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Comparison of Terrestrial Gravity and EGM 2008 Data on Extracted Lineaments: A Case Study of the Adamawa Massif, North Cameroon

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Abstract A structural study on the Adamawa Massif highlights the major structures (faults) of the shear zone as well as the igneous intrusion near Mayo Baleo. Through this study, a comparison on the use of gravity data from the EGM 2008 and terrestrial models was carried out on the basis of gridded gradient data obtained by applying the MAGMAP filtering algorithm on the Oasis Montaj software system. Using the gradients has an advantage in that they contain much information especially on geological structures. The resulting maxima have strong density contrasts, enabling them to be used as tools in explaining geological contacts. Gravimetric lineaments marked by the geometry of the peaks (elongated shape) and the igneous intrusion corresponding to the circular peak were detected on the horizontal gradient maps. Reconciliation with the geology, the slope map and satellite images justifies the presence of the Djohong-Ngaoundal-Dir-Tibati, Tibati-Banyo and Tignère-Banyo lineaments which indicate the underlying Foumban (extension), Tibati and Tcholliré-Banyo faults respectively, comprising the shear system residing in the massif underlain by a gneiss-migmatite bedrock. The limitation on the use of gravity data from the EGM 2008 model is manifested through the Djohong lineament correlating with the large mylonitized feature trending NE-SW, defined as a steep relief (27° to 60°), separating the Mbere basin from the upper unit with about 358 m in height difference. This terrain is a small area of relief with morphological units adapted as in the case of the mountainous areas of the West to the use of gravity data from the EGM2008. The other lineaments that are part of the shear zone fault system are not elucidated because they correspond to deep mega structures that the EGM 2008 model resolution cannot attain at depth. The use of this model is suitable for studies of superficial structures which are associated with huge formations such as the volcanic dome of Mayo Baleo, an intrusion of young trachytes with steep slopes (27° to 60°) at an altitude of 2419 m.

Keywords: *gravity, horizontal gradient, Bouguer anomaly, lineaments*

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1. Introduction

Airborne, altimetric, and terrestrial gravity data were combined to build the EGM2008 model, a model successfully applied in many works. Among these, we note the work of [1] in the study of the depth of the Moho discontinuity under the CVL. Reference [2] leads the way on the use of terrestrial gravity data and 2008 EGM data in the 3D modeling of the Moho depth in Iran. These are in addition to [3] its analysis on a West African rift system and [4] relating these data to Cameroon. These authors find interesting similarities between the terrestrial gravity and the 2008 EGM data that are used nowadays to compensate for the absence and scarcity of terrestrial gravity data. This suggestion is confirmed by the consistency of the work in [1] with previous studies that used seismic data allied with earth gravity data. In 2018, [5] conducted a study on the Cameroon Volcanic Line using 2008 EGM data because of its suitability in mountainous volcanic domains where terrestrial gravity surveys cannot be easily carried out. And yet [6] had to use these terrestrial gravity data to study the internal

structure of the CVL and its suggested asthenospheric uplift.

Compensating for the absence and scarcity of terrestrial gravity data with EGM 2008 data is a suggestion that only has potential for surface geophysical studies i.e. lineaments with water traps (for drilling, for example). A limitation of this method is raised by structural studies that require deep work (deep structures). Thus the extraction of lineaments from maxima (horizontal gradient) could be a drawback in the use of EGM 2008 data. The objective of this paper is to compare again these two data by investigating the subsurface of the Adamawa Massif.

2. Geological Setting

The Adamawa Massif is a Neoproterozoic to Pan-African morpho-structural zone underlain by Precambrian basement rocks of Palaeoprotozoic age such as gneisses, migmatites or granulites [7], Meso-Neoprotozoic sequences with volcanic, sedimentary and metamorphic features [8] and granitoids. It comprises two geotectonic domains identified by [9]: the West-Cameroon domain separated from the Adamaoua-Yadé domain by the Tcholliré-Banyo Fault (Figure 1). The Cameroon Volcanic Line and the Benue Trough are the two major structures associated with the Adamawa Massif, which is crossed by shear zones (CCC). This zone is a ductile occurrence of average direction N70, with dextral shearing [10,11,12]. The Cretaceous basins of Djerem and Mbere, made up of conglomerates, arkosic sandstone and limestone, form the South Adamawa Trough that bounds the massif to the south, while the Benue Trough bounds it to the north.

The basement on which the Adamawa Massif rests is covered with basaltic and basalto-andesitic lavas of essentially Tertiary age [13]. However, [14] had grouped them into three series: the recent basaltic series of Mio-Pliocene age (10.0 to 7.0 ± 0.2 Ma and 11.39 ± 003 to 9.28 ± 0.03 Ma) [15,16,17], the intermediate series dominated by trachytic, phonolitic and ancient basaltic series of late Cretaceous age [13]. The recent basaltic series is represented by three types of basaltic flows: the lower basaltic lava flows that outcrop in the lowlands, the upper flows that outcrop on the hilltops and the intermediate flows consisting of basalt, hawaiite and mugaearite that outcrop on the peneplains and hillsides [18]. The intermediate series of Miocene age [17] is represented by necks, domes and dome-falls. The ancient basaltic series, which has no visible volcanic apparatus, represents 3/5 of the surface covered by volcanic formations and is of fissure type [18].

The volcanic activity of the Adamawa Plateau is characterized by strongly to moderately alkaline basaltic flows, followed by flows of rare Q-trachytes and Ne-trachytic lavas [19] that can be derived from hawaiite by 62% fractional crystallization [16]: 34 wt% plagioclase, 13.9 wt% clinopyroxene, 12.8 wt% olivine, 6.5 wt% magnetite and 1.8 wt% apatite. It is then known from [16], continuing his studies on the Adamawa plateau, that silicic volcanism on this plateau is dominated by normative nepheline trachytes associated with strongly alkaline basalts and basanitic rocks (volcanism undersaturated in SiO_2). These Ne - trachytes contain phenocrysts of alkali feldspar, oligoclase, Mg-rich salites and rare small crystals of Ti-magnetite. Notably [20] argue on clinopyroxenes that suggest a cogeny of strongly alkaline basalts and Ne - trachytes.

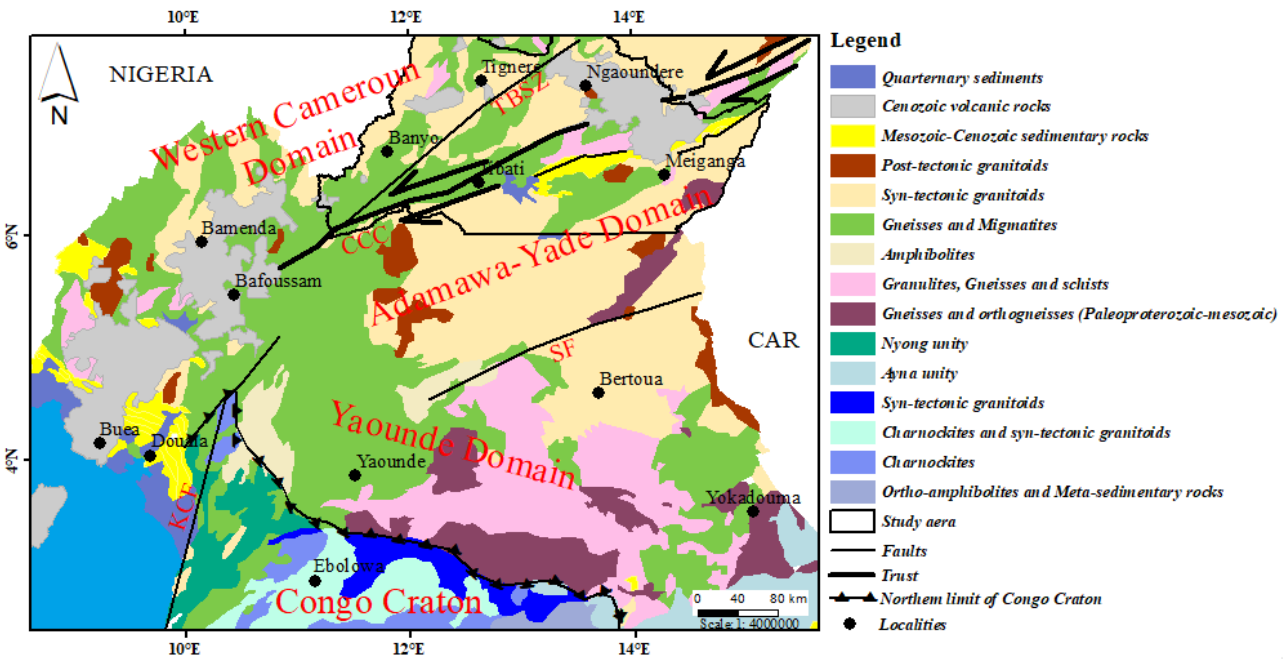

Figure 1. Geologic map of southern Cameroon modified from the International Geological Map of Africa Scale: 1:5.000.000; Third Edition 1985 - 1990. CCC = Central Cameroon shear. TBSZ = Tcholliré - Banyo Fault. SF = Sanaga Fault. KCF = Kribi Campo Fault

3. Data and Methodology

3.1. Data

Obtained via the Bureau gravimétrique International (BGI), Earth Gravitational Model 2008 (EGM 2008) which is a geopotential model consisting of spherical harmonic coefficients used to derive a geoid referenced to WGS 1984 [3]. This gravity model, complete to degree and to the order 2159, containing extensions to degree 2190 [21], has been corrected using GRACE (Gravity Recovery and Climate Experiment) satellite data.

The terrestrial data are extracted from the ORSTOM (Office de la Recherche Scientifique des Territoires d'Outre-Mer) database dating from 1960 to 1968. These gravity data were collected using Lacoste & Romberg (model G, n° 471 and 823), Worden (n° 69, 135, 313, 600 and 1153), World Wide (n° 36), Canadian Scintrex (n° 305G) and North-American (n° 124 and 165) gravimeters. The density of the data is about 220 stations per squared degree and the inter-station distances were 3 to 5 km while they were 4 to 10km for those performed by the other agencies namely: [22]; Société E.L.F. (Essences et Lubrifiants Français) 1980; [23] (Univ. De Leeds); IRGM and Univ. De Leeds, 1984-1985 and 1986. The accuracy of the gravity values is about 0.2 mgal. The measurements were attached to the reference stations called gravimetric bases of the Martin network.

3.2. Bouguer Map

Extracted from ORSTOM and EGM data, Bouguer's anomaly values range from -124.9 to 22.5 mGal and from -144 to 23.5 mGal, respectively. On the Bouguer map (Figure 2), to the north of it, three positive anomalies characterize a large gravity panel with peaks of varying amplitudes P1 (64 to 26 mGal), P2 (64 to 58 mGal) and P3 (64 to 40 mGal). Other positive anomalies form a gravity band extending from west of Tibati to east of Dir with amplitudes of 60 mGal and 68 mGal respectively. Negative anomalies are noticed in the eastern part of the study area with closed iso-anormal curves of little variable amplitude (-122 to -102 mGal). Figure 3 shows in this same part of the Bouguer map (EGM), two series of light anomalies with peak amplitudes of -116 mGal (low series) and -118 mGal (high series). Positive anomalies are distributed to the south near Tibati (62 mGal), Dir (68 mGal) and occupy the entire northern part of the study area.

Analysis of the Bouguer anomaly maps shows that the alignment of the three heavy anomalies corresponds to the limit of a large structure in the north of the study area. By topographic reconnaissance, this large, high gravity domain coincides with the Ngaoundere mountainous zone while the gravity depression zone located to the east correlates with the extension of the Mbere trench [24]. Geologically, this slight anomaly can be associated with metamorphic and sedimentary rocks because it is underlain by the Lom series of metasediments (schists), and is characterized to the north of this gravity depression by NE-SW trending sandstone formations. However, the positive gravity anomaly in the southern zone coincides with the gneissic surface observed [24]. On the other hand, in the northern zone, the surface geology is in the form of granitic mats and according to [25], the huge anomalies that occur there do not correlate with this geology because this zone includes basaltic rocks in the basement. From the reconciliation of the Bouguer maps with the geology (local and/or regional), the huge anomalies in the north reflect the responsibility of the uplift of the Pan-African basement. This Pan-African is the period when heavy plutons were emplaced and would be associated with the anomalies observed around Tibati and Dir.

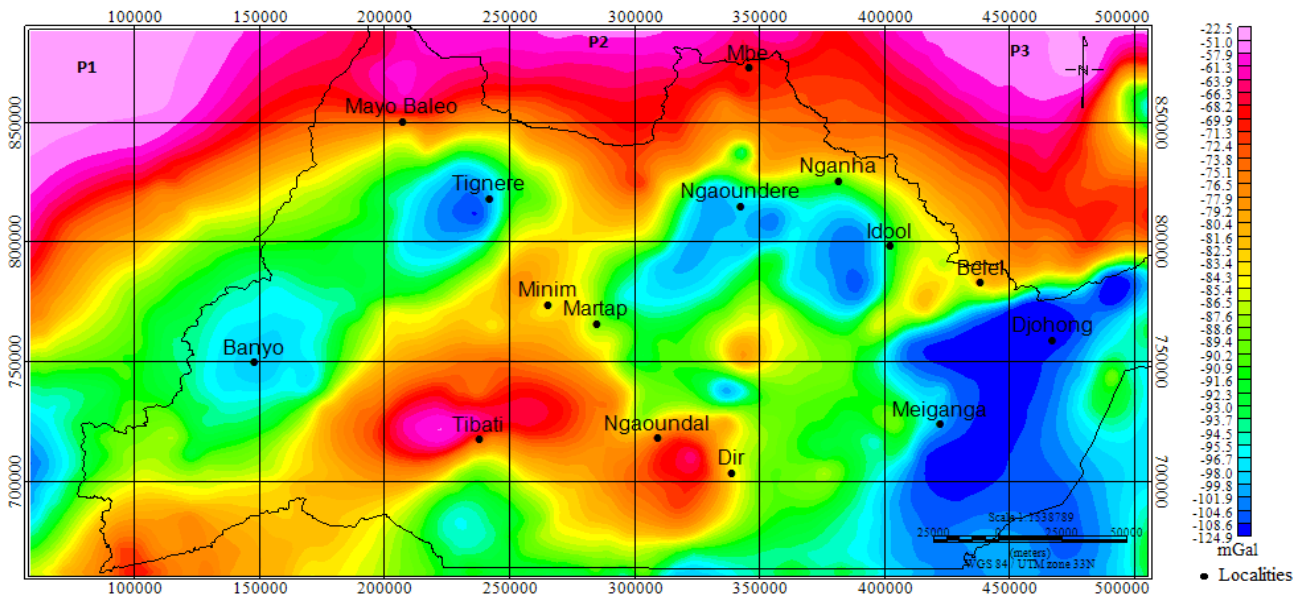

Figure 2. Bouguer anomaly map from terrestrial gravity data

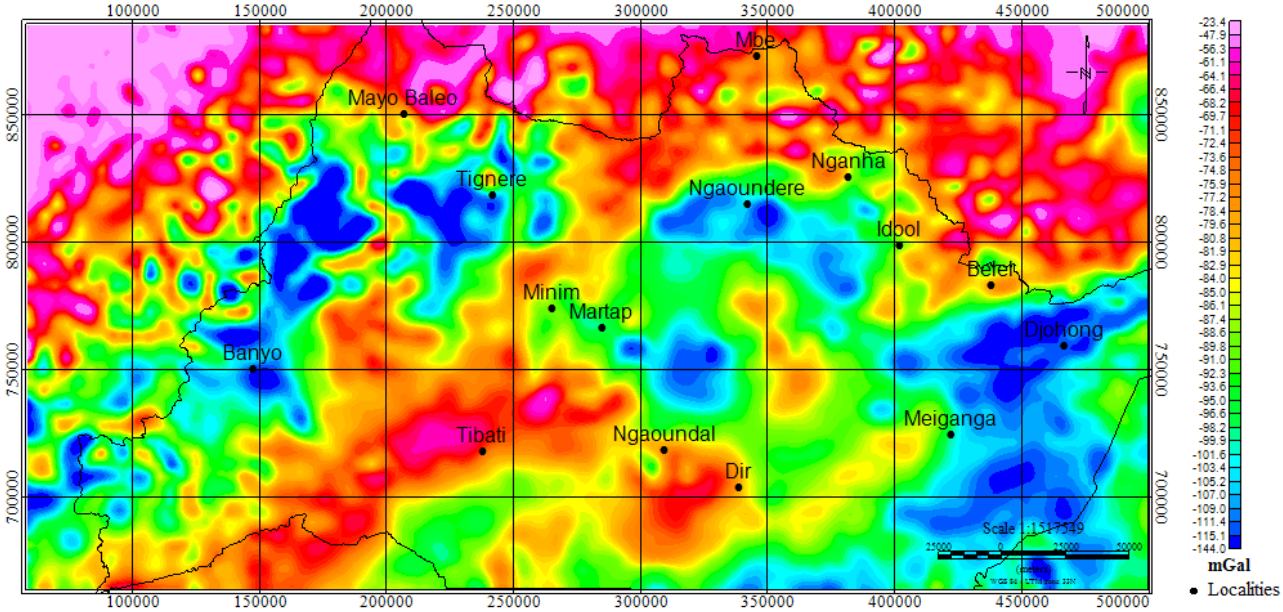

Figure 3. Bouguer anomaly map from EGM 2008 gravity data

Indeed, the northern part of the study area is separated from the southern part by an abrupt drop known as the "Ngaoundéré cliff" [10]. This escarpment is identified by the gradient zones which are only the transition zones between the heavy and negative anomalies. In the eastern part of the study area, the contact zone between the Mbere Graben and the southern piedmont of Adamawa is outlined by a corridor with amplitudes of -93 to -90 mGal (Figure 2) and -98 to -90 mGal (Figure 3). This gradient zone corresponds to a broad band of mylonite that indicates the presence of a fault at depth [26]. Other gradient zones are also visible on the Bouguer maps bounding the Tibati and Dir anomalies that do not correlate with linear geological structures. However, by filtering and analyzing the horizontal gradients of the Bouguer maps, it is possible to better identify these hidden geological contacts.

3.3. Methodology

3.3.1. Horizontal Gradient

The orientation of the different geological structures is visible after application of the horizontal gradient. The operation consists of making a lateral shift in depth. The expression (equation 1) will therefore be used to manifest the local maxima of the potential field [27,28] which are only responses of geological contacts (faults, faults, fractures, intrusions) with a strong density contrast [29].

$$HG = \sqrt{\left(\frac{\partial G(x,y)}{\partial x}\right)^2 + \left(\frac{\partial G(x,y)}{\partial y}\right)^2} \quad (1)$$

Where G(x, y) is the potential field.

This expression is governed by [28] which observes in the potential field data, that the horizontal gradient finds stability in the presence of noise: this would be an advantage of this technique.

3.3.2. Coupling between the Upward Continuation and Horizontal Gradient filter

'Upward Continuation' is a technique that smoothens a map through the application of a low-pass filter that attenuates short wavelengths while amplifying long wavelengths [30]. This low-pass filter is applied to Bouguer anomalies at successive depths. Low- frequency structures are highlighted from the near surface to a certain depth giving the geodynamic evolution of these structures in the subsurface of the region. Horizontal and vertical gradients are applied to the filtered anomaly maps, and the combination of these gradients (equation 1) enables the maxima to be highlighted. These maxima appear on each map for a predefined depth during the upward continuation filtering. The superposition of these different filtered maps (maxima) generates the peaks that will define the different geological contacts.

The lineament and intrusion phenomena that occur during contacts between low frequency structures are thus highlighted. They are manifested through the geometry of the peaks resulting from the superposition of the maxima. The orientation of these peaks [5] allows us to define the vertical dips (superposition of maxima located at a point at different depths) and the dip orientations (displacement of maxima). Intrusions will correspond to curved or circular peak contours while a peak elongation (straight alignment of several peaks) will refer to lineaments.

4. Results

4.1. Horizontal Gradient

Figure 4 and Figure 5 show the horizontal gradients of the study area obtained respectively from the Bouguer anomaly maps generated above (Figure 2 and Figure 3). The sharp density contrasts are identifiable from the magnitudes that provided the maxima during filtering [29]. Peak elongations and circular peaks are detected in

each of the figures highlighting lineaments (faults), igneous intrusions (domes, dykes, diapirs) according to the local or regional geology of the study area.

On Figure 5, the maxima of the potential field are concentrated in the northwestern part of the map. Among them, a circular peak located to the northwest of the study area stands out. Three elongated or more or less rectilinear peaks are located near Djohong. Referring to the geological map of Adamawa, the circular peak is associated with a dome while the linear peaks (Djohong) follow the faults that bound the Mbéré basin. These linear geological contacts also have a strong density contrast in Figure 4, which shows several horizontal gradient maxima that are only elongated and mostly oriented in a NE-SW direction.

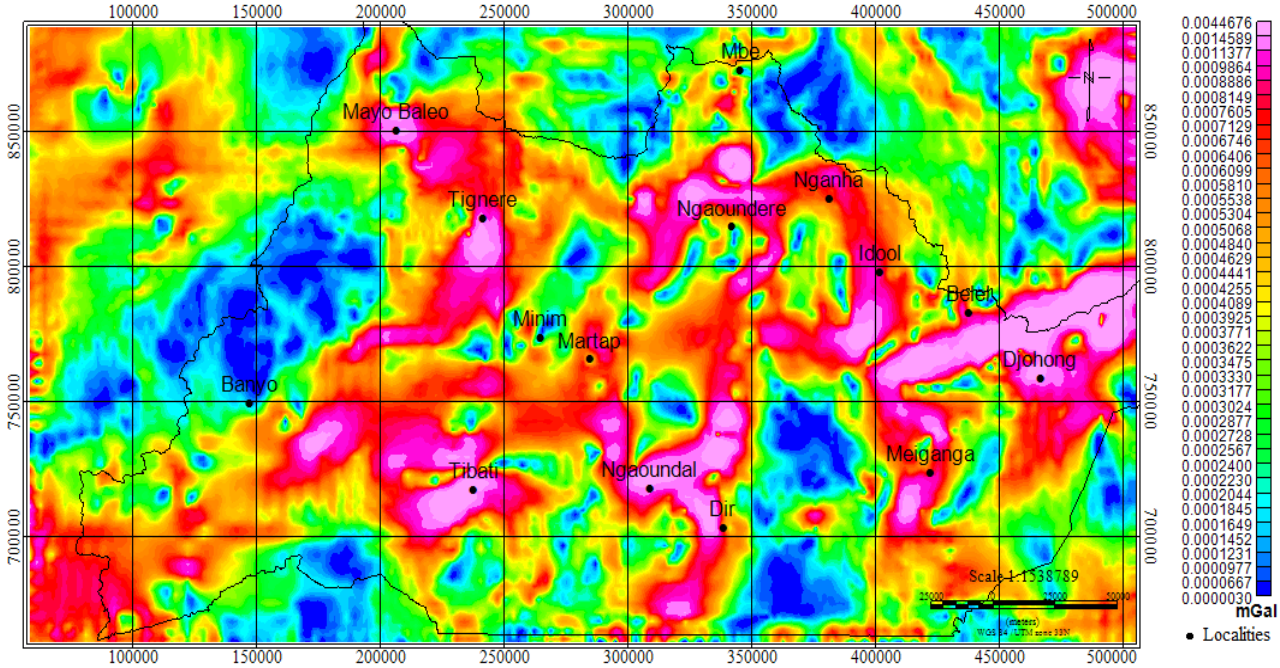

Figure 4. Horizontal gradient map from terrestrial gravity data

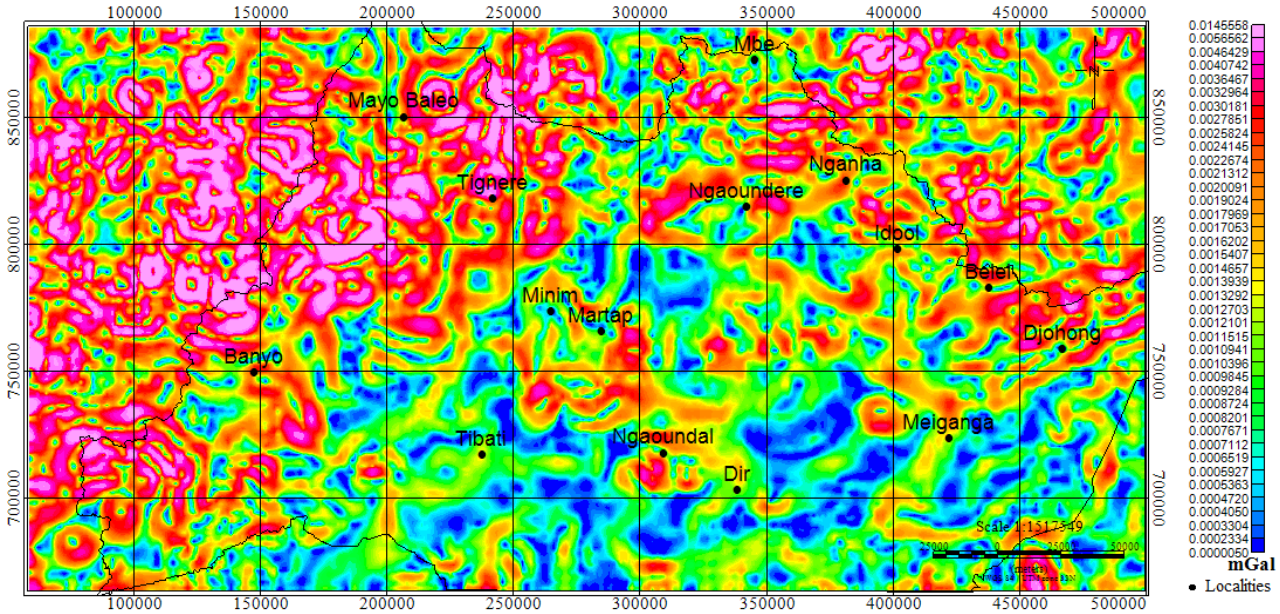

Figure 5. Horizontal gradient map from EGM 2008 gravity data

4.2. Coupling between the Upward Continuation and Horizontal Gradient Filter

The combination of the upward continuation and horizontal gradient filters is illustrated for our two cases in Figure 6 and Figure 7. To perform the upward continuation on the different Bouguer maps, a regular and gradual distance of 1 km is set as a step and the maximum height of this continuation is 20 km.Twenty colors are assigned to the horizontal gradient maxima for each extension. The maps resulting from this coupling show the displacements and inclination of the geological contacts detected during the horizontal gradient. Figure 6 affirms the NE-SW orientation of most of the lineaments by associating the magnitude of the peaks with the orientation of the troughs while the lineament dips are better illustrated in Figure 7.

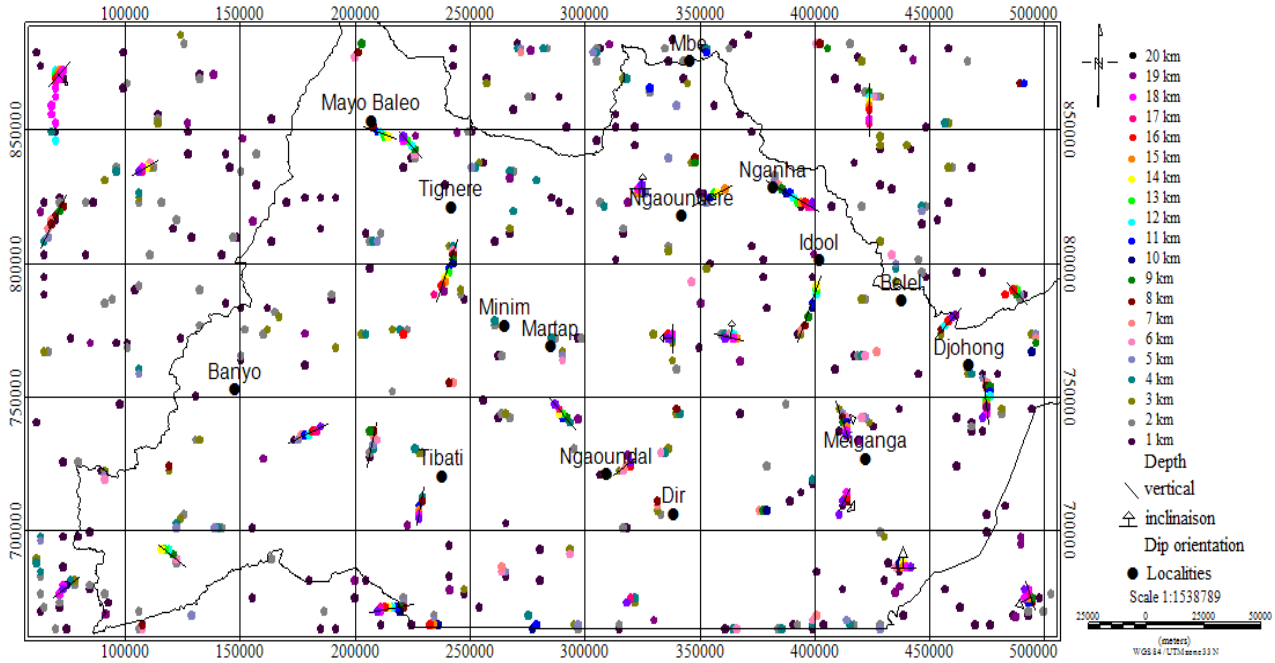

Figure 6. Horizontal gradient maxima from terrestrial gravity data

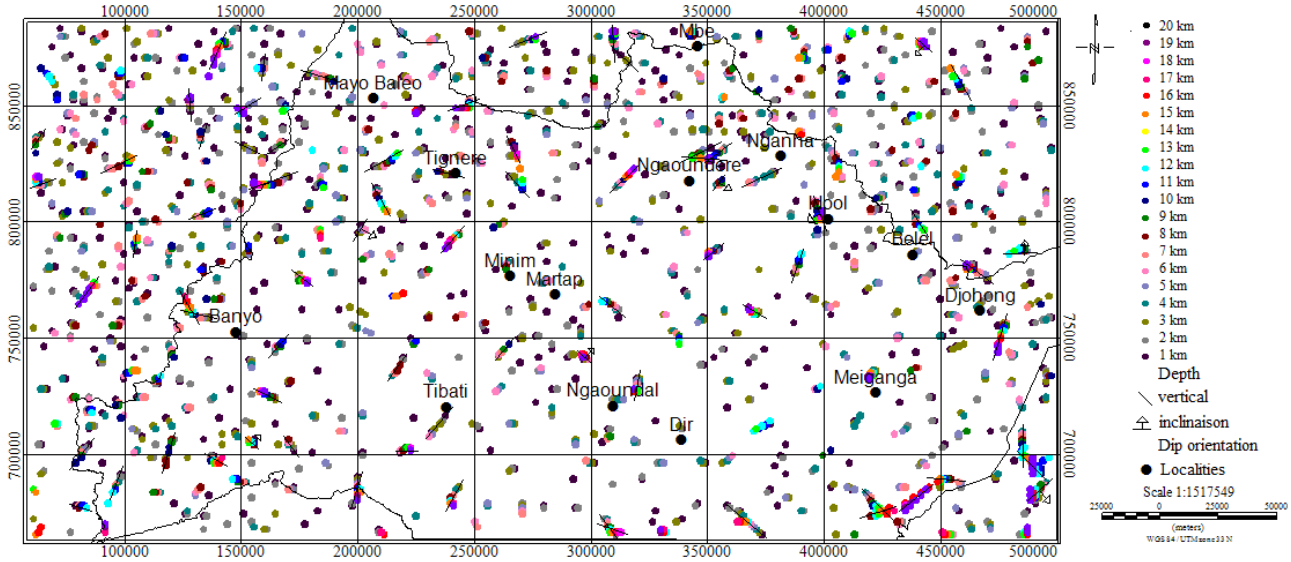

Figure 7. Horizontal gradient maxima from EGM 2008 gravity data

5. Discussion

The Bouguer anomaly map generated from the terrestrial data is smooth compared to the map from the EGM2008 data. In their analysis, the negative anomalies observed to the east of their maps are due to basement collapse. However, on Bouguer's EGM2008 map, this collapse of the Pan-African basement is only responsible for part of the negative anomaly, which is related to another anomaly whose source is the Lom series. As for the buoyancy map (terrestrial), this slight anomaly is defined as a response to the effect of the Mbere trench that extended toward the Meiganga locality.

The horizontal gradient map (terrestrial) shows several major peaks (more or less straight) along the NE-SW direction. The alignment of the Djohong, Ngaoundal-Dir and Tibati peaks reflects the extension of the Foumban Fault; the Tibati and Banyo peaks refer to the Tibati Fault and the Chollire-Banyo Fault is associated with the alignment of the Tignère and Banyo peaks. These three peak alignments with pronounced density contrasts highlight the shear zone. A circular peak is observed at Mayo Baléo indicating an intrusion. The geometry of the Mayo Baleo peak (circular) corresponds to an intrusion. This intrusion is also highlighted by the EGM 2008 horizontal gradient map which also shows the dipping lineaments around Djohong. The tectonic lineaments are not shown on this map. This shows that the EGM 2008 data are not ideal for use in the detection of mega structures.

Confirmation of the geological contacts from the gravity data is established through correlation with local or regional geology, slope map and shading maps. The intrusion found in Figures 4 and 5 correlates closely with trachytic (young) rocks younger than 15 Ma. On the geologic map, these trachytes are volcanic intrusions that

rest on a gneissic-migmatic basement [31] prior to intense granitization during the Pan-African in Adamawa. The mylonitic zones observed on the geological map correlate with the peaks (more or less rectilinear) of strong density contrast (terrestrial). The presence of these faults at depth [26] is consistent with the dip of these lineaments (Figure 7).

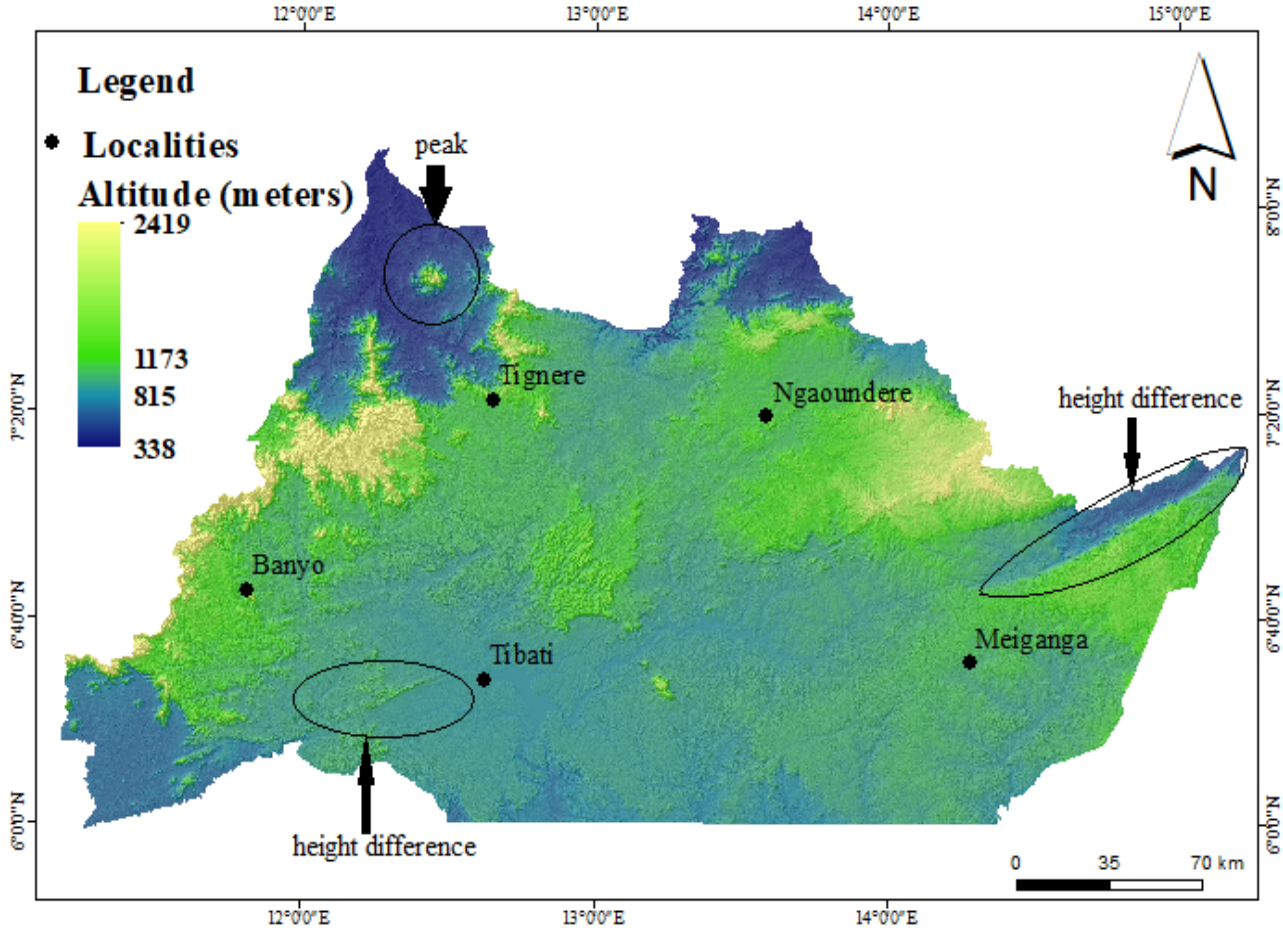

Figure 8. Altitude map of the Adamawa massif

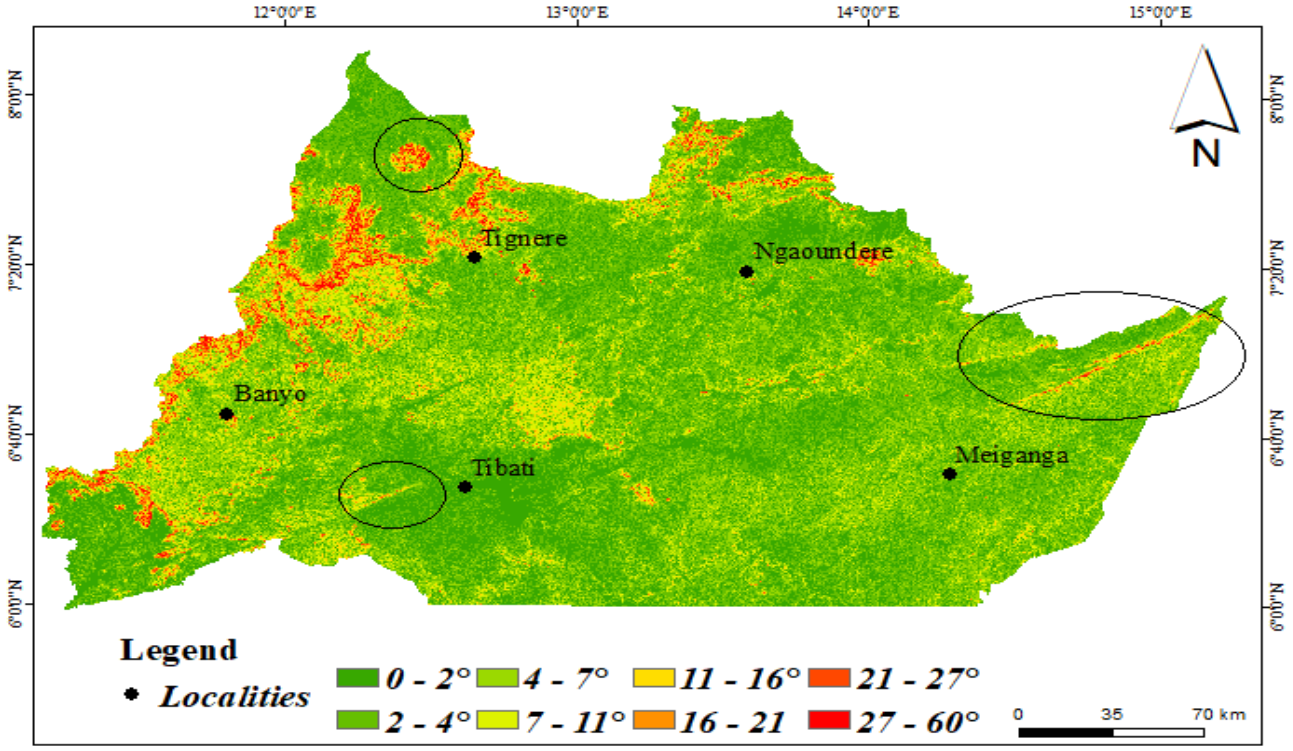

Figure 9. Map of the slopes of the Adamawa massif

The intrusive contact is located on a peak of 2419 m altitude (Figure 8) while some lineaments lie on dips that have no influence on the validation of the lineaments. Steep slopes are sometimes used as indicators of the presence of lineaments. Depending on the shape of the lineaments, three steep slopes (21° to 60°) highlight the rugged areas (Figure 9). The steep slopes located south of the Belel locality represent the great Pan-African accidents of N70 direction [32]. Based on the work carried out by [33], two hypotheses can be suggested to justify the presence of these two escarpments that border the Mbere trench and the one located at Tibati:

- Some escarpments must have been created by the movement of tectonic plates or by volcanism (ancient for the massif).
- Others may result from erosional irregularities resulting from differences in the strength of sedimentary rock.

The first hypothesis seems the most likely due to the fracturing of Gondwana during the Jurassic and Cretaceous periods that gave rise to the shear zone. The latter is a system of faults dating back at least 640 Ma [34], among which is the Foumban fault, whose extension goes as far as to limit one side of the Mbéré trough passing around Tibati. Oriented ENE - WSW, this extension has given rise to escarpments (fault scarps) in some places. The latter may have been subsequently affected by isostatically induced erosion in which the lithospheric structures buried at shallow depths were forced to the same pressure, disregarding the topographic anomalies at the surface. This erosion, known as littoral erosion, would therefore be at the origin of these retreating escarpments. This recession is observed on the slope map and on a satellite image south of the town of Belel.

Figure 10 show shaded relief maps. The SRTM 90m images having undergone filtering on different azimuth angles (0°, 45°, 90° and 135°) cause shading effects that allow better visualization of the lineaments. They are detected around Banyo (0°, 45°, 90° and 135° azimuth shading), Tibati (0°, 45°, 90° and 135° azimuth shading), Tignère (45°, 90° and 135° azimuth shading) and Mbere trough under 90° and 135° shading.

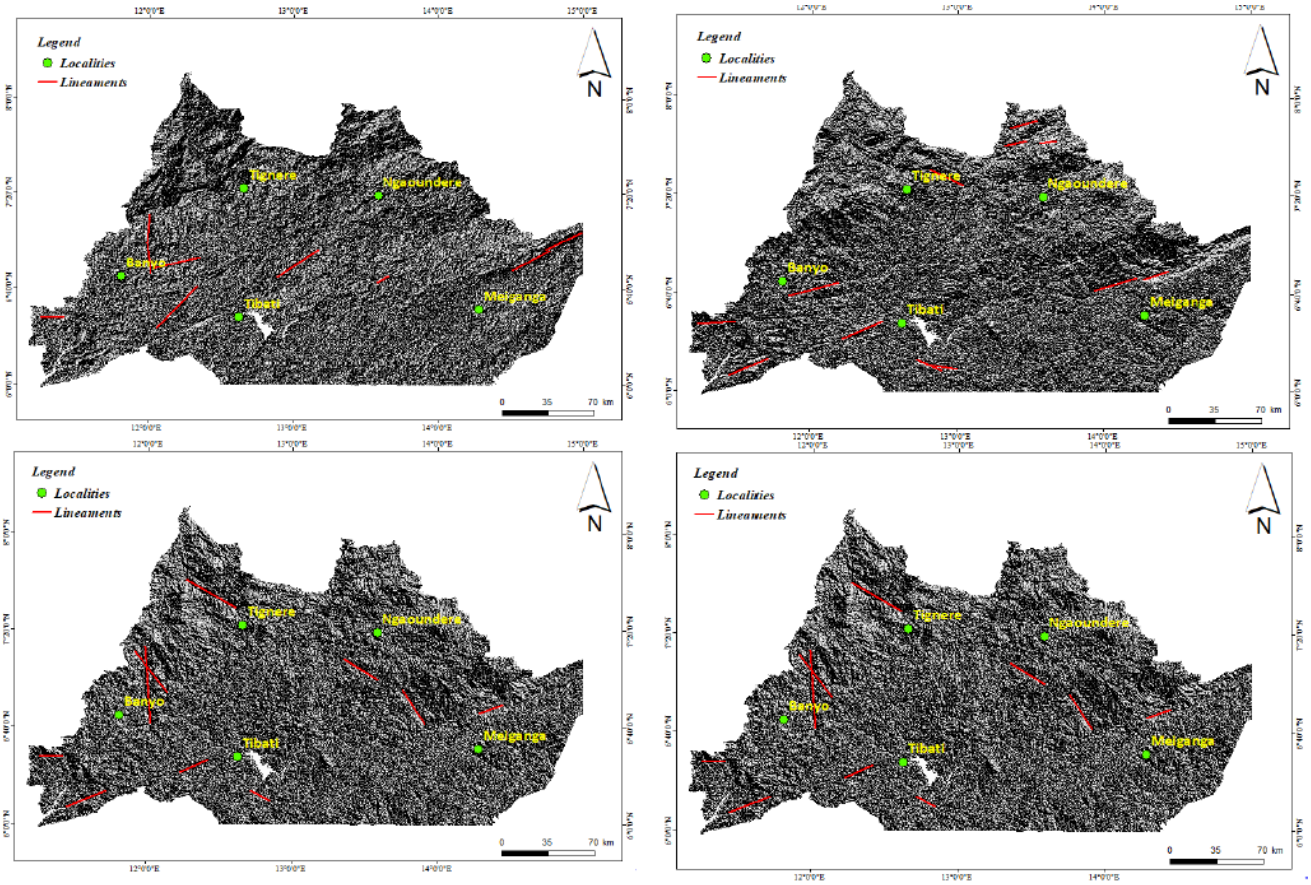

Figure 10. Maps of the shaded relief of azimuth 0°, 45°, 90° and 135° (respectively from left to right) of the Adamawa massif

The Mayo Baleo intrusive contact from the 2008 EGM gradient map closely matches the local geology, topography and morphology of the study area. This intrusion associated with trachytes (young) is a steeply sloping volcanic dome (27° to 60°) located at 2419 m altitude and resting on a gneissic-migmatite basement. The circular peak shown in Figure 4 does not correlate with the geology and even the relief of the area. This may be caused by the absence of missing gravity data in this area certainly due to the very variable steps taken during the gravity surveys (3 to 10 km). This remark follows the logic of [5] in the sense that the gravity data of EGM2008 are adapted to mountainous and volcanic areas where terrestrial gravity surveys cannot be easily carried out. However, not all tectonic lineaments such as the Djohong-Ngaoundal-Dir-Tibati lineament, the Tibati-Banyo lineament and the Tignère-Banyo lineament that are part of the shear system in Cameroon are highlighted in Figure 5. Only the Djohong lineament along the Mbere Basin correlates with the large NE-SW trending mylonite

fault. This lineament coincides with the steep relief (27° to 60°) that separates the Mbere Basin from the upper unit of about 358 m in elevation. This environment is defined as a small area of relief with morphological units adapted as in the case of the mountainous areas of the West to the use of gravity data from the EGM2008. Thus, Figure 5 shows through the high contrast density, the West Cameroon mountainous area that is bounded by the Tcholliré - Banyo fault that corresponds to the Tignère - Banyo lineament shown in Figure 4. Thus, the limitations highlighted by the geological lineaments (mega structures) are not visible using the 2008 EGM data.

6. Conclusion

In order to present the limitations on the use of EGM2008 data, a comparative study on the use of terrestrial and EGM 2008 data was conducted in the structural framework of the Adamawa Massif. The Bouguer anomaly maps are visually and statistically similar, yet also contain differences, particularly in the negative anomalies to the east of the map. A great impact on the use of these data is pronounced through the horizontal gradient maps. Reconciliation with the geology, the slope map and satellite images justifies the presence of the Djohong-Ngaoundal-Dir-Tibati, Tibati-Banyo and Tignère-Banyo lineaments and a volcanic intrusion. It follows that the mega structures illustrated by these lineaments do not provide strong density contrasts to the point of being detected on the horizontal gradient map of the EGM 2002 model: This constitutes a limitation on the use of gravity data from this model. The terrestrial gravity data are suitable for a better structural study because from the horizontal gradient maps, they highlight the local and regional lineaments. The structural study of the Adamawa Massif has allowed us to highlight the shear zone and the volcanic intrusion near Mayo Baleo. Using data from the EGM2008 model for a structural study would be possible in a framework of superficial structures for example to detect lineaments as water traps (drilling). This requires a shallower study.

Acknowledgements

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