Cameroon could suggest the presence of metamorphic rocks such as schists, which are rocks from the Congo Craton.

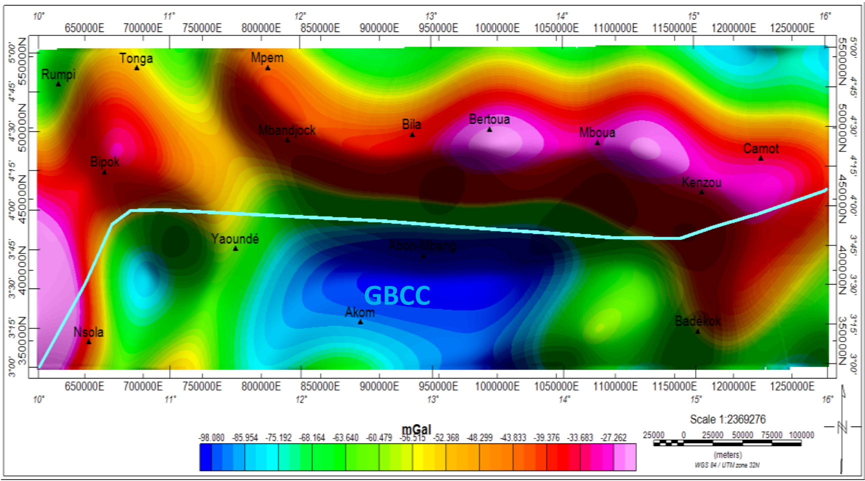

Figure. 3. Map of Bouguer anomalies in our study area

The tilt-angle

The tilt-angle method was carried out using Oasis Montaj software version 8.4. The generated tilt-angle map displays all possible lineaments of major contact zones in our study area. A zone with significant gradient (2.03 mGal/km) is visible, featuring an elongated ridge-oriented E-W along the 4°30'E parallel, extending from Bipok to Carnot. This zone could correspond to the northern geophysical boundary of the Congo Craton in the study area. The lineament map (Fig. 4) indeed presents a contact zone between two (02) significant structures. This zone correlates well with the suspected tectonic boundary in the study area. The northern limit of the Congo Craton is also well represented in the southwest part of the study area, with an elongated, nearly rounded ridge suggesting the presence of a fault and an intrusion of heavy rocks. The results obtained from processing gravity anomalies in the study area confirm and clarify the pattern of tectonic structures identified by geological studies, illustrating the main boundaries between zones with significant density contrast [3], [24]. In the southern part, another NW-SE trending contact zone is observed, covering approximately 602.1 km. This fault could represent the northern limit of negative anomalies of the Congo Craton, illustrated here by the large block to the south. Comparison with the geology of the region suggests that this structure corresponds to the transition zone between the Congo craton and the Pan-African belt. This transition zone has been highlighted in the past by lineament mapping studies in Cameroon and gravimetric imaging of crustal structures, with their tectonic implications in the region, using gravity data [3]. Therefore, it can be concluded that the northern tectonic boundary of the CC has a deep origin in the region, this is not the case for the geological boundary of the CC.

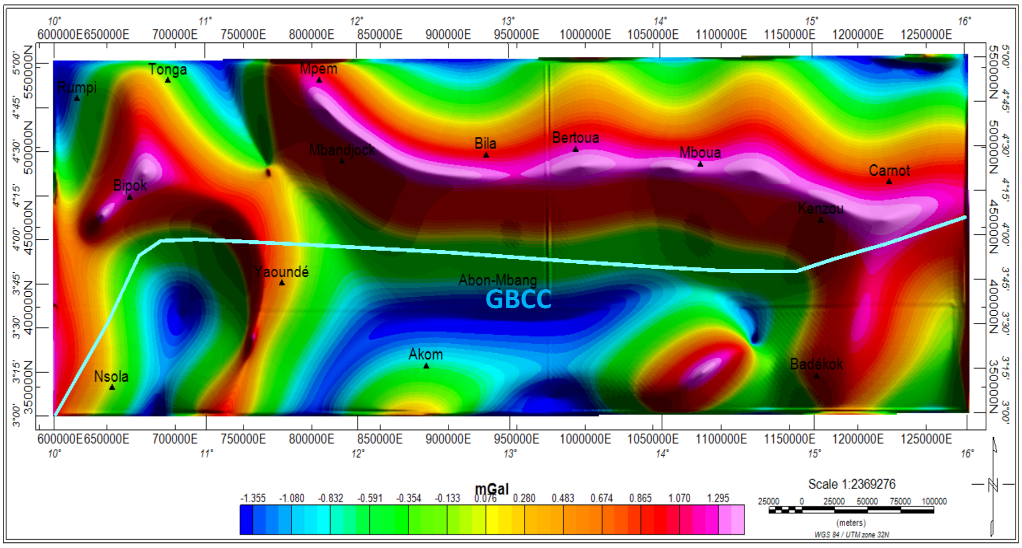

Figure. 4. Tilt angle map of Bouguer anomalies

Residual anomalies map

The map of residual anomalies (Fig. 5) has been obtained using the isostatic separation method with typical values such as a crustal density of 2670 kg/m³, a mantle density of 3300 kg/m³, and a compensation depth of 40,000 meters. This map highlights shallow crustal structures often obscured by anomalies observed on the Bouguer map. It presents anomalies with amplitudes ranging from -36 to 37.1 mGal. Similar to the Bouguer map, positive anomaly zones are separated from negative anomaly zones by gradient zones, indicating abrupt variations in anomaly values characteristic of tectonic features or intrusions ranging from shallow to moderate depths [24]. Positive anomalies observed around the cities of Bipok, Mbandjock, Bali, Bertoua, Mboua, Kenzou, and Carnot extend in the W-E structural direction. These anomalies are thought to be of mantle origin and would characterize an uplift of the Pan-African base in this region, thus marking the transition and boundary between the Congo Craton and the Central African Pan-African Belt. No offset of this boundary between deep and shallow structures is noted, suggesting that the fault separating the CC and the CAPB is normal in the study area. In the southern part of the map, a negative anomaly is observed around the areas of Akom and Abong-Mbang. This anomaly is attributed to the light rocks of the Congo Craton, including granites, schists, and quartzites [3].

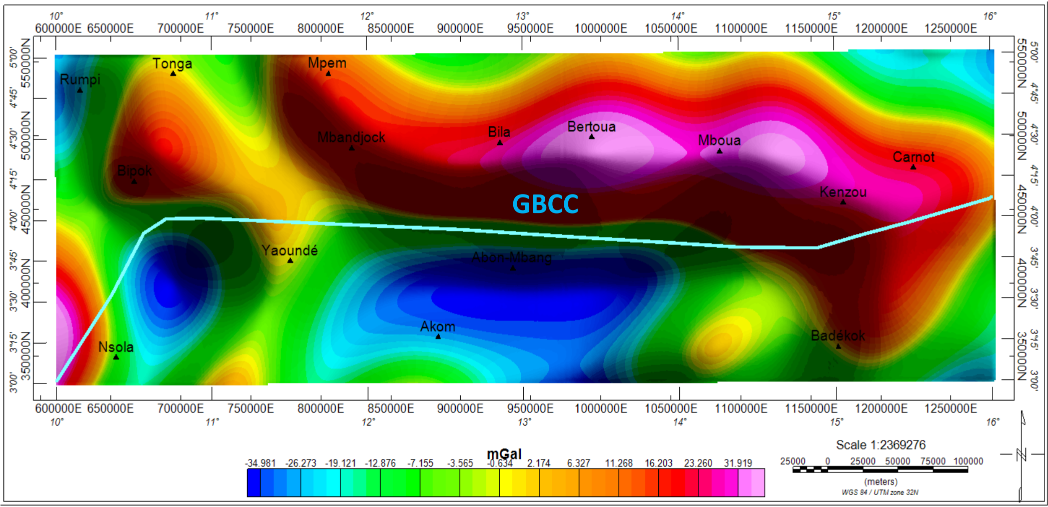

Figure. 5. Map of residual anomalies in our study area

Estimating the depth of intrusive sources using spectral analysis

The data used for the spectral analysis come from six (06) profiles. The profiles, selected on the residual anomaly map following the directions intersected by the networks of isogonic lines, traverse the suspected intrusion zones. They are marked by gray lines crossing the most significant anomalies, outlined in black on the residual map (Fig. 6). These profiles must be chosen perpendicular to the axis of the suspected structure and must extend well beyond the suspected area to account for the edge effect created by underground and distant masses. The anomaly spectra, calculated from the data of each of the six individualized profiles, will serve as constraints for modeling the bodies in our study area. Observing the obtained results, each spectrum reveals three distinct interfaces: the first in the low frequencies (from 11.50 km to 14.20 km), the second in the mid frequencies (from 1.37 km to 2.85 km), and the third in the high frequencies (from 0.29 km to 0.81 km). The depths of the structures responsible for these positive anomalies seem to indicate that they belong to the same anomalous structure. It is important to note that the values of the different errors were obtained by considering that they represent 5% of the average depth obtained from the spectral analysis [15]. The various results of the spectral analysis are recorded in Figure 7.

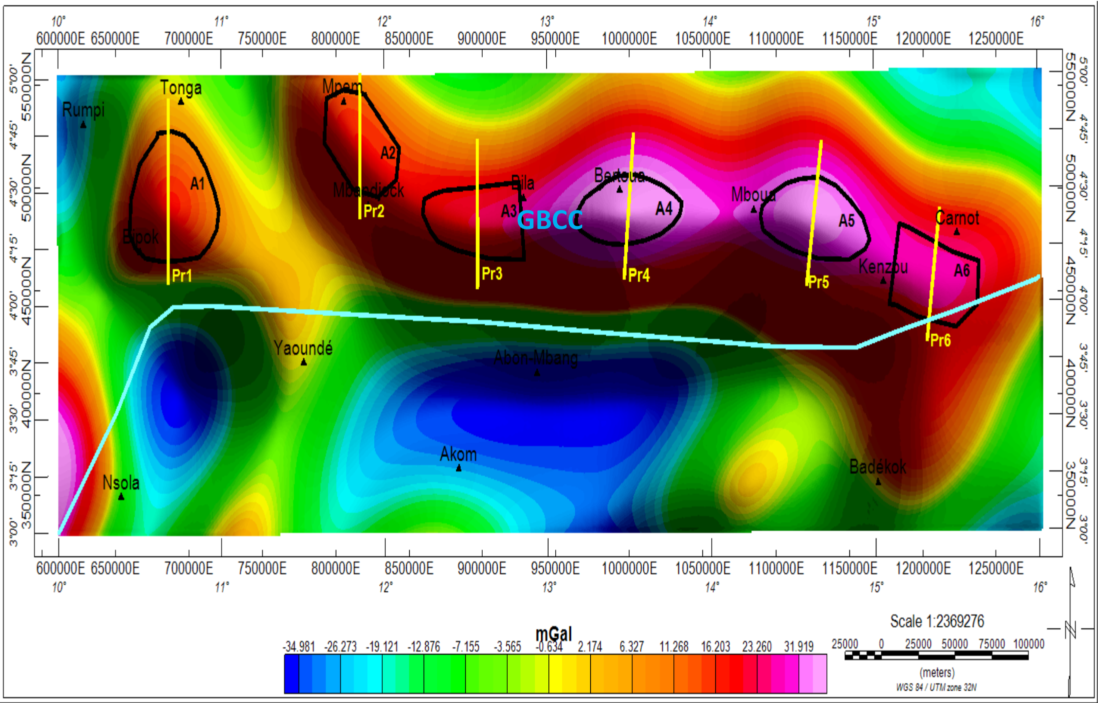

Figure 6. Residual anomalies map showing the six profiles studied

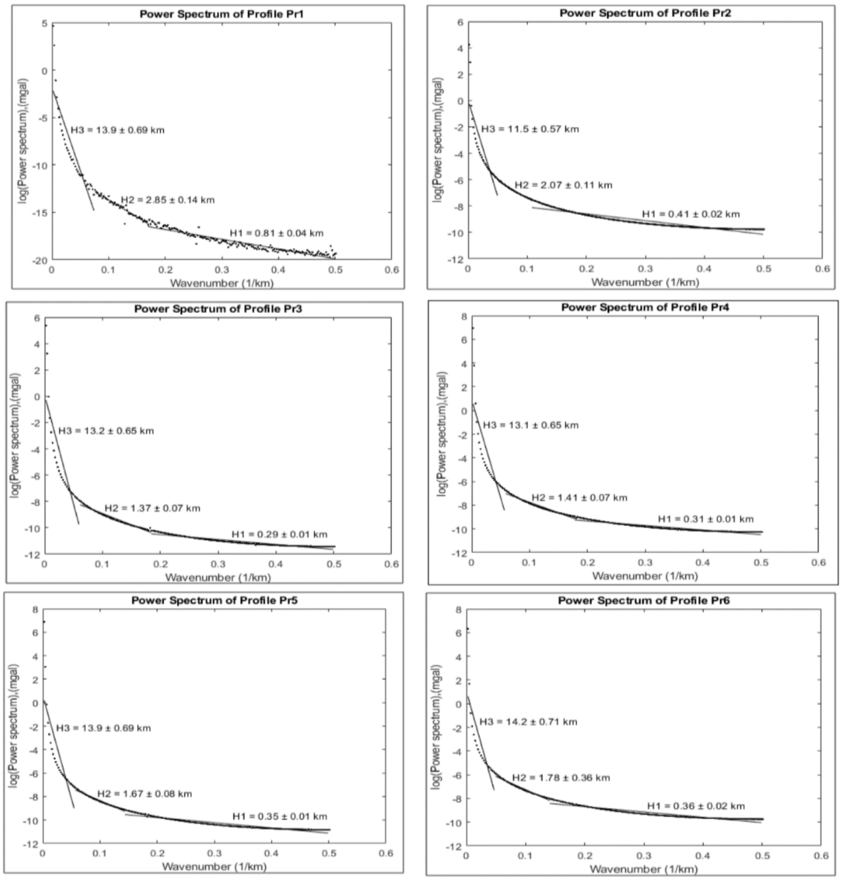

Figure. 7. Spectral curves for Profiles Pr1, Pr2, Pr3, Pr4, Pr5 and Pr6

3D modeling of surface anomaly sources along the tectonic boundary

Three-dimensional modeling enables precise visualization of the volumes of geometric structures responsible for the observed anomalies. To achieve this, we utilize Potent software version 4.17. From the map of observed residual anomalies, we created a series of 3D models to delineate and characterize the fault that marks the boundary between the Congo Craton and the Pan-African Belt. The modeling principle of the different intrusive bodies responsible for the gravity anomalies observed on the residual involves calculating the theoretical anomaly by adjusting a model of simple-shaped structures to the observed anomaly as closely as possible. These sources are then analyzed in terms of density distribution in the subsurface. Through a combination of geological and geophysical constraints and previous work, the geological formations responsible for the observed anomalies are identified. The blue lines in Figures 8, 9, 10, 11, 12 and 13 represent the fit to the theoretical models, symbolized by the red lines.

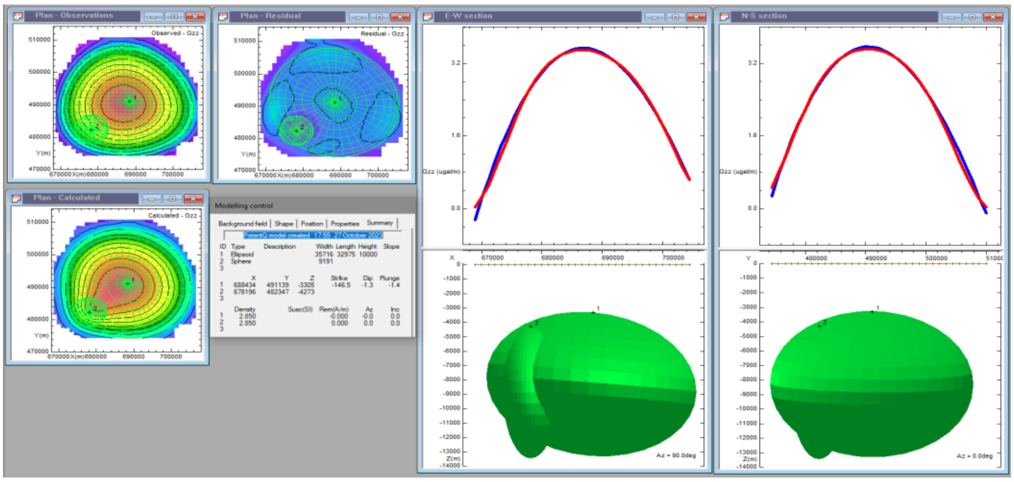

Figure. 8. Representation of the subsurface structure of anomaly A1

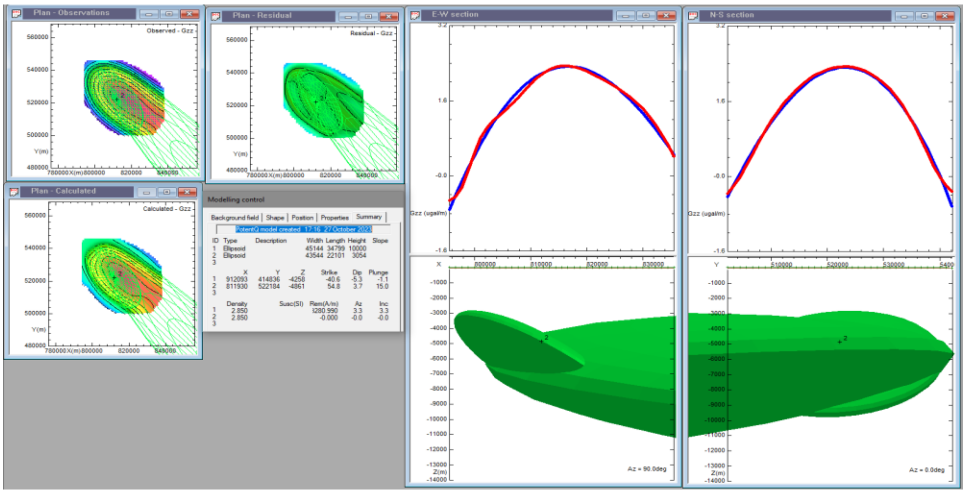

Figure. 9. Representation of the subsurface structure of anomaly A2

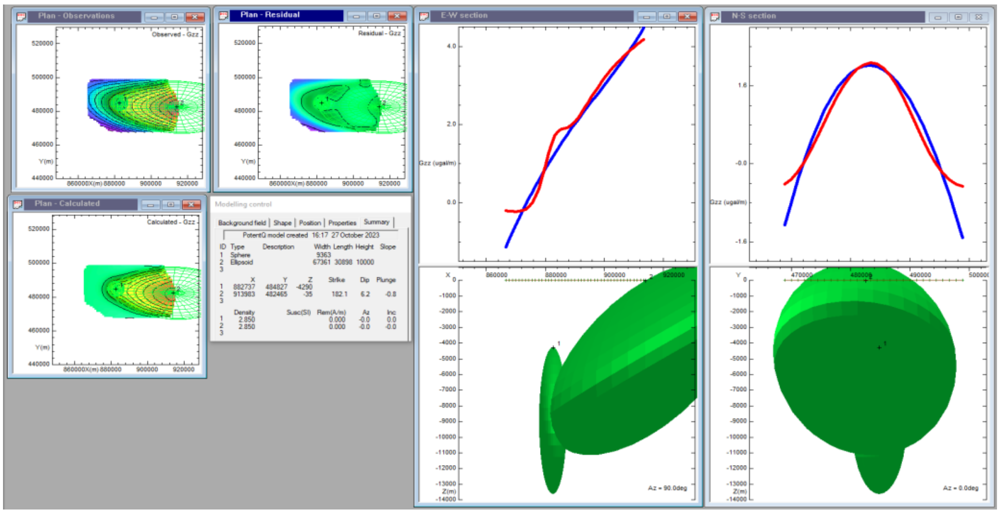

Figure. 10. Representation of the subsurface structure of anomaly A3

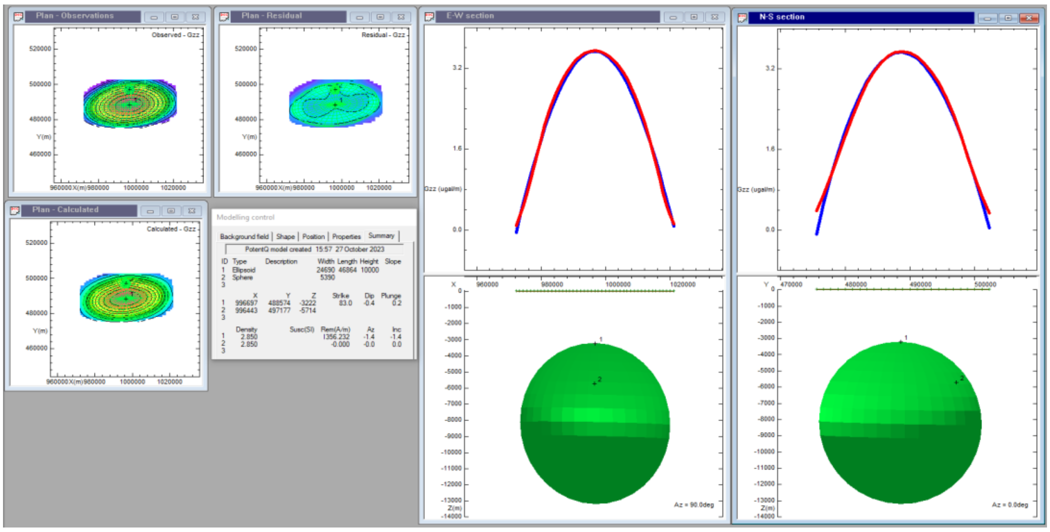

Figure. 11. Representation of the subsurface structure of anomaly A4

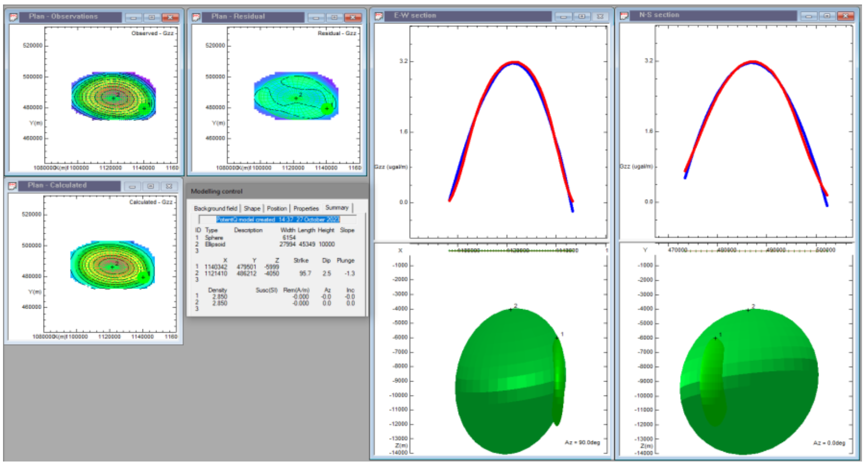

Figure. 12. Representation of the subsurface structure of anomaly A5

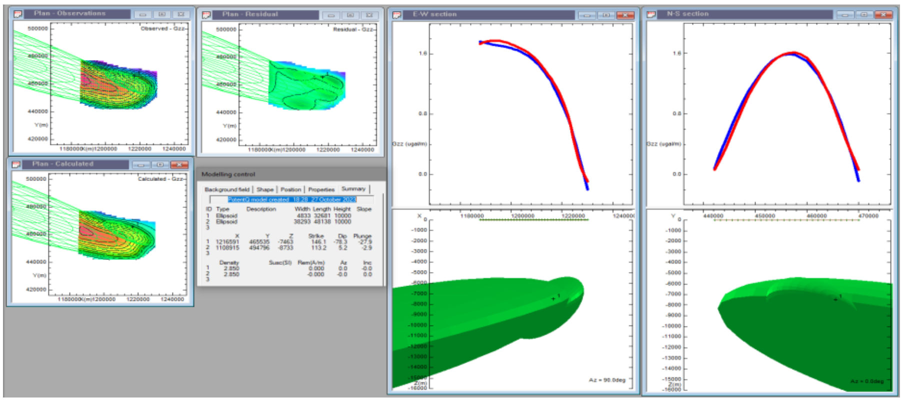

Figure. 13. Representation of the subsurface structure of anomaly A6

Estimation of the magnitude of spill of the Pan-African Belt on the Congo Craton

The map of lineaments of residual anomalies allowed for overlaying the geological and tectonic boundaries of the Congo Craton in the area under study. It appears that the Tectonic Boundary of the Congo Craton is located around the parallel 4°30’N, while the geological boundary is situated around the parallel 4°N (Fig. 14). There is, therefore, a significant distance between these two boundaries, confirming that a portion of the CC is buried beneath the CAPB. Previous studies suggest a spillover of Pan-African formations onto the CC due to a collision between the CC and the CAPB over geological time [1],[8]. The delineation of the TBCC shows that the maximum spillover amplitude (~83.5 km) is observed at the west part of the study area between Mpem and Yaoundé in Cameroon, while the minimum amplitude (~18.5 km) is observed at the east part of the area around Carnot in the Central African Republic (Fig. 14). The central domain is dominated by a relatively constant amplitude, with an average amplitude of approximately 55.5 km.

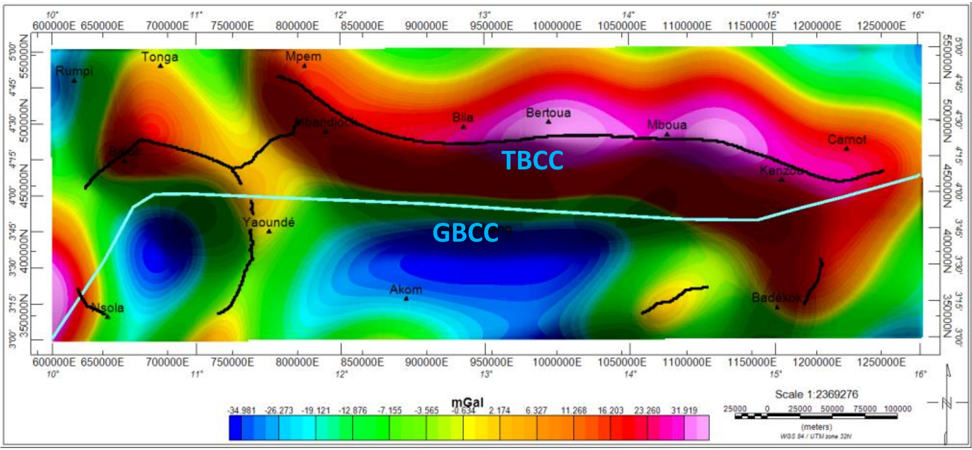

Figure. 14. Geological and tectonic boundaries of the Congo Craton in the study area

IV. Discussion

The Bouguer anomalies map and the fishnet map

The Bouguer anomalies map obtained from satellite data of the EIGEN-CG03C gravity model is similar to the maps obtained by [1],[2],[15],[25] in the study area, indicating that the use of satellite data has not obscured any signatures revealed by ground data. The residual map obtained through isostatic separation is also consistent with recent studies conducted in the vicinity of the study area [1],[3],[15],[24].

The maps obtained by the tilt angle method

The application of the tilt angle method using Oasis Montaj software version 8.4 on the maps of Bouguer anomalies and residual anomalies has allowed the identification of a contact zone between two major structures. This boundary, which lies around the parallel 4°30'N, is referred to as the Geophysical Boundary (Tectonic Boundary) of the Congo Craton in various studies [1],[8]. The fact that this boundary is highlighted on the Bouguer map indicates that it has a deep origin. The fact that the TBCC maintains exactly the same position for both deep and shallow structures suggests that the fault separating the CC and the CAPB is a normal fault.

Depths of investigation

Spectral analysis applied to all six (06) profiles plotted on the residual map has shown that all the structures responsible for anomalies in the transition zone between the CC and the CAPB are located between 0.29 km and 14.20 km depth. These depths are of the same order of magnitude as those found by [15], ranging between 0.18 km and 14.80 km in a part of the study area. They encompass depths determined by [1], ranging between 0.40 km and 7 km. The work of [24] in the vicinity of our study area also indicates similar depths in the investigation of shallow structures. These depths have been a strong constraint for the 3D modeling of the geological structures constituting the transition zone between the CC and the CAPB. It is noteworthy that there is an intermediate formation whose roof oscillates between 0.29 km and 0.81 km, and the base between 1.37 km and 2.85 km depth. Most of the work carried out in the study area does not refer to this formation; it could be the Pan-African formations that spilled onto the CC. Their density seems to be very close to the crustal density (2.67 g/cm³) in the region. Therefore, it could be understood why this formation does not appear in the 3D models. It appears in our hypothesis that the thickness of the pan-african formations spilling onto the CC varies between 0.29 km and 2.85 km. It should be noted that the formation located between 0.00 and 0.29 km depth consists of weathered rocks, that is, soils.

Models

The modeling of the structures responsible for the observed gravity anomaly in the transition zone between the CC and the CAPB was conducted under a set of constraints that allowed considering the average density of the basement as 2.67 g/cm³. Indeed, this value is consistent with the literature, indicating that it corresponds to the average density of continental crust. Geophysical studies conducted in neighboring regions [2],[4],[26] have also adopted this value as the average value of the basement, and current satellite data are collected based on this average density of the continental crust. In all six (06) models, the different rocks identified as responsible for the observed anomalies are granulites. The range of densities (2.70-290 g/cm³) chosen for these granulites is consistent not only with the literature [27],[28] but also with geophysical and geological studies conducted in the region [4],[26],[29]. The average value of granulites, set at 2.85 g/cm³ [30], remains quite close to that adopted by [4] in a neighboring region of the study area and those indicated by [2],[26] in regions close to the study zone. Recent works by [3],[24] also confirm that the structures responsible for anomalies in the transition zone between the CC and CAPB have densities of 2.80 g/cm³ and 2.85 g/cm³ respectively in certain parts of the study area. The works of [26] show that granulites are non-outcropping formations belonging to the Pan-African, which is geologically consistent with this investigation. The basement has been judged to be granito-gneissic according to previous works by [4] and the works of [31] carried out in the western border of the Central African Pan-African Belt. Ultimately, the significant positive anomaly observed on the maps of residual and Bouguer anomalies in the transition zone between the CC and the Pan-African Belt can be explained by the presence of granulite facies rocks tectonically brought to the surface during the Pan-African collision, as suggested by [32] at the suture zone between the eastern edge of the West African Craton and the Pan-African Belt. These granulites likely derive from the metamorphism of granites during the collision between the CC and the CAPB. Such intracrustal formations are generally interpreted as structures established in the suture zone during collision [31].

Tectonic structures

The geological and tectonic history of the region indicates the existence of two main structural zones (the CC and the CAPB) in the area [10],[33],[34],[35],[36], established as a result of a series of tectonic events that affected the Earth in general and the African plate in particular [4]. Magnetotelluric and gravimetric studies report a southward spill of pan-african formations onto the Congo Craton [2],[4],[37],[38]. The works of several authors in the fields of magnetotellurics [4],[38],[39], gravimetry [2],[4],[26], and aeromagnetism [8],[40] highlight the existence of a fault in the transition zone between the CC and the CAPB. This fault materializes the underground boundary of the CC. The materialization of the Geological Boundary (which is around the parallel 4°N) confirms the overlap of the southern pan-african formations onto the northern formations of the CC, whose underground boundary is around the parallel 4°30'N. The tracing of the TBCC indicates a maximum spill amplitude (~83.5 km) to the west of the study area between Mpem and Yaoundé in Cameroon, while the minimum amplitude (~18.5 km) is observed to the east of the area south of Carnot in the Central African Republic. The central domain is dominated by an amplitude that varies little, with an average amplitude of approximately 55.5 km. This is relatively consistent with the works of [1], which indicate a maximum southward spill amplitude of pan-african formations onto the CC of 150 km. With more modern tools and very recent data, we evaluate this maximum amplitude to be approximately 83.5 km and the average amplitude is 55.5 km, no other works attempting to assess this amplitude in the region.

V. Conclusion

The main objective of this study was to evaluate the extent of the southward spill of pan-african formations onto the CC. To accomplish this, we constructed a Bouguer map of the study area using satellite data. The Bouguer anomaly map was used to derive the residual anomaly map. The tilt angle method was employed to generate lineament maps from both datasets, confirming that the TBCC has a deep root and is buried beneath the CAPB, as it lies beyond the geological boundary. Establishing the TBCC allowed for the assessment of the extent of the southward spill of pan-african formations onto the CC, ranging between 83.5 and 18.5 km, with an average extent of approximately 55.5 km. 3D modeling of the structures responsible for anomalies in the transition zone between the CC and the CAPB indicates the presence of granulites, which are suture and metamorphic formations formed under high pressure and temperature. The presence of these granulites between the CC and the CAPB confirms the hypothesis of collision and spillage, as the CC is denser than the CAPB. Spectral analysis supported the hypothesis of the deep root of the LTCC and led to the conclusion that the thickness of the pan-african formations spilled onto the CC appears to vary between 0.29 and 2.85 km.

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