Nigerian Journal of Physics (NJP)
ISSN online: 3027-0936
ISSN print: 1595-0611
DOI: https://doi.org/10.62292/njp.v35(s).2026.639
Volume 35(S), 2026

Gravity Method for Delineation of Iron Ore Deposit Geometry in Oko, Southwestern Nigeria

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Keywords:
Bouguer Anomaly,
Depth Estimation,
Depositional Thickness,
Gradient Amplitude Method,
Oko Banded Iron Formation (BIF)

Submitted: 07 July 2026

Accepted: 07 Aug. 2026

Published: 11 Sept. 2026

ABSTRACT

Solid mineral deposits possess significant economic advantage to a nation if they are properly mapped and exploited. Several researches have shown that there are myriads of solid mineral resource deposits in Nigeria with significant portions in the southern part of the nation, but there is a knowledge gap in the quantity and quality of geophysical and geological information available about them. This study is therefore aimed at providing more information by estimating the thickness and depth to iron ore formations in Oko, South-Western Nigeria using gravity method of geophysical survey due to its efficiency in mapping the density contrast between the iron deposit and the host rocks. Ground gravity survey was carried out at 220 gravity stations and 11 traverses using a Scintrex CG-5 gravimeter to cover a 250 m x 100 m area. Coordinates, time and elevation were also taken at each gravity station, gravity reductions and removal of regional trend were also carried out. Qualitative analysis using first vertical and horizontal derivatives was used to identify positive bouguer anomalies in the map while quantitative analysis using Half width, Peter's half slope and Gradient Amplitude methods with Euler de-convolution and source parameter imaging methods were applied to image the sub-surface and to determine the depths to top and centre of the anomalous bodies. The qualitative analysis revealed E-W trending geological structures which Euler solution confirmed to be a fault. Depth estimation revealed that average depth to the centre of the deposit ranged from 5.61±2.48m to 14.57±6.45m and the depth to top estimates ranged from 6.77±3.14m to 11.28±5.24m while the thickness of the ore body was also estimated to range between 3m to about 20m. The study revealed that the Oko banded iron formation (BIF) is occurring in lineaments trending majorly in the E-W direction with a depositional thickness of about 20m.

INTRODUCTION

The Gravity method is a non-invasive geophysical method based on Newton's law of universal gravitation; it measures the gravitational attraction exerted by the earth on a body at a location on the surface of the Earth. The magnitude of the gravitational field is directly proportional to the mass and density of subsurface materials but inversely proportional to the distance of these bodies from the measuring equipment (Shendi et al., 2008). Variations or anomalies in the earth's gravitational field are the result of the variation in the density of subsurface materials, an area with denser subsurface rocks will exert a slightly stronger gravitational force while less dense rocks will have weaker gravitational force. Gravity survey can provide information about densities of underground rocks and therefore researchers can make inferences about the distribution of strata of these subsurface rocks (Williams et al., 2006; Hinze et al 2013; Abuga, 2013).

Solid minerals are mostly studied using potential field methods especially gravity method because of its non-invasive tendency and its capability to map resources based on their density gradient. The gravity method is useful in investigating near surface, heavy weight and ore bodies (Abuga, et al 2013). Several researchers such as Nguru 2019, Layade et al 2021 have carried out ground gravity survey to investigate the presence and extent of mineral deposit such as iron ore deposit in Kimachia (Kenya) and Gbede (Nigeria). The iron ore deposit at Gbede is part of the banded iron formation of Ogbomosho, south-western Nigeria. A preliminary investigation of the geology and structural trends of lower Proterozoic basement rocks in Ogbomosho, south-western Nigeria by Afolabi et al. (2013) provided some significant information about the banded iron formation, He observed that the banded iron formation occurs as narrow lenses and bands which are mostly hematite-magnetite iron formation and that the pegmatite bodies of Ogbomosho basement rocks served as host to disseminated iron ore body that appears as products of magmatic segregation processes (liquation). He suggested that geophysical and geochemical research be caried out on the Oko iron deposits to properly determine its depth, geometry and the composition of the deposit. The aim of this study is to determine the depths to top, depth to centre and to delineate the geometry of the iron ore deposit using geophysical method.

MATERIALS AND METHODS

Geology of the Study Area

Geographically, Oko is bounded by latitudes 07^0 57′ 0″ N 4^0 20′ 0 ″ E as shown in Figure 1a and Figure 1b below. The average elevation of the study area is 379 m above mean sea level. It is located in Surulere local government area of Oyo state. Geologically, the rocks within this area consist of Migmatite-gneiss, banded gneiss, porphyroblastic biotite-gneiss, Granite and quartzite as shown in figure 1a below. Migmatite-gneiss is the widest spread rock type within the area, it covers about half of the study area, and porphyroblastic biotite-gneiss is spatially located at the north – western end of Ogbomosho town towards Ikoyi (Afolabi et al 2013). The granite body is a low-lying massive rock with gentle elevation, field observation show that the granite body is not homogeneous. Quartzite are metamorphosed arenaceous rock usually formed by the metamorphism of sandstone from thermal regional metamorphism, this rock type dominates the south- eastern parts of Ogbomosho area. (Afolabi et al 2013; Oladunjoye et al 2013).

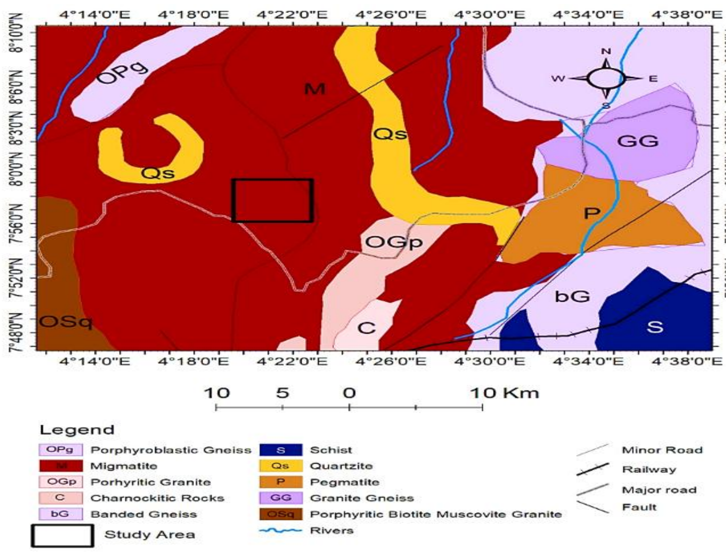

Figure 1a: Geologic Map of the Study Area

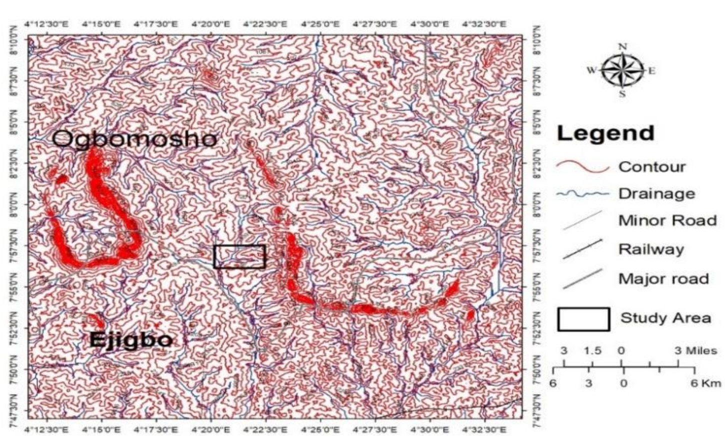

Figure 1b: Topographic Map of the Study Area

Gravity Data Acquisition

Ground gravity survey covering an area of about 250 m x 100 m and consisting of 11 traverses spaced 10 m apart was carried out to map the Oko iron ore deposits and to determine the depth to the ore bodies as well as its geometry. The gravity station along each profile was spaced 10 m apart to cover a length of 250 m per traverse. A base station, in an accessible area outside of the survey grid, was established for drift corrections. Data were acquired from all stations using Scintrex Autograv CG-5 gravimeter. The gravimeter was levelled firmly before making the observed gravity reading. A Global Positioning System (GPS) and a stopwatch were used to record each station's horizontal position in terms of northings and eastings, date, time and elevation.

Gravity Data Reduction

Different corrections were applied to the gravity data in order to remove noise and to obtain correct interpretation of the gravity measurement, these corrections are collectively referred to as "Gravity reduction". These corrections are drift correction, latitude correction, elevation correction (free-air and Bouguer corrections), tidal correction, and Eötvös correction (for a moving platform). Drift correction involves Gravimeter readings which drift with time as a result of elastic creep in the springs, producing an apparent change in gravity at the given station. The drift can be determined simply by repeating measurements at the same station(s) at different times of the day, typically every 1 – 2 hours. The differences between successive measurements at the same location are plotted to produce a drift curve. Observed gravity values from intervening stations can then be corrected by subtracting the amount of drift from the observed gravity value. In modern instruments such as the Scintrex Autograv, the meter automatically applies the drift corrections. Latitude correction is needed because of the ellipticity of the Earth. Gravity values is reduced at low latitudes because of the Earth's shape and because of rotation. Bouguer correction is used to account for the average density of rocks as a function of elevation. Free air correction is used to account for variations in gravitational acceleration with elevation. For this study, drift, free air, Bouguer slab and latitude corrections were carried out on the gravity readings.

Gravity Data Processing

A control gravity station was established some 500 m-1000 m northwest of the survey station. This was aimed at determining the contrast between the gravity values in the survey area and in an area estimated not to have the iron ore deposits, such that the variations between these readings will provide values strictly representing the gravity effects of the iron ore deposits. These net gravity values were entered into a table using Microsoft Excel for each traverse together with the latitude and longitude after the gravity data has been reduced. Then the gravity data was imported and gridded in the X and Y directions, using the minimum curvature method in Geosoft Oasis Montaj 6.4.2. The gridded data produced variograms showing the areas of interest marked by gravity highs and possible intrusions in the study area marked by gravity lows. An upward continuation filter was applied to the gridded data, this filter attenuates shallow local anomalies and enhances long wavelength deeper regional features.

RESULTS AND DISCUSSION

After data reduction and processing, the results of the study were obtained through qualitative and quantitative analysis of the data.

Qualitative Interpretation

The Bouguer gravity anomaly was processed and gridded using the minimum curvature algorithm in Oasis Montaj 6.4.2 (HJ) to obtain the Bouguer gravity anomaly map which represented the observed anomaly of the total study area. The Bouguer gravity anomaly map, as shown in Figure 2 revealed areas of gravity highs (red to purple) and gravity lows (blue to green) which were due to positive gravity contrast and negative gravity contrast respectively. The areas of gravity high represented the areas of interest as the density of iron ore is greater than the density of the surrounding rocks. These areas of gravity high trend majorly in the east-west direction as shown in the Bouguer gravity anomaly map below in Figure 2. In order to obtain the residual anomaly which is of interest in this study, an upward continuation filter was applied to the data to remove the regional field effects from the data. The upward continuation filter is effective for separating regional magnetic field sources from residual or local field sources. The data was upward continued to a depth of 5m to remove the regional field effects from the total Bouguer gravity field and obtain a residual Bouguer anomaly map as shown in Figure 3. Regions of high-density anomaly (500 mGal – 1200 mGal), which is most likely iron ore, can be observed in the southern and south-western part of the study area and trending in the east-west direction in the study area.

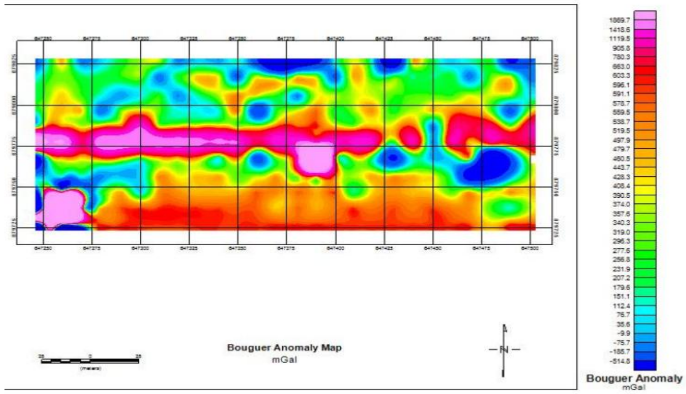

Figure 2: Bouguer Gravity Anomaly Map of the Study Area

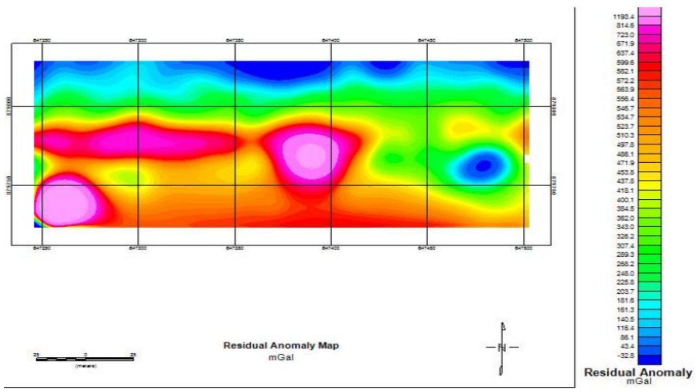

Figure 3: Residual Bouguer Anomaly Map of the Study Area

Quantitative Interpretation

Quantitative interpretation of Bouguer gravity anomaly aims to estimate the depth to top/centre of causative body, geometry and orientation of causative body. The depth to anomalous body is obtained using the semi-automated methods and the analytic methods of potential field depth estimation. The semi-automated methods used include: Euler deconvolution method (EDM) and Source parameter imaging (SPI) while the analytic methods used are the half width method (HWM), gradient-amplitude method (GAM) and the Peter's half slope method (PHSM). The Bouguer gravity data was gridded using the kriging interpolation technique in Golden Software Surfer™ 21 to obtain a contour Bouguer anomaly map. Areas of interest characterized by gravity highs were picked as profiles for quantitative analysis using analytic depth estimation methods.

Semi-automated depth estimation methods:

The semi-automated methods for depth estimation in gravity operate on the basis of Fast Fourier Transform (FFT) and they comprise of the Euler Deconvolution method (EDM) (Reid et al., 1990), the source parameter imaging (SPI) and statistical spectral techniques, for the purpose of this study.

Euler Deconvolution Method (EDM): EDM was used to image and map the depth of gravity structures in the study area. Structural indices (SI) of 0 (indicating fault geometry), 1.0 (indicating horizontal cylinder geometry) and 2.0 (indicating a spherical geometry) was used. The SI of 1 (indicating horizontal cylinder geometry) and SI of 2 (indicating a spherical geometry) were rejected as the solution cluster was sparse around the geologic structures hence, they were not representative of the Bouguer gravity obtained in the study area. However, the Euler solutions of SI value of 0 was the best and a good match because there were significant clusters around some notable anomalies of the Oko BIF and along synform and antiform-like features. Hence SI of 0 was used for interpretation and analysis since it best represents the geological structures in which the iron ore frequently occurs in the study area as shown in Figure 4. The clustering solution as displayed on the 3-D Euler map Figure 4 for SI=0 establishes the presence of a fault trending in the east-west direction which agrees with the lineaments derived from the derivative maps. From the solution plot for SI = 0, it can be observed that the depth estimates to the causative body (iron ore deposits) ranges from 0.2 m to 15.0 m with an average depth of 9.38 m ± 2.49 m.

Source Parameter Imaging (SPI): The SPI (Figure 5) shows a depth estimate to the iron ore body of 8 m to 13 m with an average depth of 9.93 m± 1.28 m. The result obtained shows that the depth to banded iron deposits are shallow and near surface and this agrees with depth estimates obtained from the Euler deconvolution method in this study.

Radial Power Spectrum**:** As shown in Figure 6 the depth curve has three tangential straight-line segments whose slope has an inverse relationship with frequency. The peaks within the first segment with greatest descent give the depth estimate of deepest source, whilst the peaks within the least gradient give the depth estimate of the shallowest source with the intermediate source in between the deep and shallow sources. The maximum depth yielded by the radial power spectrum is about 12 m. The radial averaged power spectrum also showed that there is little to no noise in the Bouguer gravity data.

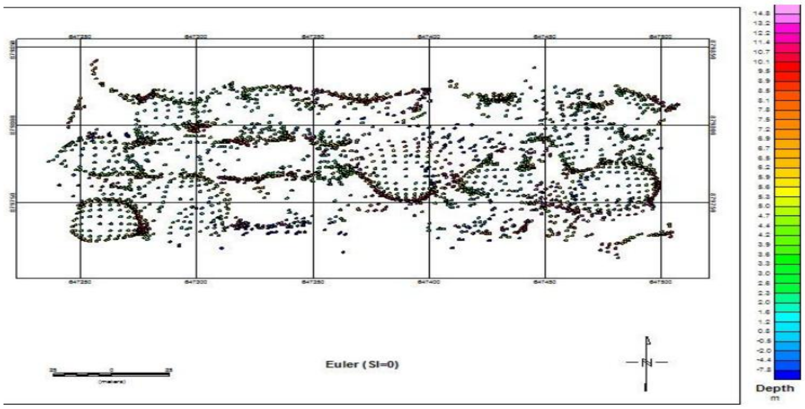

Figure 4: Euler Deconvolution Solution Plot for Structural Index 0

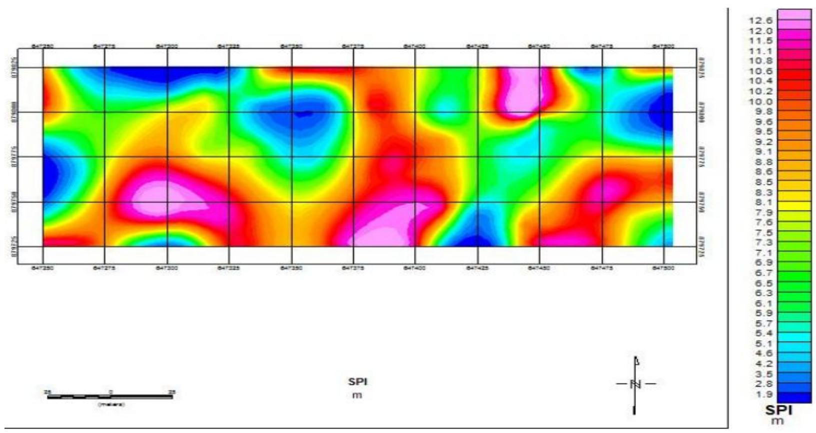

Figure 5: Source Parameter Imaging Map of Study Area for Depth Estimation

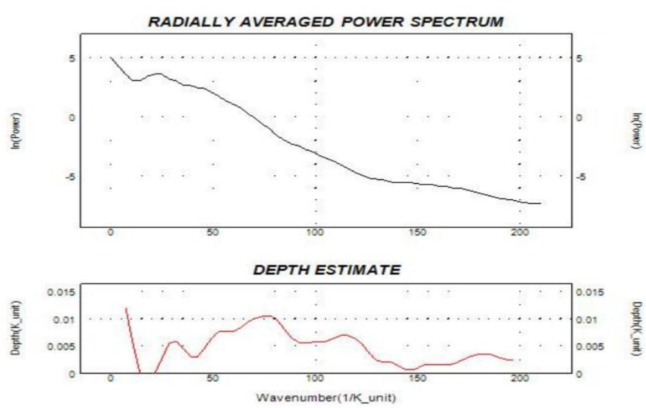

Figure 6: Depth Estimation Using Radial Power Spectrum

Analytical Depth Estimation Methods

Analytic depth estimation methods give information on the anomalous body which is not dependent on the real shape of the causative body (Keary et al., 2002). The Half Width method (HWM), the Gradient-Amplitude ratio method (GAM) and Peter's Half Slope method (PHSM) were used for this work. Each of these depth estimation methods except PHSM will provide an overestimate of the limiting depth, which is the maximum depth to the top of the anomalous body such that it will still give a gravity anomaly. Profiles across regions with gravity highs were drawn and regional trends from the profiles removed using Microsoft Excel™. Six profiles were obtained over areas characterized by gravity high to obtain the depth to causative body. The choice of profile was guided by distribution and orientation of positive gravity anomalies which are representative of the iron ore deposits.

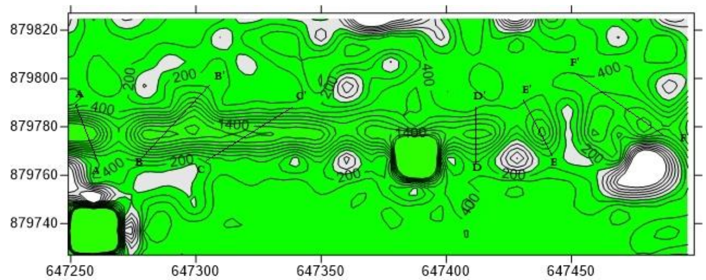

Figure 7: Gravity Anomaly Map Showing Profiles Taken for Depth Estimation

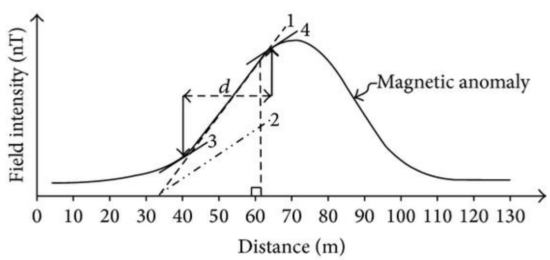

Figure 8: Profile Curve for Depth Estimation

Half Width Method (HWM)

The half width method of depth estimation yielded depth values for different geometry of the anomalous body ranging from sphere to a vertical thin plate. The values of depth estimate obtained for each of the profile across the diverse geometry are given in Table 1. From this depth estimate, it was observed that the depth estimate for 3D shapes such as spheres and vertical cylinders were higher than those of 2D shapes like vertical fault, horizontal cylinders with profile BB having the maximum depth estimate and profile DD the minimum. Correlating the result obtained from the Euler deconvolution method to that of the HWM shows that the depth estimates across the profiles for the following geometries agree (vertical cylinder, narrow dike or vertical fault and vertical thin plate) with that of the fault geometry using EDM. The average depth estimates across the profiles for vertical cylinder, narrow dike or vertical fault and vertical thin plate geometries using HWM are 6.50±2.88 m, 5.61±2.48 m, 7.85±3.47 m respectively

Table 1: Depth Estimates for All Selected Profiles Across Different Geometries Using Half Width Method

Profile	x1/2	Sphere	Horizontal Cylinder	Vertical Cylinder	Narrow Dike or Vertical Fault	Vertical thin Plate d=h	Vertical Thin Plate d~h
AA	8.21	10.67	8.21	4.76	4.11	5.75	8.21
BB	16.52	21.48	16.52	9.58	8.26	11.56	16.52
CC	16.05	20.87	16.05	9.31	8.03	11.24	16.05
DD	5.71	7.42	5.71	3.31	2.86	4.00	5.71
EE	6.47	8.41	6.47	3.75	3.24	4.53	6.47
FF	14.29	18.58	14.29	8.29	7.15	10.00	14.29

Gradient-Amplitude Method (GAM)

GAM measures the depth to centre of the anomalous body using 2D and 3D geometry. The results obtained are shown in Table 2. The result obtained showed that the depth estimate for 3D bodies is greater than those of 2D bodies. This is in agreement with the observations inferred from the HWM. Profile BB has the maximum depth estimate while profile DD has the minimum, which is also in agreement with the result obtained using HWM. This could be as a result of the high amplitude ratio of profile BB which is a function of its low gradient compared to that of profile DD which has a low amplitude ratio.

Table 2: Depth Estimate for All Selected Profiles Across Different Geometries Using GAM

Profiles	Amplitude Ratio	2D	3D
AA	8.21	5.34	7.06
BB	16.52	10.74	14.21
CC	16.05	10.43	13.80
DD	5.71	3.71	4.91
EE	6.47	4.21	5.56
FF	14.29	9.29	12.29

The average depth estimates across the profiles for the 2D and 3D geometries are 7.29±3.22 m and 9.64±4.26 m respectively. These results agree with the estimate obtained from EDM, SPI and HWM.

Peter's Half Slope Method (PHSM)

The Peter's Half-Slope method is used to compute the depth to top of anomalous body with the following results as shown below, the table gives the depth estimate obtained using Peter's Half Slope for thin, intermediate, and thick bodies. The average depth estimate across the profiles for the thin, intermediate and thick body geometries are 11.28±5.24 m, 8.46±3.93 m, 6.77±3.14 m respectively.

Table 3: Depth Estimate for All Selected Profiles Across Different Geometries Using Peter's Half- Slope Method PHSM

Profiles	d	Thin	Intermediate	Thick
AA	8.41	7.01	5.26	4.21
BB	20.87	17.39	13.04	10.44
CC	12.61	10.51	7.88	6.31
DD	8.33	6.94	5.21	4.17
EE	9.12	7.60	5.70	4.56
FF	21.90	18.25	13.69	10.95

These results establish that the result of HWM, GAM is an overestimate of the depth to top (limiting depth). Correlation between the results obtained through HWM, GAM, and PHSM method established that the depth estimate for profile BB yielded the maximum depth to centre/top of anomalous body across the geometries and methods used while profile DD yielded the minimum for all considered geometries in HWM, GAM and PHSM. The combined depth estimates for the three methods are shown in Table 4.

From the results obtained from all the depth estimation methods used, it was observed that the Euler deconvolution method through the solution plot of the structural index (SI) equals 1 confirmed that there is a fault existing in the study area. Since the results obtained from HWM and GAM are representative of the depth to centre of the anomalous body (banded iron ore deposit) which is an overestimate of the limiting depth (depth to top) obtained from PHSM (Layade et al., 2021)., then the probable thickness of the ore body for the geometries discussed above can be estimated by evaluating the difference between the values of HWM GAM and PHSM. The estimated thickness for these geometries of the banded ore deposits is calculated using equation:

$$\text{Thickness} = 2(\text{Half} - \text{Width depth estimate} - \text{Peter's half slope depth estimate}).$$

The result shown in the Table 5 below showed that the estimate of the Oko banded iron deposits ranges from 3.8m – 20m which agrees with literature on banded iron formation.

Table 4: Average Depth Estimate for All Selected Profiles Across Different Geometries Using HWM, GAM, PHSM, EDM, and SPI

Half Width (m)						Gradient-Amplitude (m)		Peter's Half slope (m)			Euler DM (m)	SPI (m)
Sphere	Horizontal Cylinder	Vertical Cylinder	Narrow Dike or Vertical Fault	Vertical thin Plate d=h	Vertical Thin Plate d~h	2D	3D	Thin	Intermediate	Thick	SI=0	
14.57 ± 6.45	11.21± 4.96	6.50± 2.86	5.61± 2.48	7.85± 3.47	11.21± 4.96	7.29 ± 3.22	9.64± 4.26	11.28 ± 5.24	8.46 ± 3.93	6.77 ± 3.14	9.38 ± 2.49	9.93 ± 1.28

Table 5: Table of Estimated Thickness of Iron Ore Deposits

Profiles	Vertical Thin Plate d>>h Half-Width(m)	Thick (m) Peter's Half-Slope	Estimated Thickness (m)
AA	8.21	4.21	8
BB	16.52	10.44	12.16
CC	16.05	6.31	19.48
DD	5.71	4.17	3.08
EE	6.47	4.56	3.82
FF	14.29	10.95	6.68

CONCLUSION

Qualitative analysis of the residual Bouguer anomaly map showed that the lineaments obtained from the total first horizontal derivative map and first vertical derivative map indicated possible fractures, folds or low geologic boundaries as the dominant geologic features of the study area. These lineaments were further confirmed with the Euler solution plot for structural index 0 which confirms the presence of a fault in the study area. These lineaments trend predominantly in the E-W direction and minorly in the NE-SW direction. Quantitative analysis yielded depth estimates to centre and top of anomalous body for different structural indices and geometries using half width method (HWM), gradient amplitude method (GAM), Peter's half slope (PHSM) as analytical methods and Euler deconvolution method (EDM) and statistical radial analysis as semi-automated methods. These methods yield depths to centre of BIF ranging between 5.61±2.48m to 14.57±6.45m for diverse source body geometry and indices while the depth to top estimate ranges from 6.77±3.14m to 11.28±5.24m. The vertical thin plate geometry has a depth estimate of 11.21±4.96m. The estimated thickness of the ore deposit ranged from 3m to about 20m. It could therefore be inferred from the results obtained from this study that the Oko banded iron formation is occurring in lineaments trending majorly in the E-W direction with probable thick body geometry along a fault line trending in the E-W direction. These observations agree with the information available in literature on the Oko banded iron formation but also provide more information on the orientation, geometry, depth and depositional thickness of the Oko BIF.

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