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Interpretation of the locally high gravity anomalies using terrestrial gravity data in Bagodo, North Cameroon

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Abstract:

In this work, we interpreted the gravity data in order to determine the structural characteristics responsible for high gravity anomalies in Bagodo. These anomalies have not been characterized through a local study. Thus, regional-residual separation of the gravity anomalies using the polynomial method is undertaken. Geophysical signatures of near-surface small-extent geological structures are therefore revealed. In order to conduct the quantitative interpretation of the gravity anomalies, one profile was drawn on the residual Bouguer anomaly map and therefore was interpreted using spectral analysis, ideal body solution and 2.5 modeling methods. Our results showed that the intrusive body in Bagodo area consists of two trapezoids blocks. The first and the second block have roofs of about 7.5 and 14 km depths respectively while their bases are about 17km depths. The values are in accordance with those obtained by ideal body which shows two cells with density contrast of 0.3 g·cm^{-3} in comparison to the surrounding rocks. Its density is estimated to about 3gcm^{-3}. The topography of these rocks shows that they are basaltic rocks that would have cooled in fracture zones as an intrusion.

Keywords: polynomial method; gravity anomalies; spectral analysis; ideal body; 2.5 modeling.

1. Introduction

The study area is located between latitudes 5°N–8°N and longitudes 13°E–18°E. This zone constitutes an important morphotectonic structure located in the central part of the North Equatorial Pan-African chain. It has already been the subject of various geophysical works. In gravimetry, we can cite the works of Poudjom-Djomani et al. (1997); Noutchogwe Tatchum et al. (2006); Apollinaire et al. (2017); in seismology, the works of Dorbath et al. (1986); Tabod et al. (1992), and recently in magnetotelury those of Kande (2008). All these studies were carried out in a regional framework and extend over several hundred kilometers. No research work was done in a local setting. In this work we are interested in study of local high gravity anomalies present in Bagodo. These anomalies have not been characterized by any previous study. The physical characteristics of the units, such as their limiting depth, their lateral extent and their geographical position are not well known. To achieve this goal we exploited gravity anomalies to determine the physical (density contrast) and geometric (horizontal, vertical extensions and depth) characteristics of the Bagodo's intrusive material. This material is generally generated by magmas which migrated towards the surface through faults. On residual Bouguer anomaly map, spectral analysis, ideal body solution and 2.5D modeling methods were used. The obtained trapezoids bodies do not present uniform roof, base or volume. There is one greater than the other. The high anomaly observed on gravity maps is probably due to the effects of these bodies. Similar methods have already been successfully used by Apollinaire et al. (2018), Njeudjang et al. (2020) to determine the major subsurface structure of the Adamawa Plateau.

2. Geological and Tectonics Setting

The geological works of the Adamawa Plateau undertaken have permitted to regroup the geological formations into two large groups (Figure 1): the basement and the cover formations (Temdjim, 2006; Kamgang et al., 2010). The basement regroups on one side the Pan-African formations (syn-tectonic granites and schist) then on the other side the Paleoproterozoic formations (gneisses with high degrees of metamorphism) (Soba et al., 1991; Kapajika, 2003). The cover formations are represented by the Cretaceous sedimentary series and the Cenozoic volcanic formations. The Cretaceous sedimentary series are constituted by the filling sediments of Djérem basin and Mbéré ditch. The Djérem basin presents series constituted of red clays which rest on sandstone. In the Mbéré ditch, there are marls, clays and conglomerates sometimes masked on the surface by basanites (Le Maréchal and Vincent, 1971). The Cenozoic volcanic formations consist of basaltic rocks in form of extended lava flows. Dorbath et al (1986) mentioned that basaltic rocks were discovered around Bagodo. These rocks underwent metamorphism at high temperatures and high pressures. They are generally generated by magmas which migrated towards the surface through faults. The cooling was done gradually under the crust. According to Moreau et al. (1987) and Meyers et al. (1998) one Part of the magmatic liquid would have escaped to the surface, giving place to the volcanic effusions encountered on the Adamawa Plateau, while the other part would have cooled and frozen in form of an intrusion. These basaltic flows, thus the mode of emission is that of fissural volcanism, are at the origin of many recent Strombolian cones. This idea is supported by the findings of Kampunzu et al. (1986) and Temdjim (1986). The Adamawa Plateau has a complex and uneven tectonic structure. Its tectonic evolution would have taken place in several geological time. Three major tectonic structures are involved in the study area: the Foumban Shear Zone, Cameroon Volcanic Line and the South Adamawa Trough.

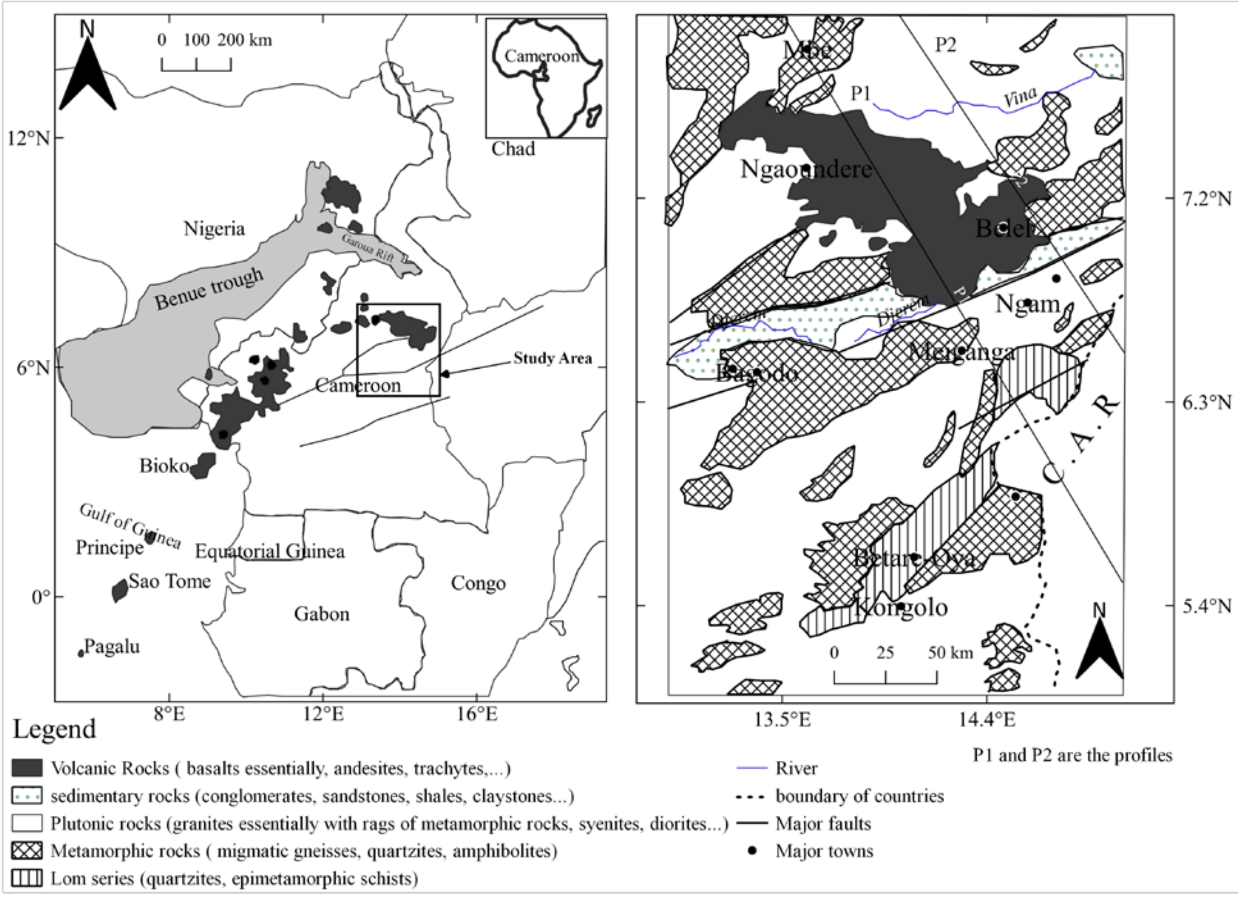

Figure 1. Geological map of the study area, modified after Le Maréchal and Vincent (1971).

3. Processing and Interpretation of Gravity Data

3.1 Analysis of Bouguer Anomalies

Terrestrial gravity data used in this work were collected by many independent prospectors and international organizations during the various reconnaissance campaigns of Cameroon and its surroundings. We can cite: ORSTOM (Office de la Recherche Scientifique et Technique d’Outre Mer) now called IRD (Institut de Recherche pour le Développemen) from 1960 to 1967, the University of Princeton (in 1968), the University of Leeds (1982-1988) and the Institute for Geological and Mining Research (1984-1988) (Legeley et al., 1996). These prospectors and organizations have a very large database and excellent quality recognized internationally. In this study a total of 672 measured points have been obtained. The base station was located in Ngaoundéré airport tied to the network of ORSTOM. The acquisition campaigns were carried out by car, along the available roads or carossable tracks in the whole territory and its surrounding. The space between stations varied from 1 to 5 km, depending on access facilities. The location of the stations was determined on topographic maps and by compass tracking. The elevation of the stations was obtained with barometric readings, using the Wallace and Thomnen or Tiernan altimeters (type 3B4). The uncertainty of the station position is about 100 m. The variations of the gravity field were measured using Lacoste and Romberg (N.471 and 823), Worden (N.313 and N.600) and North-American gravimeters. The gravity value at each station was corrected for the lunisolar tide and the instrumental drift. A mean crustal density of 2.67 $g{\cdot}cm^{-3}$ was used for Bouguer anomaly reduction. The maximum error was not expected to exceed 0.15. This value agrees with the findings of Poudjom-Djomani et al. (1997) and Zanga-Amougou et al. (2013). Due to the presence of relatively smooth topography, no terrain correction was added. Bouguer gravity anomalies obtained by interpolation were then plotted to have a new Bouguer anomaly map (Figure 2). This map is very similar to the one obtained by Poudjom-Djomani (1993) and, Njeudjang et al. (2020).

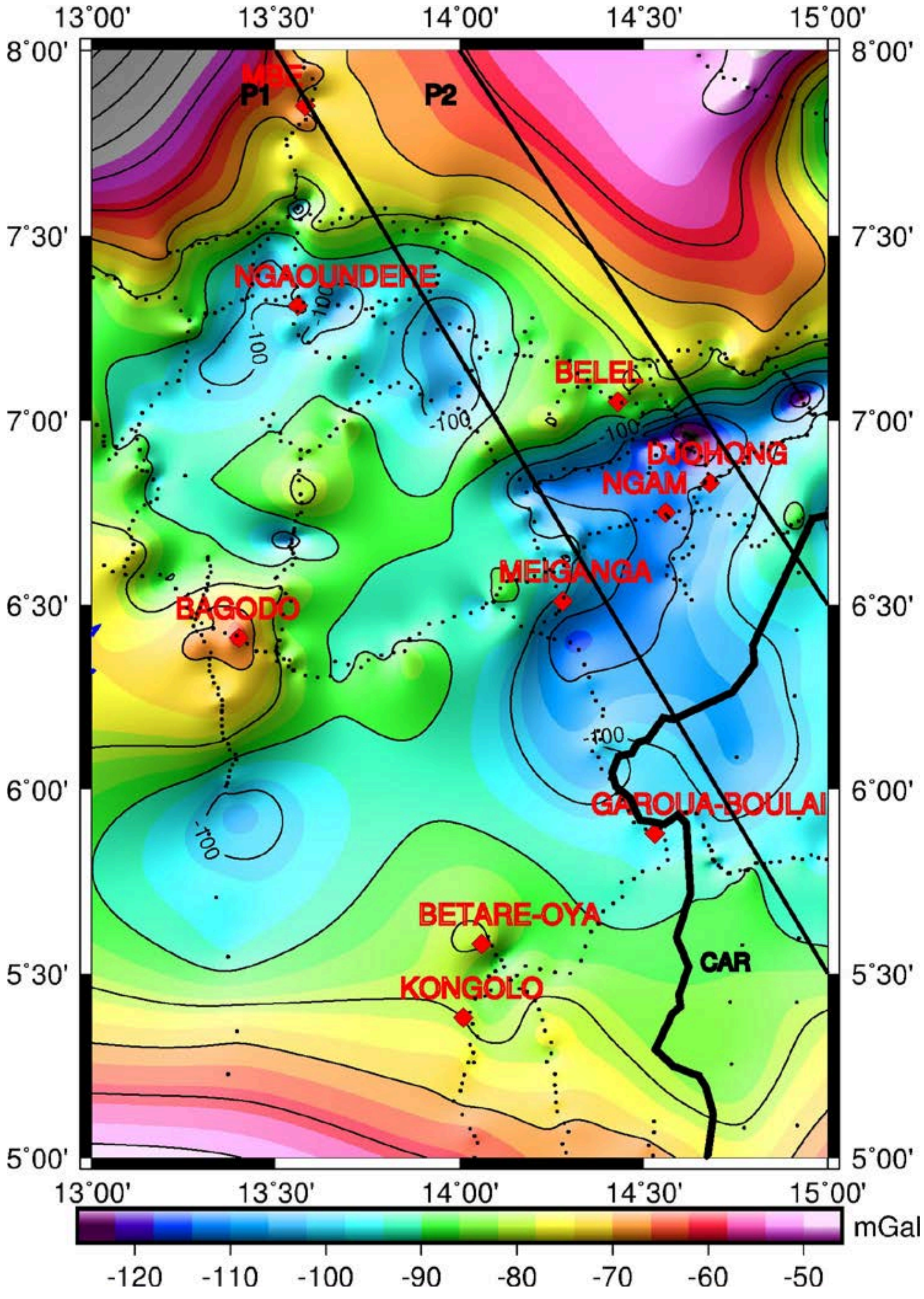

Figure 2. Simple Bouguer anomaly map of the Adamawa Plateau.

In order to determine the physical and geometric characteristics of intrusive material of Bagodo, the simple Bouguer anomaly must be smoothest and should contain low frequency information. In this case, a plot of free air anomaly, Bouguer anomaly and topography versus distance was conducted along the profiles P1 and P2 as showed on the **Figure 3**.

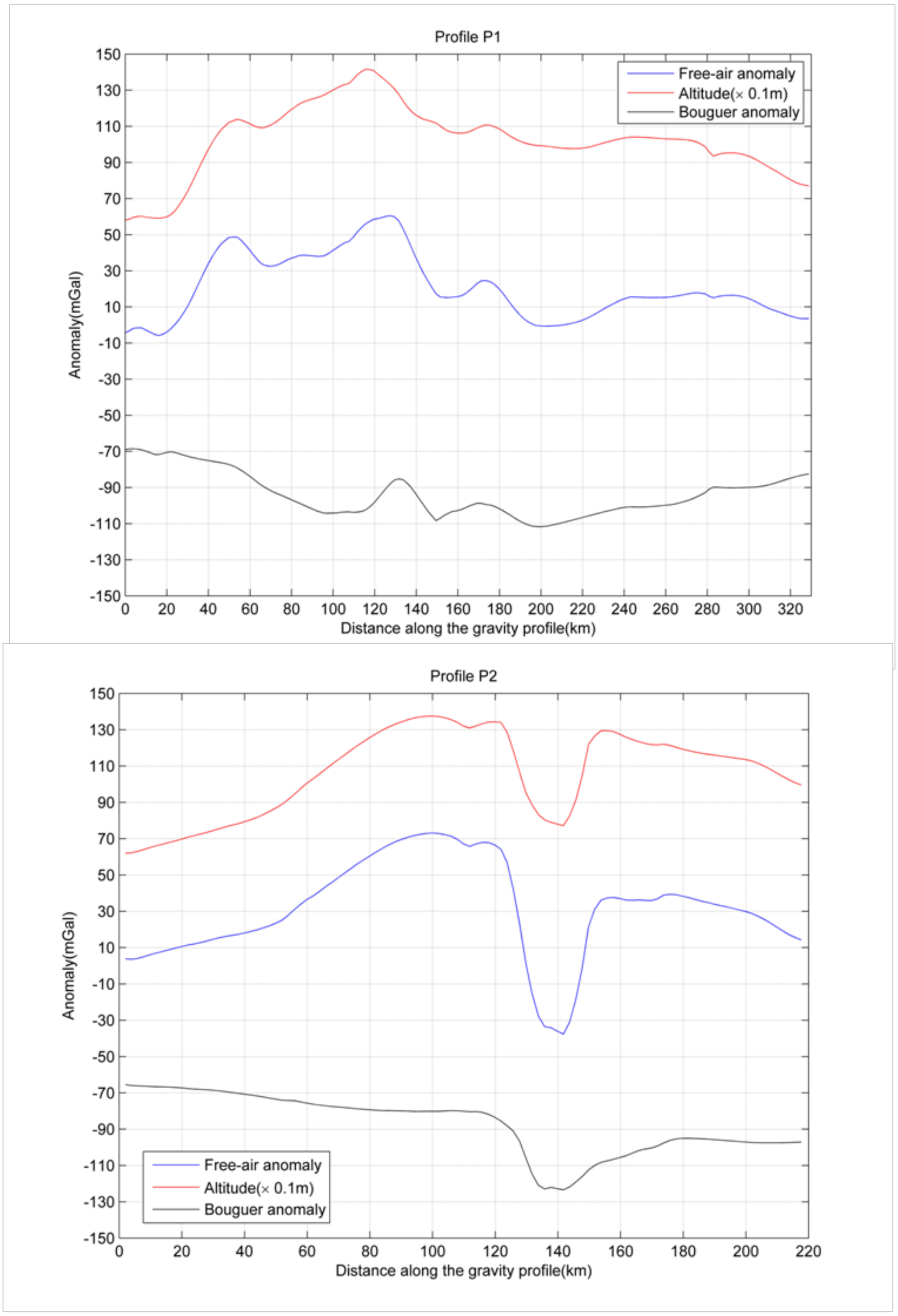

Figure 3. Variation of free air anomaly (blue line), simple Bouguer anomaly (black line) and topography (red line) along the profiles P1 and P2.

The free air anomaly curve is similar to the topography. The similarities cannot be noticed on the Bouguer anomaly. The three curves have a step gradient from 120 to 200 km for the profile P1 and from 120 to 160 km for the profile P2. In these portions of profiles, none of the anomaly seems truly more smoothed, this may be due to the presence of a complex geological formation or the presence of an imposing abnormal mass in the basement. Nevertheless, for profile P1 between 0 and 120 km and beyond 200 km, the free air anomaly and the surface topography are positively correlated, but they remain uncorrelated with the Bouguer anomaly. Removing the influence of topography along profiles P1 and P2 reduces the variability of the gravity field. Free air anomaly and topography curves have greater variability than the simple Bouguer anomaly. The curve of the Bouguer anomaly is therefore the smoothest and appears to contain low frequency information.

The Bouguer anomaly map was obtained automatically by using the Generic Mapping Tools (Wessel and Smith, 1995) (Figure 2). This map shows a relatively high anomaly domain located at Bagodo, north and south of the study area. These anomalies would be due to the intrusion of high density material at great depth. Besides these high anomalies, the map shows a large low region located throughout the central part of the study area with a minimum of -120mGal. These anomalies would be a mark of low density formations linked to the Mbéré ditch. In order to isolate the deep-seated anomalies from those at shallow depth, regional-residual separation was done on the Bouguer anomaly map.

3.2 Regional-residual Separation

The separation of Bouguer anomalies was performed by using the polynomial method. A FORTRAN program was used to generate regional gravity anomaly and the residual ones at the observation points (Radhakrishna and Krishnamacharyulu, 1990). The regional gravity anomaly $T_n(x_i, y_i)$ of degree n at the point (x_i, y_i) is given by:

$$T_n(x_i, y_j) = B_1 + \sum_{j=1}^{n} \sum_{l=0}^{j} B_m A_{jl}(x_i, y_i) \qquad (1)$$

or $T_n(x_i, y_i) = \sum_{m} C_m . A_m(x_i, y_i)$, where C_m are coefficients of the polynomial,

with $A_m(x_i, y_j) = x_i^l y_i^{(j-l)}$ and $m = \frac{j(j+3)}{2} - l + 1$

The Bouguer anomaly $G(x_i, y_j)$ at the same point (x_i, y_j) is given by:

$$\sum_{i=1}^{n} G(x_i, y_i).A_k(x_i, y_i) = \sum_{m=1}^{(n+1)(n+2)/2} C_m \sum_{i=1}^{n} A_k(x_i, y_i).A_m(x_i, y_i) \qquad (2)$$

where $k = 1,2,3....(n+1)(n+2)/2$

Using the least squares method, the residual field can be obtained by:

$$R_n(x,y) = G(x,y) - T_n(x,y) \tag{3}$$

For small values of n, the regional seems too smooth, all the deep lines of the crust have been removed and their effect appears on the residual. When the degree of polynomial increases, the regional takes into account the shape of the Moho and corresponds to the gravitational effect of masses located beyond the crust. According to Noutchogwe Tatchum et al. (2006), the third-order of residual accounts for density contrasts within the crust in the study area. This residual anomaly (Figure 4) was obtained by subtracting a regional one.

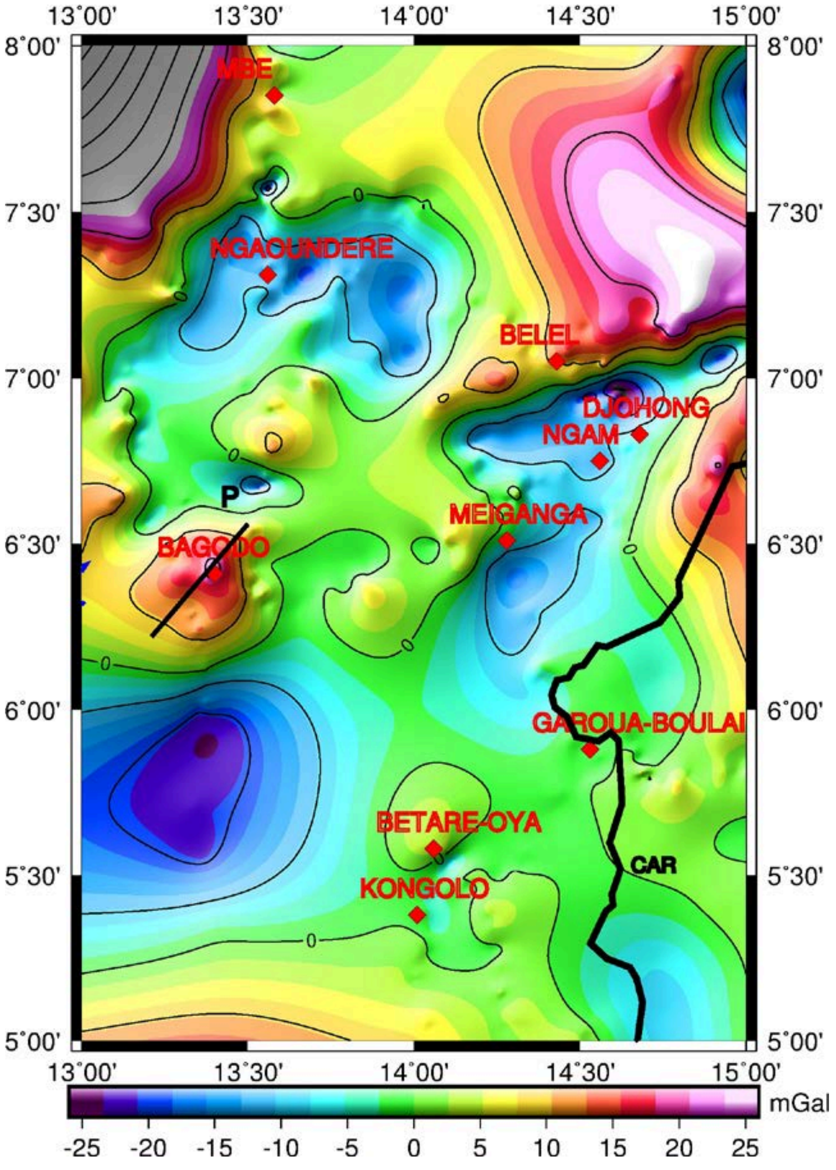

Figure 4. Residual gravity anomaly map of the Adamawa Plateau, showing profile P.

The residual Bouguer anomaly map shows values between –25 and +25 mGal. An overview of this map highlights the main gravimetric areas which reflect the structure of the study area. We distinguish the areas with positive and negative anomalies separated by areas of high gradient. Positive anomalies are associated with basaltic intrusions or the thinning of the crust, negative anomalies are associated with sedimentary basins, granites in the socle and the gradient zones are identified as discontinuities such as faults or flexures.

3.3 Source-depth Estimation Using Spectral Analysis

It is a technique which helps to estimate the average depth of gravity anomaly source from the energy spectrum. An extended anomaly with amplitude which rapidly decreases is characterized by high frequencies. On the other hand, a large anomaly whose amplitude decreases weakly is characterized by the spectrum concentrated towards the low frequencies. When plotting the logarithm of gravity energy as a function of frequency, we choose segments lines whose slopes are proportional to the depth of the disturbing masses. These depths are given by the relation of Gerard and Griveau (1972):

$$h = \frac{\Delta(LogE)}{2\pi\Delta k} \tag{5}$$

where $\Delta \log E$ is the variation of the logarithm of the energy spectrum, Δk is wavenumber, and h (km) is the depth of perturbing body. Figure 5 shows the energy spectrum as a function of frequency, h_1 corresponds to the deep density contrast plane and h_2 is shallow density contrast plane. According to Nnangue et al. (2000), Zanga-Amougou et al. (2013), Apollinaire et al. (2018), the errors value on each profile is 5% of the mean depth value. Two half-lines are chosen to determine the slope of linear regression in order to calculate the average depth of the disturbing mass.

The first slope which corresponds to the low frequencies is located at 8.4 km. It represents the crust-mantle interface and would indicate the base of the intrusive body whose origin is high anomalies observed in the locality of Bagodo. The second slope located at the high frequencies is located at 2.6 km. It would correspond to the roof’s depth of Bagodo's intrusive body.

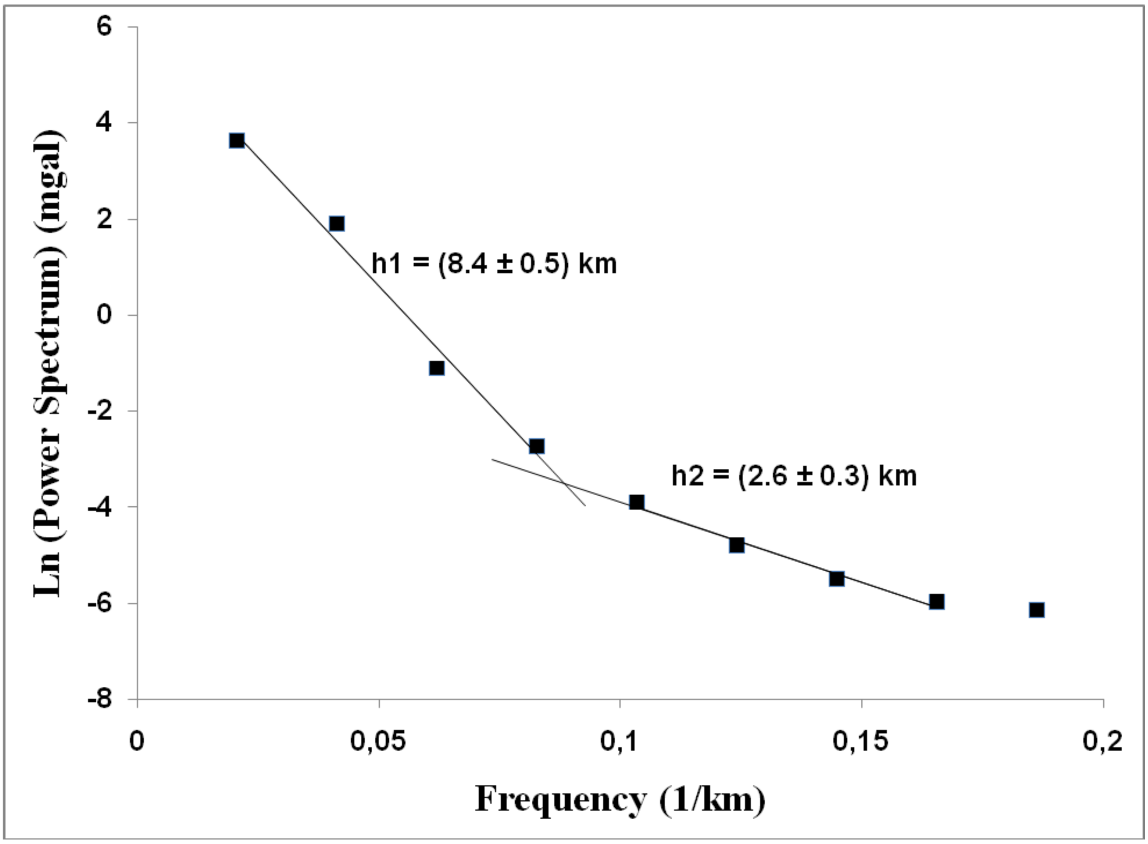

Figure 5. The power spectrum of profile P, showing depths (h_1 and h_2) of the interfaces.

3.4 Solution of the Ideal Body

It is a technique that helps to determine the density contrast of the body from the anomaly created on surface. In this study, we used the IDB2 FORTRAN Program developed by Huestis and Ander (1983), Koumetio et al. (2018) which calculate the Parker's ideal body by using the simplex algorithm for linear programming (Parker, 1974, 1975). The solution of the ideal body is calculated along the profile and the characteristics of the starting model for the inversion of these data are:

- Horizontal length of cells: $\Delta x = 1.8km$
- Vertical length of cells: $\Delta z = 0.7km$
- Number of cells following the horizontal: $nx = 20$
- Number of cells following the vertical: $nz = 10$
- Error on the value of the anomaly: 1mGal.

The residual and fitting gravity anomalies are better presented with the ideal body solution. In fact many residual features correlate more clearly with the Adamawa uplift location. On this contour map, the signature of the intrusive material in Bagodo has clearly identified. The high anomalies observed in the study area and along the profile are due to this material whose density contrast, in comparison to the surrounding rocks, has been evaluated. Figure 6 shows the ideal body solution. It is an intrusive body with density contrast of 0.3g/cm^3 disposed in two blocks and separated from each other by the substratum. Its disposition between 3 and 10km depth, agree with those results obtained by spectral analysis. These results demonstrate that, the residual components provide more information on near surface geology and help constrain the limiting depths of some geological features of the Adamawa subsurface.

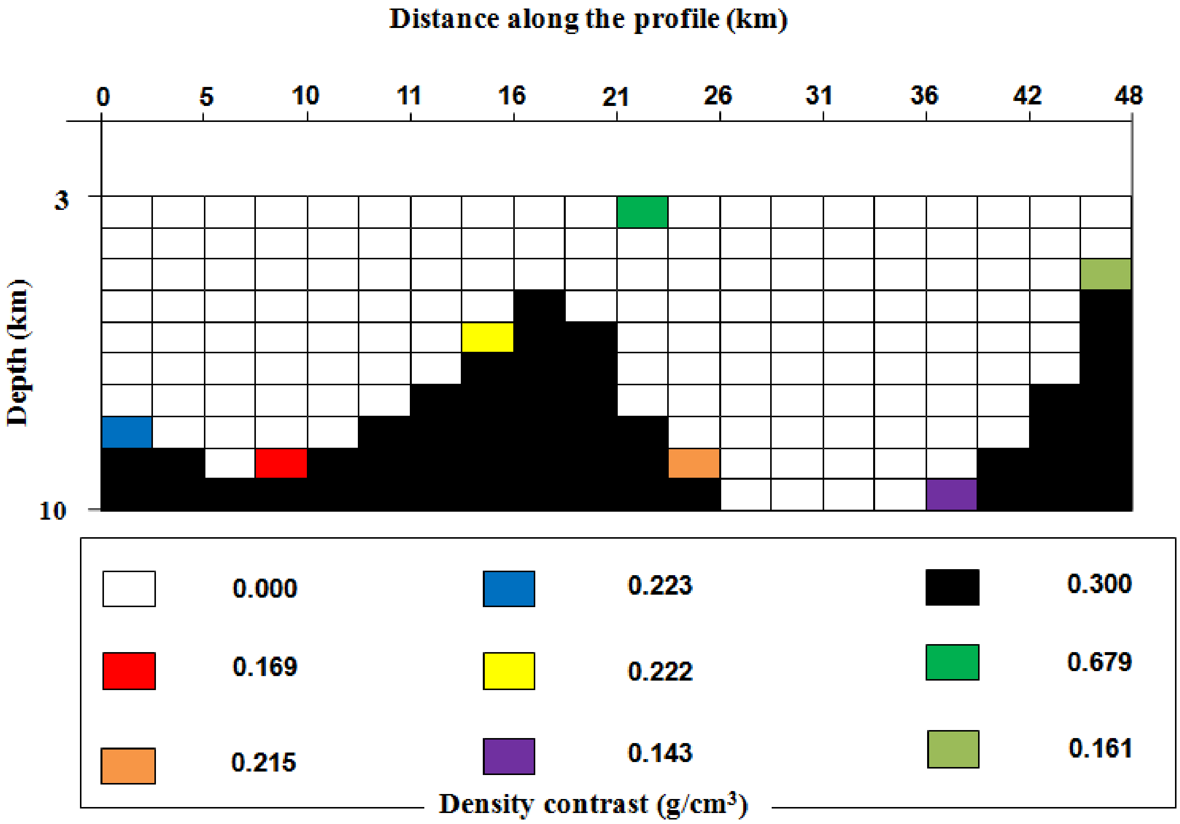

Figure 6. The ideal body solution.

3.5 Direct Modeling

The 2.5 modeling consist in fitting the observed anomalies and computed curves, based on bodies representing the possible geological units present in the subsurface. It used to infer the subsurface structure along the profile and control lateral extension of structures. This method was described in the works of Cady (1980), Apollinaire et al. (2018), and Njeudjang et al.

(2020). In general, we consider that the density is uniform and the measured gravity field is vertical, we have:

$$g_z = -G\rho \iiint \frac{\delta}{\delta z}(x^2 + y^2 + z^2)dxdydz\,. \tag{6}$$

The resolution of this integral permits to calculate the effects of structure with polygonal section and finite elongation.

In this work, we used the Grav2dc software developed by Cooper (2008). This software offers the advantage to control the longitudinal extension of gravity anomalies. Its graphic possibilities highly developed permit to modify and visualize iteratively the models and calculated curves. The best model retained is the one whose gravity signature is in accordance with the observed anomalies. In this study, the model showed in Figure 7 fund that the intrusive body of Bagodo comes in almost two similar trapezoids blocks lying with different direction. These blocks with density contrast of 0.30 g·cm^{-3} are separated from each other by the surrounding rocks whose density is obtained by the inverse method. The first and the second block have roofs of about 7.5 and 14 km depths respectively while their bases are of about 17 km depths.

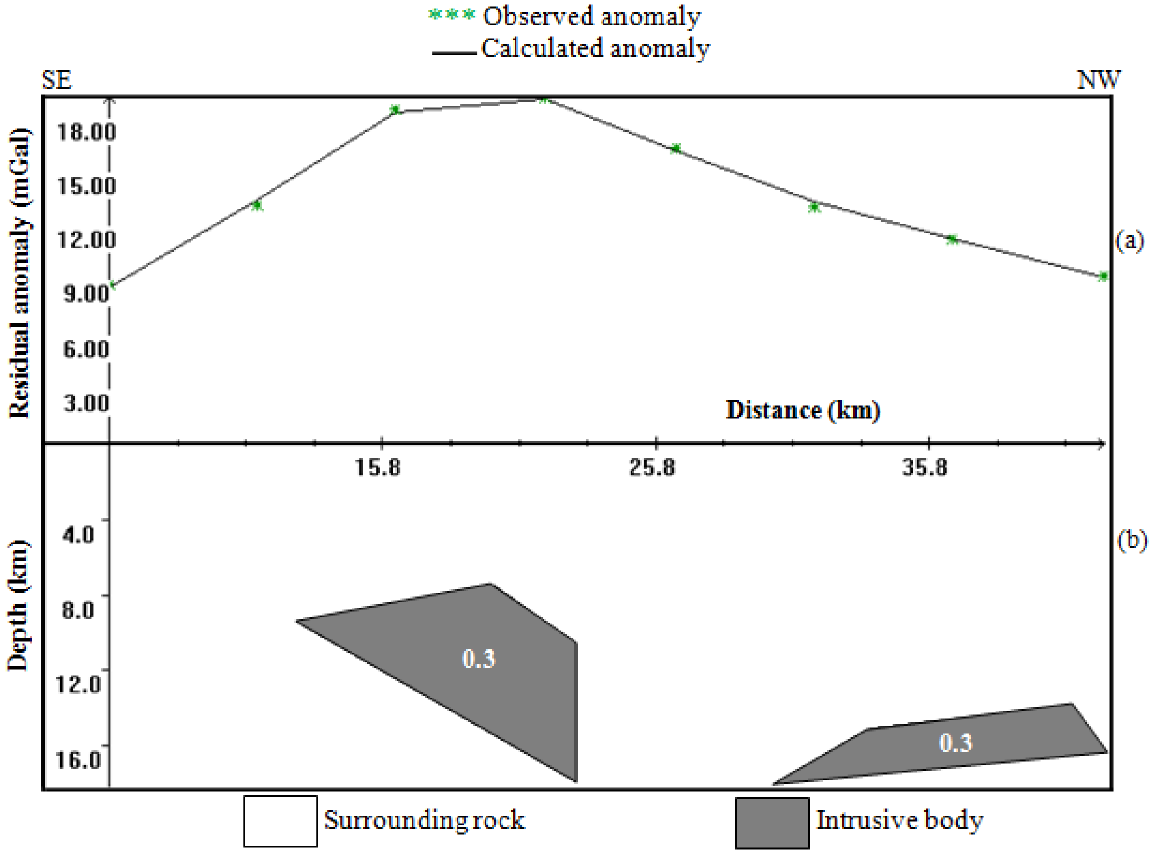

Figure 7. Interpretative structure model of the intrusive material of Bagodo.

4. Discussion of Results

In this study the third-order of polynomial was used to highlight a relatively high gravity anomaly area located in low environment. The results showed that the structural model of the intrusive body at Bagodo consists of two trapezoids blocks. The first and the second block have roofs at depths of about 7.5 and 14 km respectively while their bases are at the depths of about 17 km. These values are in accordance with those obtained by ideal body solution which shows two cells with density contrast of 0.3 g·cm^{-3} separated each other by surrounding rocks. The various geological formations noticed in the study area and its surroundings show the average densities of rocks constituting the possible geological units. Having no solution of density measurements on samples taken from quarries or by drilling, we estimated the density contrast of the intrusive body of Tibati–Bagodo by calculating the ideal body solution. The estimated value corroborates the previous results. The mean density of major rocks has been taken as 2.67 and 3 g·cm^{-3} (Telford et al., 1990). According to Apollinaire et al. (2018), the density contrast is calculated by $C_i = d_i - d_0$ where d_i is the average density of the *ith* formation and d_0 is the average density of granite, $d_0 = 2.67 gcm^{-3}$. In this case, a contrast of 0gcm^{-3} was given to the granites which constitute the basement and 0.3 g·cm^{-3} to the basaltic rocks. These results lead us to believe that the intrusive material at Bagodo is essentially composed of basaltic rocks and does not have a uniform roof or base located at an average depth. The disposal of these rocks in two blocks was already predicted by synthetic model which illustrates the establishment and consolidation of igneous rocks in the crust (Noutchogwe Tatchum et al., 2006). These models suggest a relatively superficial evolution of magma between basement blocks separated by faults. The roof topography of these rocks shows the correlation between the magmatic zones and fracture of the basement. According to Kande (2008) structural studies have shown two branches, oriented N65°E and N85°E under the Bagodo locality and we notice a spectacular rise of basaltic rocks which would be cooled and fixed in fracture zones as an intrusion. This ascent is observed throughout the profile. The origin of the crustal thinning is related to the asthenospheric rise which causes stretch of the earth's crust. Temdjim (1986) showed that the large volcanic mountains of the Adamawa Plateau are due to the joint points of two or more breaks in the basement.

5. Conclusion

In this work we exploited gravity anomalies to determine the physical (density contrast) and geometric (horizontal, vertical extensions and depth) characteristics of the intrusive material of Bagodo. On residual Bouguer anomaly map of order 3, spectral analysis, ideal body solution and 2.5D modeling methods were executed. Our results showed that the intrusive body at Bagodo consists of two trapezoids blocks with density contrast of 0.3 $g{\cdot}cm^{-3}$ in comparison to the surrounding rocks. These blocks have roofs at depths of about 7.5 and 14 km and bases at depth of about 17 km. The density contrast value is in accordance with the result obtained by ideal body. The analysis of the results showed that the disposal of the intrusive material in two blocks would be at the origin of the lithospheric bulge and the stretch of earth's crust. The intrusive material is probably composed of basaltic rock. Its topography shows that it would have been cooled and fixed as an intrusion under Bagodo.

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