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Structural Study of the Kakobola Area and Its Surroundings by Detecting the Edges of Gravity Anomaly Sources

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Abstract

The area covered by this study is the county of Kakobola and its surroundings. Previous studies show that those related to the study of depths by the gravity method, using other techniques, are not always carried out until now. The main goal of this article is the gravimetric characterization of our area by other approach. The interest is not only to map the lineaments and to know their dip, but also to estimate the depths of these different anomalies. The methods used for this study are the first total horizontal derivative (FTHDT), tilt angle (TA), analytical signal (AS) and horizontal gradient magnitude (HGM). The processing of the complete Bouguer anomalies (CBA) data was done mainly through software. Data analysis using the semi-finished body depth method shows depths ranging from 7.49 m to 224.6 m. Data analysis using the AS method shows values ranging from 41.7 mGal/m to 510 mGal/m. The fractures and/or geological contacts in our study area show dips ranging from −73.73˚ to 68.16˚ and North-South orientation according to the tilt angle method. The FTHDT shows several lineaments, a NE oriented fracture of Kakobola and low dip values which suggest a tabular structure of the subsurface in our study area. According to the HGM, the study area shows several preferential directions of fractures and/or geological contacts whose the most frequent directions are the NNE-SSW and WNW.

Keywords

First Total Horizontal Derivative, Tilt Angle, Analytical Signal, Dips, Depths

1. Introduction

The Kakobola county is located in the southwestern part of the central Congo basin (Ndala, 2022). The structure of this basin is poorly studied and therefore poorly known for several reasons (Kadima et al., 2011; Turnbull et al., 2021). It is also the case for most areas of this vast territory. The Kakobola area has attracted some researchers because of the construction of a hydroelectric dam on the Lufuku River near Kakobola City (Ndala et al., 2022, 2023).

Some studies have revealed the existence of underground cavities at the Kakobola site and have focused more on geochemical aspects than geophysical ones of the site (Ndala et al., 2023). The depth of the anomaly roof, the main directions of the lithologic contacts present in our study area, and their dips are not investigated in previous research on this site. The detection of the edges of the anomaly sources is not also highlighted in these previous studies. This is a shortcoming that may affect the geotechnical work undertaken at the Kakobola dam site.

To address certain geophysical aspects of the study area, we have opted to analyze gravity field anomalies. Gravity data analysis and interpretation are ubiquitous in analyzing and estimating edge of subsurface structures (Hosseini et al.; 2023; Essa 2013; Hinze et al. 2013; Essa et al., 2020, 2021). The study of the basement structures, based on the variations of the rock densities, is carried out using gravity methods. Indeed, the interpretation of gravity anomalies relative to a given region and their spatial derivatives can reveal some aspects of the subsurface structure under investigation (Araffa et al., 2015; Ekinci et al., 2013; Abdelrahman & Essa, 2015; Reynolds, 2011).

Although many gravity studies have been carried out through the world, the county of Kakobola and its surroundings remain a region whose subsurface is understudied; potential field methods are unknown in the characterization of the basement of our study area.

In order to detect the edges, roof depths and dips of gravity anomaly sources in our study area, we will apply the following filters to the complete Bouguer anomalies (CBA): analytical signal (AS), tilt angle (TA), horizontal gradient magnitude (HGM) and first total horizontal derivative (FTHDT). The complete Bouguer anomalies will be previously separated into regional anomalies and residual anomalies by applying an upward continuation filter at a well-defined elevation.

2. Description and Geology of the Region

The study area covers 4666 km^2 and is located in the southeast of Kwilu Province in the Democratic Republic of Congo (DRC) at latitude 05˚30'S to 06˚00'S and longitude 19˚00'E to 19˚30'E (**Figure 1**).

According to Cahen and Lepersonne (1948), our study area is characterized by plains intersected by rugged valleys. Our study area is characterized by altitudes up to 854 m, as shown in **Figure 2**, according to the digital terrain model (DTM).

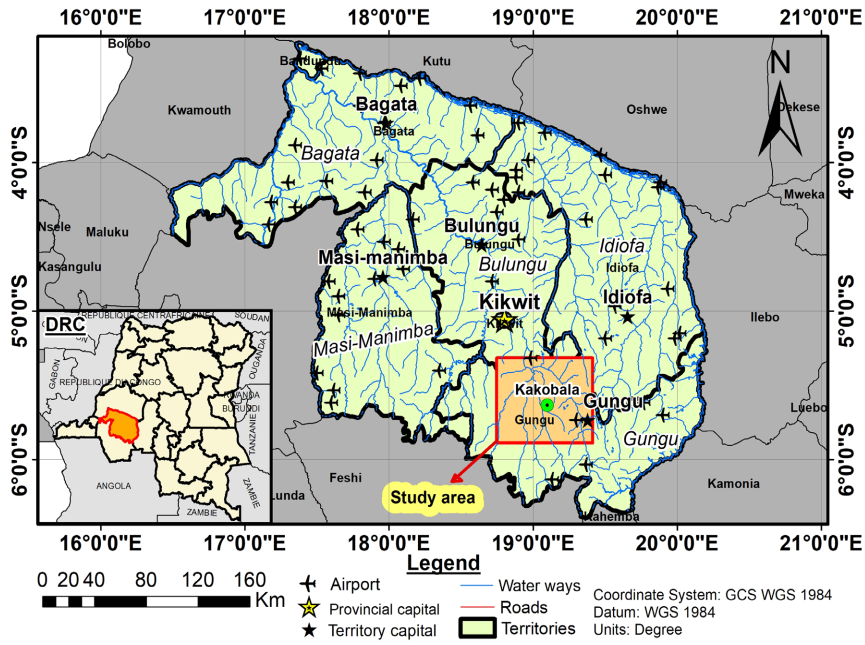


Figure 1. Location map of our study area.

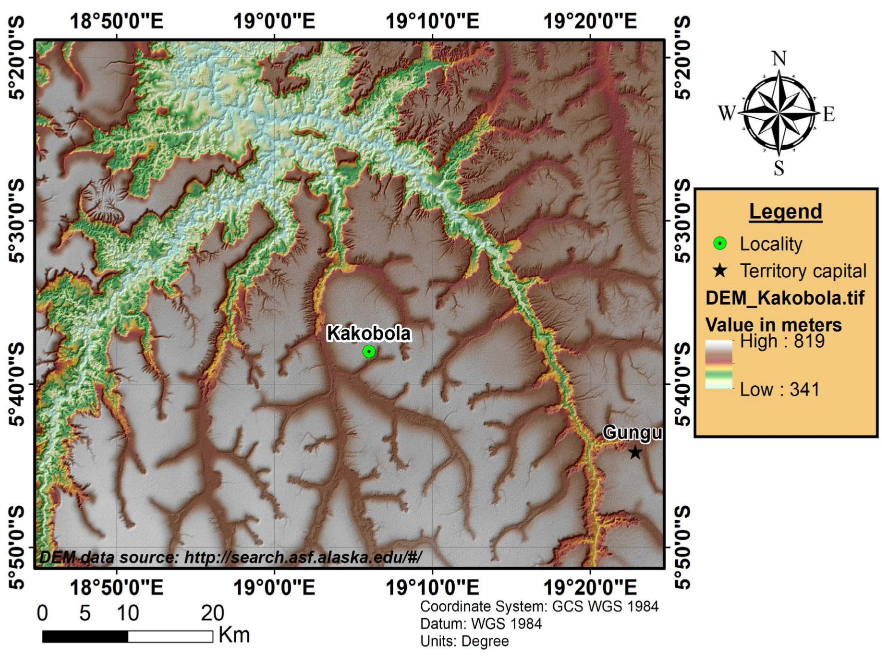


Figure 2. Relief map from the DTM.

Our study area is located in the tropical zone and is characterized by two seasons, the rainy season and the dry season. The average rainfall in our area is above 1600 mm according to the climate stations of Gungu and Kasanza over the entire Kwango plateau (Fehr, 1994). Our study area is crossed by the Lufuku, Kwilu, Lutshima and Mbwele-Milonda rivers (**Figure 3**).

From a geological point of view, our study area is made up of sedimentary formations. These sedimentary formations include from bottom to top the Kwango series followed by the Kalahari system comprising two series as follows from bottom to top (De Ploey et al., 1968): the upper series of ochre sands dating from the Neogene and the lower series of polymorphic sandstones attributed to the Paleogene. According to the National Geological Service of Congo (SGN-C: https//sgnc.cd) the study area is characterized by sands, polymorphic sandstones and soft sandstones (**Figure 3**).

3. Data and Methods

3.1. Data Collection

Gravity data for the Kakobola area and its surroundings that range from longitude 18.6˚E to 19.6˚E and latitude 5.20˚S to 6.50˚S were downloaded from the Bureau Gravimétrique International (BGI) website on 20/11/2022 at 08:35.

These data in text format are from a mesh network of 1479 virtual mesh stations equidistant of 3.69 km. They are then recorded in an Excel table (X, Y and Z), X representing the latitude, Y the longitude and Z the complete Bouguer anomaly of the study area. All useful corrections are previously performed on the gravity data by the BGI.

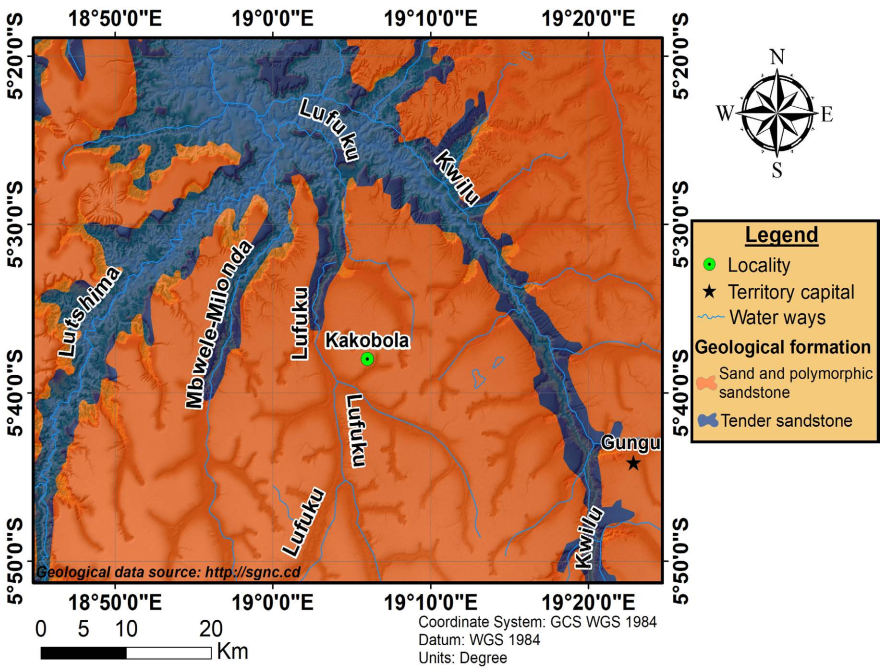


Figure 3. Geological map of our study area.

3.2. Data Processing

We apply an upward continuation to the complete Bouguer anomalies at a given elevation to separate them into regional and residual anomalies.

The upward continuation is a low-pass filter used to attenuate the high frequencies in order to emphasize the regional anomalies. The residual anomaly grid is obtained by subtracting the grid of complete Bouguer anomalies from the grid of complete Bouguer anomalies derived from application of the upward continuation to CBAs. Two heights of upward continuation are used in this work: 500 and 1000 m

The upward continuation of the gravity field anomalies at an elevation Δz from the baseline, $g_P(\Delta z)$, is given by the equation (Blakely, 1995):

$$g_P(\Delta z) = F^{-1}\left\{ e^{-\Delta z \sqrt{k_x^2 + k_y^2}} \hat{g}_z(k_x, k_y) \right\} \tag{1}$$

where:

- F^{-1} is the inverse Fourier transform of the bracketed expression;
- $\hat{g}_z$ is the Fourier transform of the gravity anomaly;
- Δz the elevation with respect to the reference level;
- k_x and k_y the inverses of the wavelengths in the x and y directions.

The CBA grid is used in the different methods described below. These different methods are implemented in Oasis montaj 8.4 software. In order to map lineaments, present in our study area, TA and HGM grids' data are introduced in Geomatica 2016 software. Mapping principal directions of lineaments is done by using Rockworks software.

3.3. Data and Methods

Tilt angle method

Defined as the ratio of the vertical derivative of the anomalies to their horizontal derivative (Miller & Singh, 1994), the TA of gravity anomalies is given by the equation:

$$\theta = \tan^{-1} \frac{\dfrac{\partial(\Delta g)}{\partial z}}{\sqrt{\left(\dfrac{\partial(\Delta g)}{\partial x}\right)^2 + \left(\dfrac{\partial(\Delta g)}{\partial y}\right)^2}} \tag{2}$$

with θ the tilt angle and Δg the gravity anomaly called also complete Bouguer anomaly. It is used to estimate the depth of the anomaly source.

The gravity anomaly due to a semi-infinite vertical cylinder is given by:

$$\Delta g = \frac{\pi G \rho R^2}{\left(x^2 + z^2\right)^{1/2}} \tag{3}$$

where

- G is the universal gravitational constant;
- ρ the density;

- R the radius of the cylinder;
- x the position coordinate;
- z the depth of the anomaly roof of this configuration which, according to Eshaghzadeh (2017), is obtained by the following relation:

$$z = x \tan \theta \tag{4}$$

with $x = \Delta x = x_i - x_0$ is the distance from the origin to the gravity points.

Idealized bodies as cylinders, spheres, thin sheets, … are inexistent in real basement (Essa et al., 2021). Thus, the estimated depth of anomaly source represented by a simple geometrical shape can be wrong and must be considered with care.

Horizontal gradient magnitude

According to Kassia et al. (2020), the horizontal gradient magnitude (HGM) highlights the fractures and/or lithological contacts of the bodies. Lineaments can be thus be detected by the HGM filter. HGM is defined by Cordell and Grauch (1982) as:

$$\text{HGM}(x, y) = \sqrt{\left(\frac{\partial(\Delta g(x, y))}{\partial x}\right)^2 + \left(\frac{\partial(\Delta g(x, y))}{\partial y}\right)^2} \tag{5}$$

where $\Delta g(x, y)$ denotes the gravity anomaly. The TA is related to the HGM by the relation:

$$\text{TA} = \tan^{-1}\left(\frac{\frac{\partial(\Delta g)}{\partial z}}{\text{HGM}(x, y)}\right) \tag{6}$$

For a vertical contact model (Salem et al., 2007; Oruç, 2018), the TA is given by the following equation:

$$\text{TA} = \tan^{-1}\left(\frac{x - x_0}{z_0}\right) \tag{7}$$

where x_0 and z_0 are the horizontal position and depth of the model, respectively. The value of TA above the edges of e contact is equal to zero radians (Oruç, 2018). The source depth estimated is equal to the half-physical distance between $\pm\pi/4$ contours of the TA (Salem et al., 2007). Contours of negative values suggest outside the source region and contours of positive values are above the source bodies.

Analytical signal method

The analytical signal (AS) filter is defined as follows (Keating & Sailhac, 2004):

$$\text{AS} = \sqrt{\left(\frac{\partial(\Delta g)}{\partial x}\right)^2 + \left(\frac{\partial(\Delta g)}{\partial y}\right)^2 + \left(\frac{\partial(\Delta g)}{\partial z}\right)^2} \tag{8}$$

where Δg is the gravity anomaly. Edge detection and depth estimation of gravity and magnetic anomaly sources can be investigated by this filter (Roest et al., 1992; Hsu et al., 1996).

First-order total horizontal derivative (FTHDT) method

FTHDT is the square root of the squares' sum of first-order directional total horizontal derivatives along the x and y directions of an original potential field (Zhou et al., 2017). The first-order horizontal directional derivatives along the x and y directions of the horizontal derivative of TDR are given by the following respective relations (Zhou et al., 2017):

$$\mathrm{FTHD}_x = \sqrt{\left[\frac{\partial}{\partial x}\left(\frac{\Delta g_z}{\partial z}\right)\cdot\frac{\partial}{\partial y}\left(\frac{\Delta g_z}{\partial z}\right)\right]^2 + \left[\frac{\partial}{\partial x}\left(\frac{\Delta g_z}{\partial z}\right)\cdot\frac{\partial}{\partial z}\left(\frac{\Delta g_z}{\partial z}\right)\right]^2} \tag{9}$$

$$\mathrm{FTHD}_y = \sqrt{\left[\frac{\partial}{\partial y}\left(\frac{\Delta g_z}{\partial z}\right)\cdot\frac{\partial}{\partial x}\left(\frac{\Delta g_z}{\partial z}\right)\right]^2 + \left[\frac{\partial}{\partial y}\left(\frac{\Delta g_z}{\partial z}\right)\cdot\frac{\partial}{\partial z}\left(\frac{\Delta g_z}{\partial z}\right)\right]^2} \tag{10}$$

The edge detector is:

$$\mathrm{FTHDT} = \sqrt{\left(\mathrm{FTHD}_x\right)^2 + \left(\mathrm{FTHD}_y\right)^2} \tag{11}$$

The FTHDT method is used to highlight the edges of geologic structures, which can be faults, fractures, geologic contacts and fold axes. The dips θ of the edges of geological structures are then given by the following relationship (Zhou et al., 2017):

$$\theta = \tan^{-1}\left[\frac{\mathrm{FTHDT}\cdot t}{\left|\Delta g_{zz}\right|^2 + k\cdot\max\left(\mathrm{FTHDT}\cdot t\right)}\right] \tag{12}$$

where

- $t = \left(\frac{\min\left(\Delta g_{zz}\right)}{\max\left(\Delta g_{zzz}\right)}\right)^2$ is a constant;
- Δg_{zz} is the first derivative of Δg along z;
- Δg_{zzz} the second derivative of Δg along z;
- k is a constant with values between 0 and 1.

4. Results and Discussions

The Kakobola and surrounding area is characterized from the complete Bouguer anomalies (CBA) by high positive Δg values to the NE and also SW, and low Δg values to the NW and SE (**Figure 4**). At an elevation of 1000 m, the regional anomalies fall into three groups:

- Anomalies with high Δg values ranging from 33.0 mGal to 46.6 mGal;
- Anomalies with low Δg values ranging from 17.2 mGal to 25.0 mGal;
- Anomalies with medium Δg values located in the center of our study area and ranging between 26.8 mGal and 30 mGal.

The upward continuation of the gravity anomalies to an elevation of 1000 m reveals the existence in the study area (**Figure 5**):

- To the southwest and northeast, some kind of massifs that could correspond to the ascent of the crystalline basement;
- To the northwest and southeast, gravity troughs in the crystalline basement, probably due to the downward movement of sedimentary rocks.

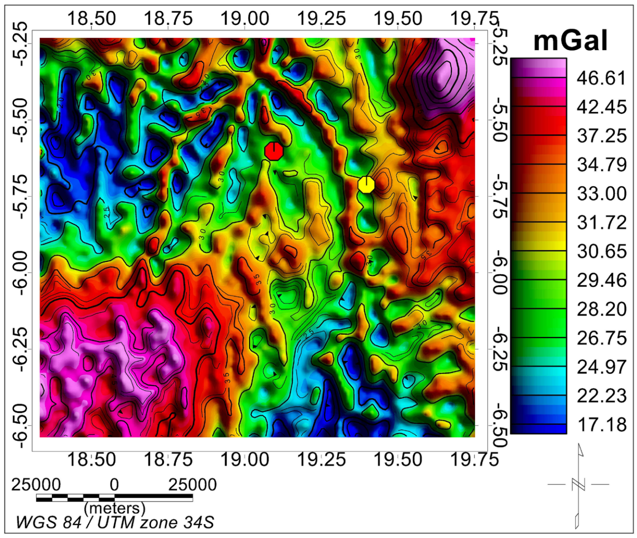


Figure 4. Complete Bouguer anomalies from our study area. Kakobola in red circle and Gungu in yellow circle.

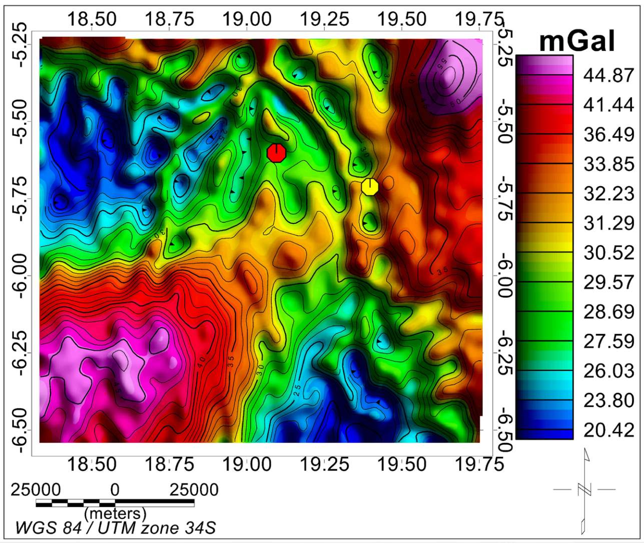


Figure 5. Regional gravity anomalies from the upward continuation of the CBAs at 1000 m elevation. Kakobola in red circle and Gungu in yellow circle.

The upward continuation of the CBAs at an elevation of 500 m highlights a little Δg variation in the same pattern as that obtained by applying an upward continuation of the CBAs at an elevation of 1000 m (**Figure 6**).

At 500 m elevation, we observe high Δg values ranging from 32.7 mGal to 46.1 mGal while low values ranging from 25.3 mGal to 18.3 mGal. The middle values are located in the center and range from 27.0 mGal to 30.6 mGal. Kakobola is located not far from a low Δg zone while Gungu straddles between a high Δg and a medium Δg part.

Residual anomalies reveal gravity lineaments with Δg ranging from approximately 0.1 mGal to 1.14 mGal and gravity lineaments with negative Δg ranging from −0.5 mGal to −1.7 mGal (**Figure 7**).

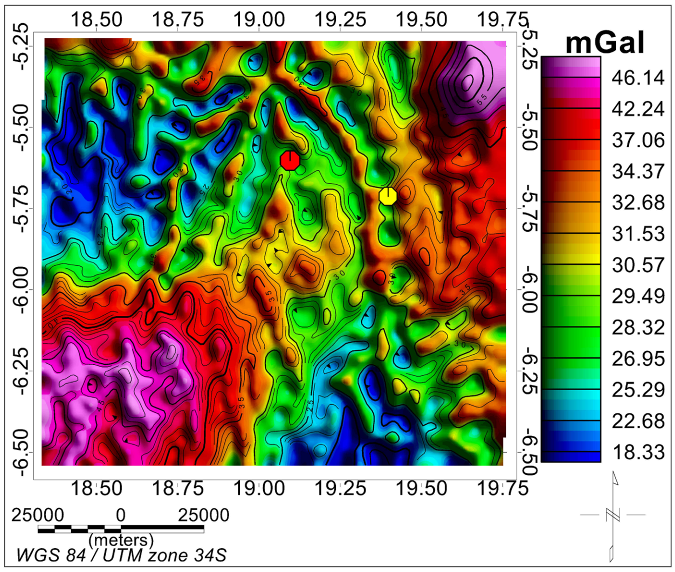


Figure 6. Regional anomalies from the upward continuation of the CBAs at 500 m elevation. Kakobola in red circle and Gungu in yellow circle.

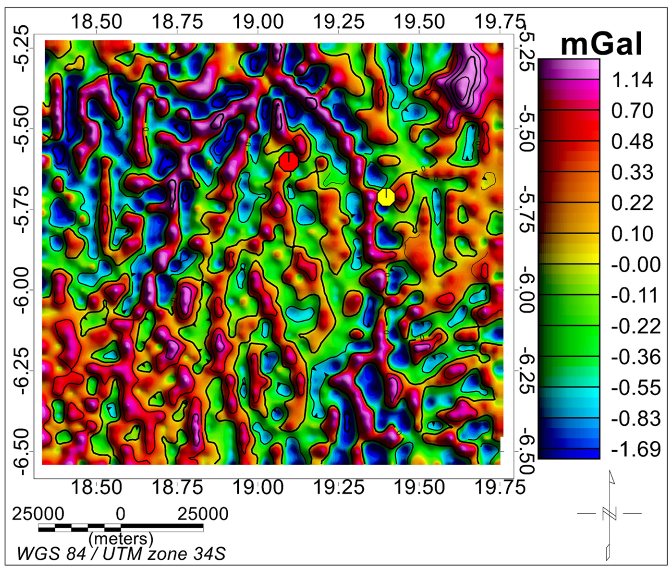
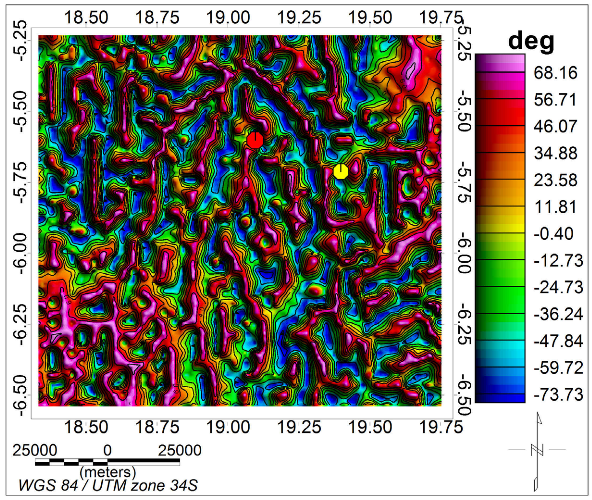


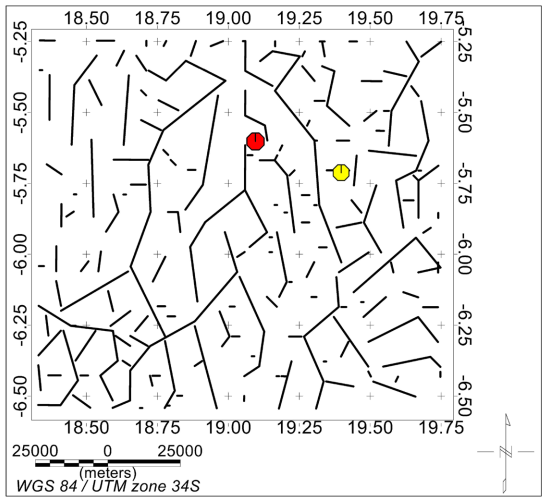
Figure 7. Residual anomalies in our study area. Kakobola in red circle and Gungu in yellow circle.

The two large gravity lineaments with high Δg values of 0.5 to 1.1 mGal appear to follow the main river in the study area, the Kwilu River. Some alignment of gravity anomaly sources is observed in surroundings of Gungu city. Gungu city is located on alignment of low and medium gravity anomalies.

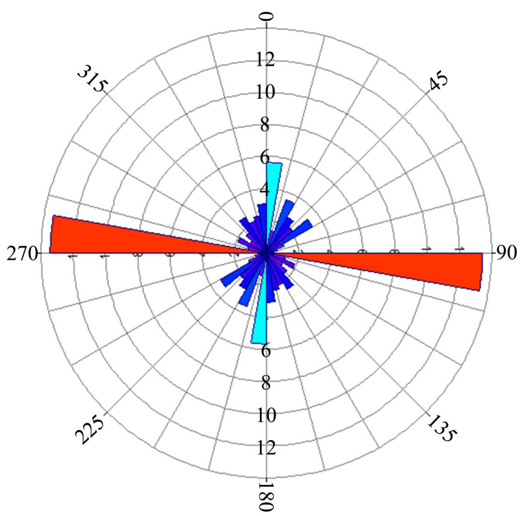
The tilt angle reveals that the faults and or geological contacts in this study area would have dips varying between −73.73˚ and 68.2˚. TA shows both deep and shallow sources but the edges are not well drawn (Prasad et al., 2021). Kakobola city is located at the edge of a SSE-NNE trending fault and/or geological contact with a dip of 12.73˚ (**Figure 8**).

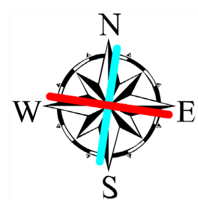


(a)



(b)





(c) (d)

Figure 8. Tilt angle of our study area. Kakobola in red circle and Gungu in yellow circle. (a) TA; (b) Lineament derived from TA; (c) Rose diagram; (d) Wind rose.

The city of Gungu is crossed by a W-E oriented fracture with a dip of 46.068˚.

The faults and/or geological contacts in the study area would have a South to North orientation. The W-E orientation is the preferred direction of fractures in this study area.

The depth of the roof of the anomalous sources, derived from the dip angles and calculated according to the Eshaghzadeh model, is shown in **Figure 9**.

Our study area would be characterized by depths of subsurface anomalies ranging from 7.49 m to 224.6 m. These depths concern a cylindric model. As idealized bodies are absent in real subsurface (Essa et al., 2021), these depths cannot be real. According to Ahmad et al. (2021), both positive and negative sign would also mean depths and both positive and negative depths are the result of positive and negative angles observed at tilt angles.

The cities of Kakobola and Gungu would be located on sites where the sources of gravity anomalies are located at 41.0 m and 72.6 m depth respectively.

The probability of the presence of hydrocarbons in this area is low because the generation of hydrocarbons occurs at a depth of more or less 3000 m (https://www.planete-energies.com/fr/).

Analytical signal of the CBAs is mapped on **Figure 10**.

Our study area is characterized by analytical signal values ranging from 41.7 mGal/m to 536 mGal/m. The whole central part is dominated by low signal analytical values while in the whole NE and SE parts, the analytical signal values are high, i.e., values ranging from 254.8 mGal/m to more than 536 mGal/m.

The city of Kakobola would be located above a shallow zone of signal analytical values i.e., more or less 41.7 mGal/m. According to previous investigations by previous researchers, cavities are observed not only on the surface but also at depth. Some cavities are characterized by low signal analytical values inferior to 41.7 mGal/m.

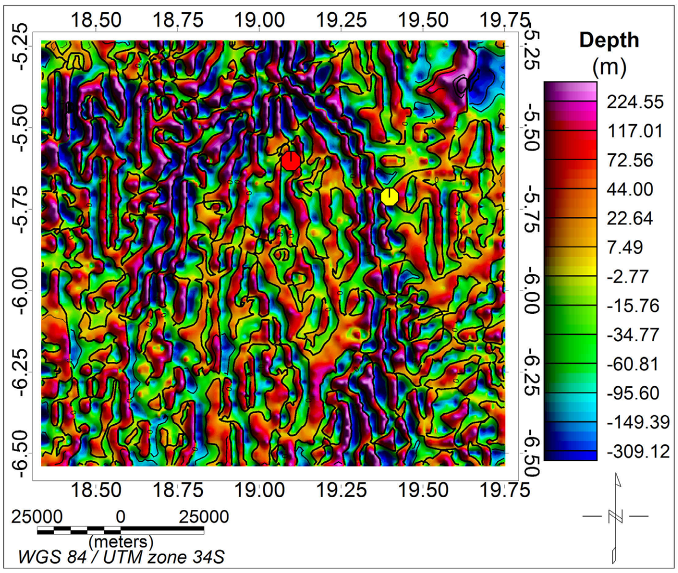


Figure 9. Depth of the subsurface source anomalies in our study area from tilt angle. Kakobola in red circle and Gungu in yellow circle.

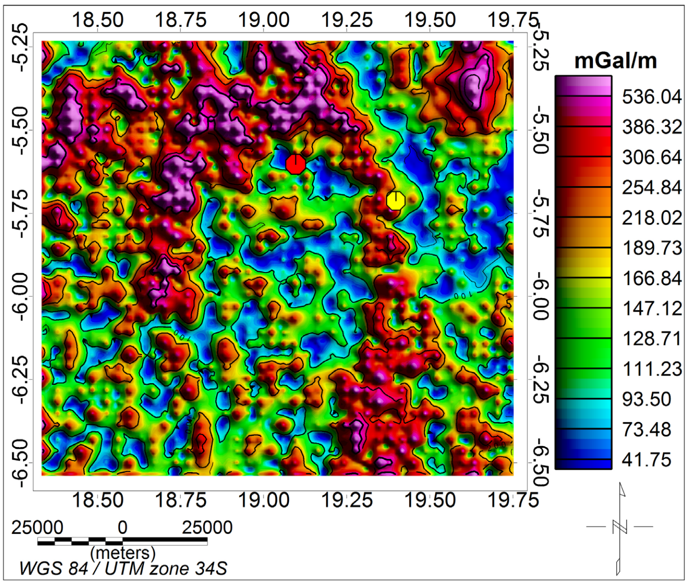


Figure 10. Analytical signal of the CBAs in our study area. Kakobola in red circle and Gungu in yellow circle.

Gungu city is located in the vicinity of a kind of mountain range lining the bed of the Kwilu River. This mountain range would have a depth to the top of the anomalies ranging from 166.8 mGal/m to over 536 mGal/m. To our knowledge, no comparison values of roof depths of gravity anomalies' sources in our study area are available in scientific literature.

The area has low potential for hydrocarbon generation due to the different depths of the anomalies observed.

The FTHDT was applied to the CBA grid in order to obtain the FTHDT map which highlights the edges of the different geological structures present in the region (Figure 11).

Figure 11 shows to the north of Kakobola the continuation of a probable break or fracture that would extend to the NE with the presence of breaks or fractures that would be perpendicular to it. Gungu is located on the left side of a fault or fracture corresponding to the bed of the Kwilu River.

As the FTDHT is calculated from the second derivatives, noise is ubiquitous in FTHDT results (Zhou et al., 2017). However, the examination of the FHDT and TA shows that Kakobola and Gungu are indeed located on sites of low or medium anomalies.

The FTHDT data grid allowed the development of the dip data grid for k set at 0.002 which, in turn, allowed the development of the dip map (Figure 12). The dip map shows the exact edges of the lineaments and indicates where we are dealing with more or less tabular structures.

Figure 12 shows that our entire study area is dominated by low dip values. These low dip values relate to largely tabular structures. Both Gungu and Kakobola are located at the edges of relatively low dip values. The subsurface geological structure of Gungu and Kakobola belongs to the tabular structures.

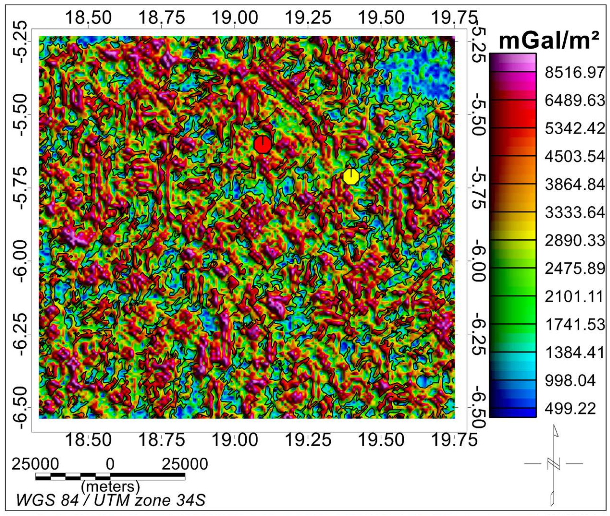


Figure 11. FTHDT of the CBAs in our study area. Kakobola in red circle and Gungu in yellow circle.

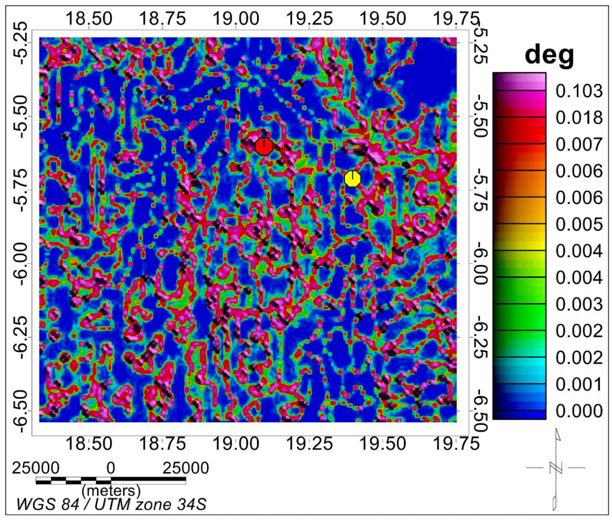


Figure 12. Dip map of the CBAs in our study area. Kakobola in red circle and Gungu in yellow circle.

The lineaments perceptible in the HGM map and visualized by Geomatica software are represented on Figure 13. From the frequency rose, we observe four preferential directions of our fractures and/or lithological contacts. The three observed directions of faults are:

- NNE-SSW: which is the most abundant in our region;
- NE-SW;
- WNW-ESE.

The cities of Kakobola and Gungu would both be located at the aplomb of a fracture and/or lithological contact of NW-SE orientation.

A close examination of the HGM and AS figures clearly shows that Kakobola and Gungu are located at sites of weak gravity anomalies. The depths as given by the AS method agree with the theory (Arisoy & Dikmen, 2013).

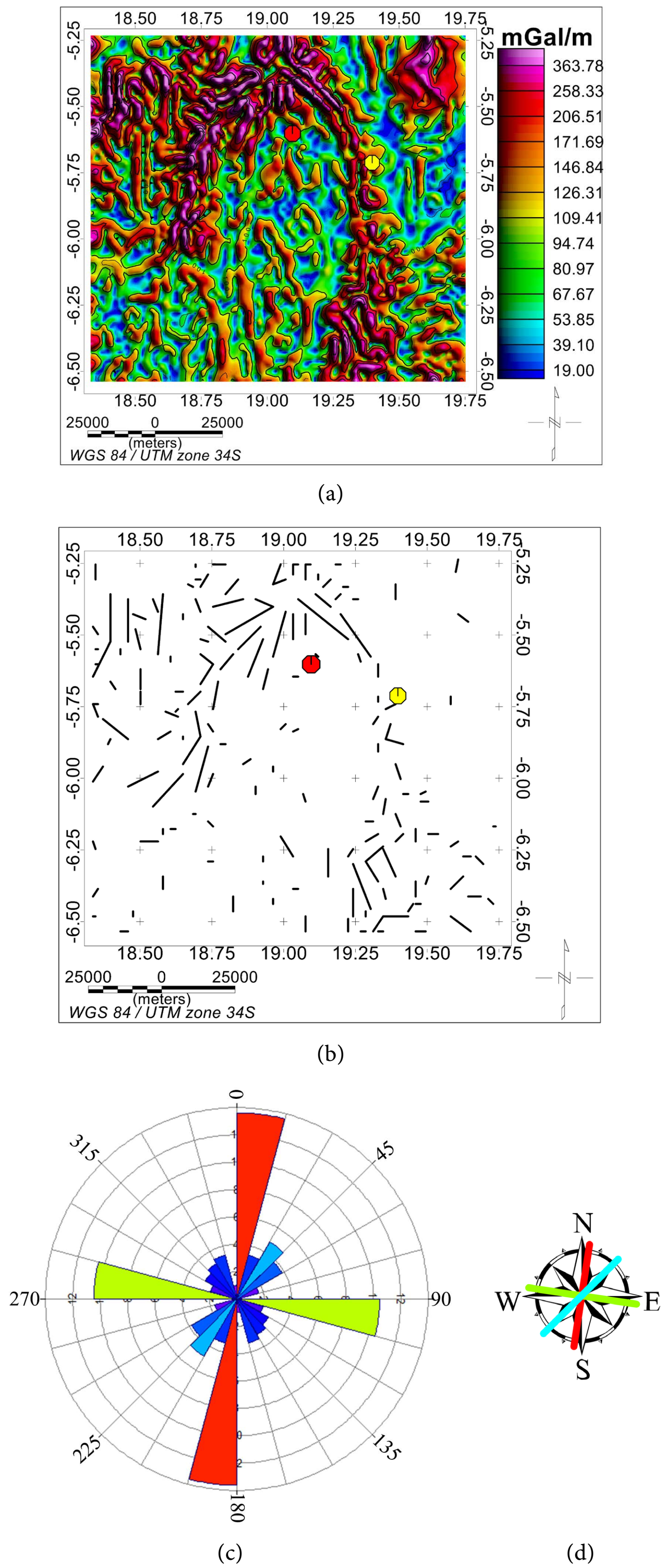


Figure 13. Magnitude of the horizontal gradient of CBAs in our study area. Kakobola in red circle and Gungu in yellow circle. (a) HGM; (b) Lineament derived from HGM; (c) Rose diagram; (d) Wind rose.

5. Conclusion

The different methods used in this study reveal that the county of Kakobola and its surroundings present two ditches, one to the NW and the other to the SE and many gravity lineaments whose two large lineaments follow the Kwilu hydrographic bed.

Three preferential directions of fractures and/or faults in the study area are observed; the most important of which are those oriented NNE-SSW and the least abundant are those oriented WNW. The study area is characterized by low dip values and superficial anomaly sources whose tops are near the surface. Kakobola and Gungu are located on geological structures of low or medium anomaly values. Some civil works in this region should take into account the unstable structure of this site before any development. The different methods used in this study, except the FTDHT, are basic methods with advantages and shortcomings. Thus, most accurate results could be obtained in future by using enhanced filter methods.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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