



Determination of hydrocarbon potentials in Masu area northeastern Nigeria using forward and inverse modeling of aeromagnetic and aerogravity data

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Abstract

Aeromagnetic and aerogravity data covering Masu area, which lies within latitudes 12°00' to 13°00' North and longitudes 12°30' to 14°00' East in Nigerian sector of Chad Basin have been interpreted qualitatively and quantitatively. Regional-residual separation was carried out by applying polynomial fitting (first order), which was fitted by least square method. First order was used because it is the best regional fit for our data as it reflected the available geological information of the area. The residual values of both magnetic and Bouguer anomalies obtained were used to produce the residual magnetic intensity and residual gravity maps respectively. These maps show intrusive basement rocks in the eastern part of Masu. The forward and inverse of aeromagnetic data modeling estimated basement depths for profiles P1 and P2 were 4300 and 1195 m, with respective magnetic susceptibility values of 0.0003 and 0.0250, which indicate minerals like limestone and marble. Similarly, the estimated basement depths from the forward and inverse of aerogravity data modeling are 6524 and 4312 m for P1 and P2 with density contrasts of 0.72 and 0.255 g/cm³. The results from this work indicate that the area has some geologic features suitable for hydrocarbon and mineral deposits. Hence, further geophysical researches need to be carried out to ascertain the type of minerals existing in the area.

Keywords Aeromagnetic and aerogravity data · Masu · Nigeria · Chad basin · Hydrocarbon potentials · Mineral deposit · Forward and inverse modeling

1 Introduction

Hydrocarbon potentials (oil and gas), over the years has been a major determinant of Nigerian economy, since large portion of the country's revenue comes from export and domestic sale of petroleum, gas and minerals resources [23]. These are mostly explored in Niger Delta area; hence the fear that soon or later the economic reserve of the country may have a hitch, as the hydrocarbon potentials and mineral deposits of the Niger Delta may be exhaustibly harnessed. Therefore, there is need to investigate the economic mineral and hydrocarbon potentials of other geologic provinces, such as the Nigerian sector of Chad Basin, which is presumed to have high

prospect for hydrocarbon and mineral deposits [1]. This is as a result of the discovery of large quantity of petroleum, gas and minerals in the neighboring countries, which have similar geological structural setting as that of the Nigerian Chad Basin.

Some geophysical works have been carried out in other parts of the Nigerian sector of Chad basin [2–5, 8–10, 14–16, 18, 20–22, 25, 27, 29, 30], however, these works were based on only magnetic geophysical method. This alone might not have given sufficient geophysical information of the area hence this work combines magnetic and gravity methods which will ascertain how each method can complement each other, since, some geological structures that may not have magnetic response, could

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be identified based on their densities. Therefore, the limitation of one method will be compensated by the other, thereby enhancing better modeling of subsurface structures in the study area. In some works lower resolution data of 1970 and 1980 were used. In addition, some of the works used data from land survey measurements, which could be restricted in some areas and might have provided information at discrete locations. These might not have given adequate information on the geological configuration, structure and stratigraphy of the Nigerian sector of Chad Basin. Hence, the area might have been highly under explored probably due to inadequate knowledge of its geology.

Masu is an area with favorable features, which encourage accumulation of hydrocarbon potentials and mineral deposits [1]. Hence, there is need for its subsurface geophysical investigations. However, no work has singly been carried out using aeromagnetic and aerogravity data of Masu, except the ones that combine aeromagnetic data of Masu with other towns [3, 5, 10, 14, 15, 20–22, 27, 30]. This might have given inadequate information on the area. In addition, this may be the first record of using aerogravity data in the area.

Subsurface materials have different densities and magnetic susceptibilities values and these materials are identified based on their densities and magnetic susceptibility. Therefore, this work applies forward and inverse modeling method on aeromagnetic and aerogravity data of the area in order to investigate the hydrocarbon potential in the study area. This work could be useful in petroleum and minerals exploration in the area.

2 Location and geology of the study area

The study area, Masu lies between latitudes 12°N and 13°N and longitudes 13°E and 14°E and due to its broad geographical extent, its physical setting is bound to be varied. A greater part of the state lies on the Chad Formation. This is an area that was subjected to prolonged continental and lake sedimentation as a result of the down-warping of the Chad Basin in the Pleistocene Period. The Chad Formation is separated by Cretaceous Bima and Kerri sandstones. The volcanic areas of the Biu Plateau and the Basement Complex areas of the Mandara Mountains are found in the south and southeast, respectively. This area is situated in the Nigerian sector of Chad basin, which is located at latitudes 12°00' to 13°00' North and longitudes 12°30' to 14°00' East (Fig. 1). The Chad basin lies within a vast area of central and west Africa at an elevation between 200 and 500 m above sea level and covers approximately 230,000 km² [4] (Figs. 2, 3). It is a very massive area of inland drainage in Africa according

to [6, 7, 17]. It extends into some areas in the republic of Niger, Chad, Cameroon, Nigeria and Central Africa. The Nigerian sector of Chad basin is about one tenth of the Basin [11, 35], and has a broad sediment-filled depression spanning north eastern Nigeria and some sector of the Chad republic. The Chad, Kerri-Kerri and Gombe formations (Table 1) have an average thickness of 130 to 400 m. Fika shale with a dark grey to black in colour, with an average thickness of 430 m are found below the formation [27]. Others are Gongila and Bima formations with an average thickness of 320 m and 3500 m, respectively [24, 26].

Generally, the area possesses some rock mineral based resources such as clay, salt, limestone, kaolin, iron ore, uranium, mica and so on, while the sedimentary rocks in the area have cumulative thickness of over 3.6 km; with the rocks consisting of thick basal continental sequence overlain by transitional beds followed by a thick succession of quaternary Limnic, fluvial and eolian sand and clay [24].

3 Source of data

The high resolution airborne magnetic data used in this research work were obtained from Nigerian geological survey agency (NGSA) Abuja. These airborne magnetic data were measured using a 3 × Scintrex CS2 cesium vapor magnetometer belonging to Fugro Airborne Surveys. The magnetic survey was flown at 80 m elevation along flight lines spacing of 500 m apart. The flight line direction was 135°, while the tie line direction was 225°. The airborne magnetic data were recorded in digital format (X, Y and Z file). X and Y represent the longitude and latitude of the study area, while the Z represents the magnetic field intensity measured in nano Tesla. The Earth's main field, which constitutes about 99% of the recorded value of the magnetic field was removed by applying international geomagnetic reference field (IGRF 2010). Similarly, temporal and spatial variations corrections were applied on the magnetic data.

The airborne gravity data were measured by national aeronautics and space administration (NASA) together with German aerospace center using satellites. The airborne gravity data were recorded in digital format (X, Y and Z file). X and Y represent the longitude and latitude of the study area, while the Z represents the Bouguer anomaly of the study area. Corrections such drift, Earth-tide, elevation and terrain, latitude and eotvos were applied on the gravity data. These corrections however were carried out by the Nigerian geological survey agency Abuja. The measurements of these data were carried out between 2008 and 2013.

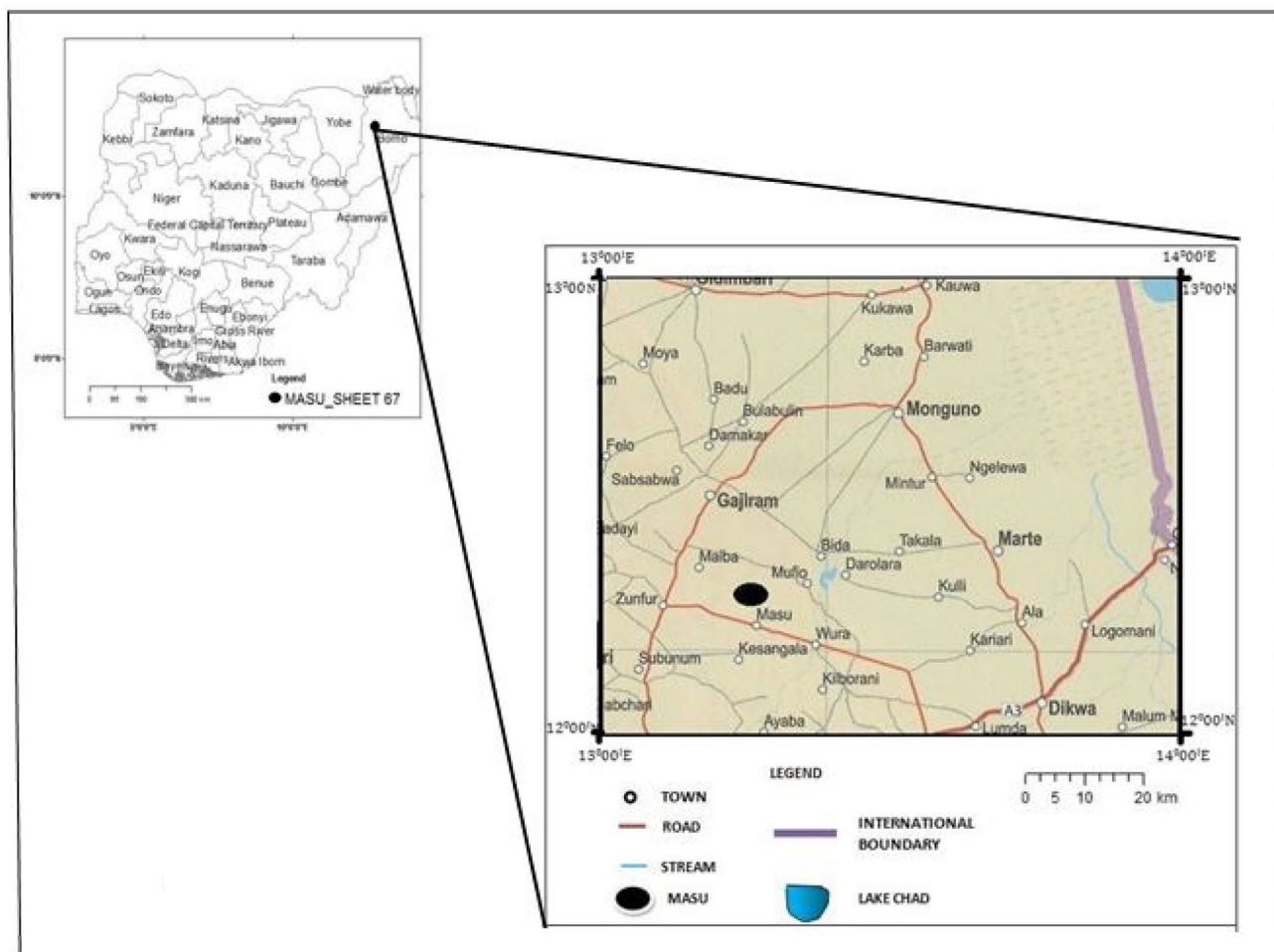


Fig. 1 The Map of Nigeria showing the location of Masu

4 Methods of data interpretation

4.1 Qualitative interpretations

Qualitative as well as quantitative interpretations were involved in this work. Qualitative interpretation was carried out by inspecting the total magnetic intensity (TMI) grid map of the study area, which was prepared by imported the total magnetic field intensity data into Oasis Montaj 6.4 software and subsequently gridded using minimum curvature. The gridded magnetic intensity data with the aid of Oasis Montaj software was used to produce the total magnetic intensity map (Fig. 4). Similarly, the Bouguer anomaly data were used to produce the Bouguer anomaly map (Fig. 5).

The total magnetic field intensity data and the Bouguer anomaly data are each made of two parts namely; the regional field and residual field [28], hence this calls for their separation, In our work the

separation was carried out by applying least—square method, which applies polynomial approximation to the observed field. This is expressed in a power series. For a regional field g_r along the x-axis, the field was represented by the polynomial $g_r = a_0 + a_1x + a_2x^2 + \dots + a_nx^n$ [28], where, n is the order of the polynomial being used to approximate the regional field. The coefficients a_0 , a_1 to a_n were evaluated from the principle of least square [31]. Different orders of polynomial were tried but, it was found that the 2nd order polynomial fitting was the best regional fit for our data as it reflects the available geological information of the area. The residual field was obtained after the regional values were subtracted from the observed field data with the aid of Oasis Montaj software. The residual magnetic intensity values and the residual gravity values were further used to produce the residual magnetic intensity and residual gravity maps (Figs. 6, 7) respectively.

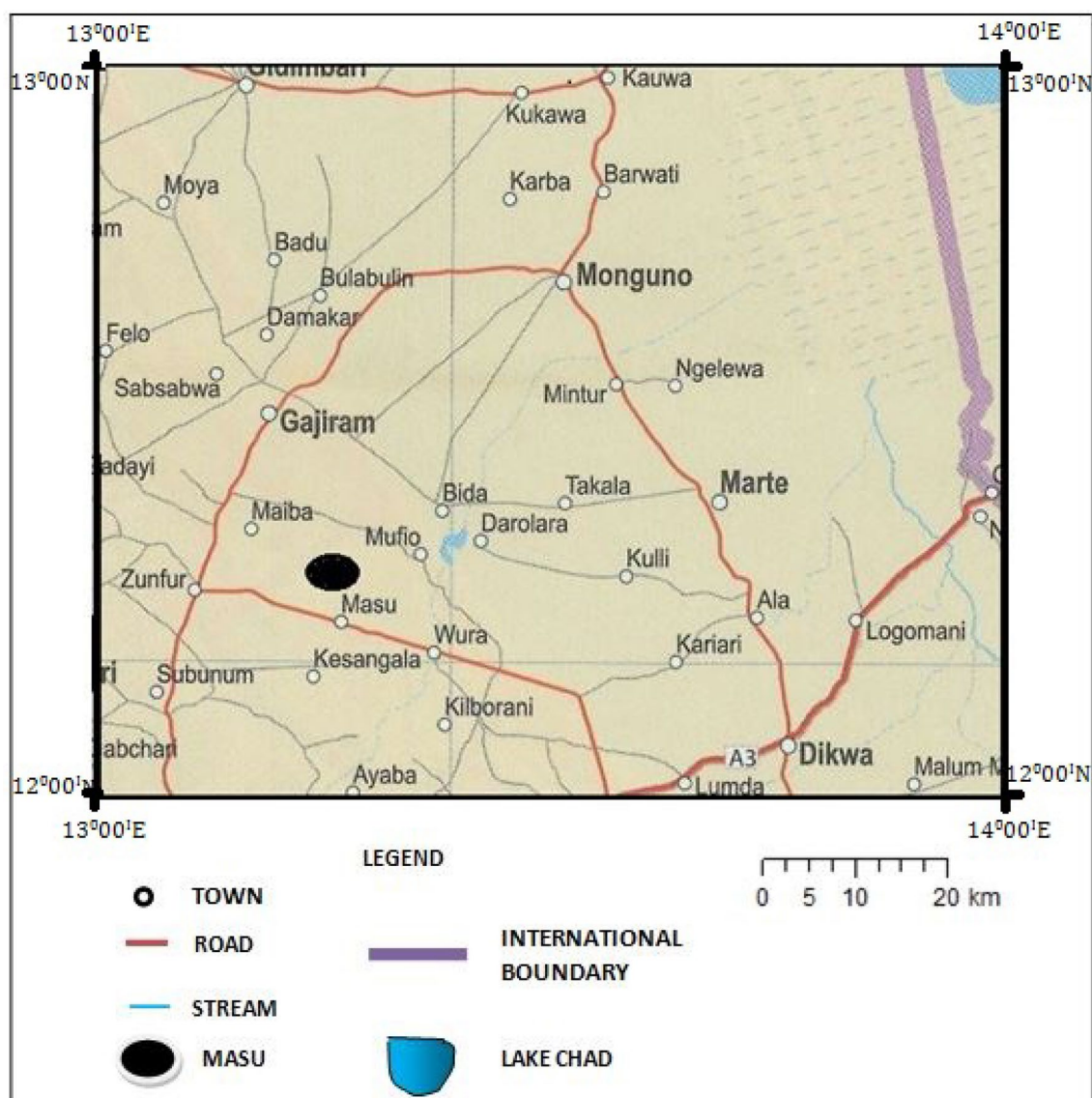


Fig. 2 Location and accessibility map of Masu (Modified after [19])

4.2 Quantitative interpretation

Inversion procedure was performed on residual magnetic and gravity data. The calculated field and the observed field values were produced using the potent Q software and were further compared. Root means square (RMS) between the observed and calculated values was minimized by the inversion algorithm. At the end of each inversion, the root means square value was displayed. This root means square value decreases as the fit between the observed and calculated field continues to improved until a reasonable inversion result was reached. Less than 5% of root means square was set as an acceptable error margin.

The residual magnetic and gravity maps were converted to residual magnetic contour grid map and

residual gravity contour grid maps (Figs. 10, 11). This is to showcase locations that might likely be suitable for modeling. The profiles in each model show the variation of the field values with distance at the area or points modeled. Two points, P1 and P2 were each taken around northwestern and northeastern parts of the residual magnetic contour grid map and modeled with an ellipsoid shape and rectangular shape respectively. Similarly, two points, P1 and P2 were taken around southwestern and northeastern parts of the residual gravity contour grid map and modeled with an ellipsoid and rectangular shapes. Forward modeling being a trial and error method, the shape, position and physical properties of the models were adjusted so as to get a good correlation between the calculated field which is represented

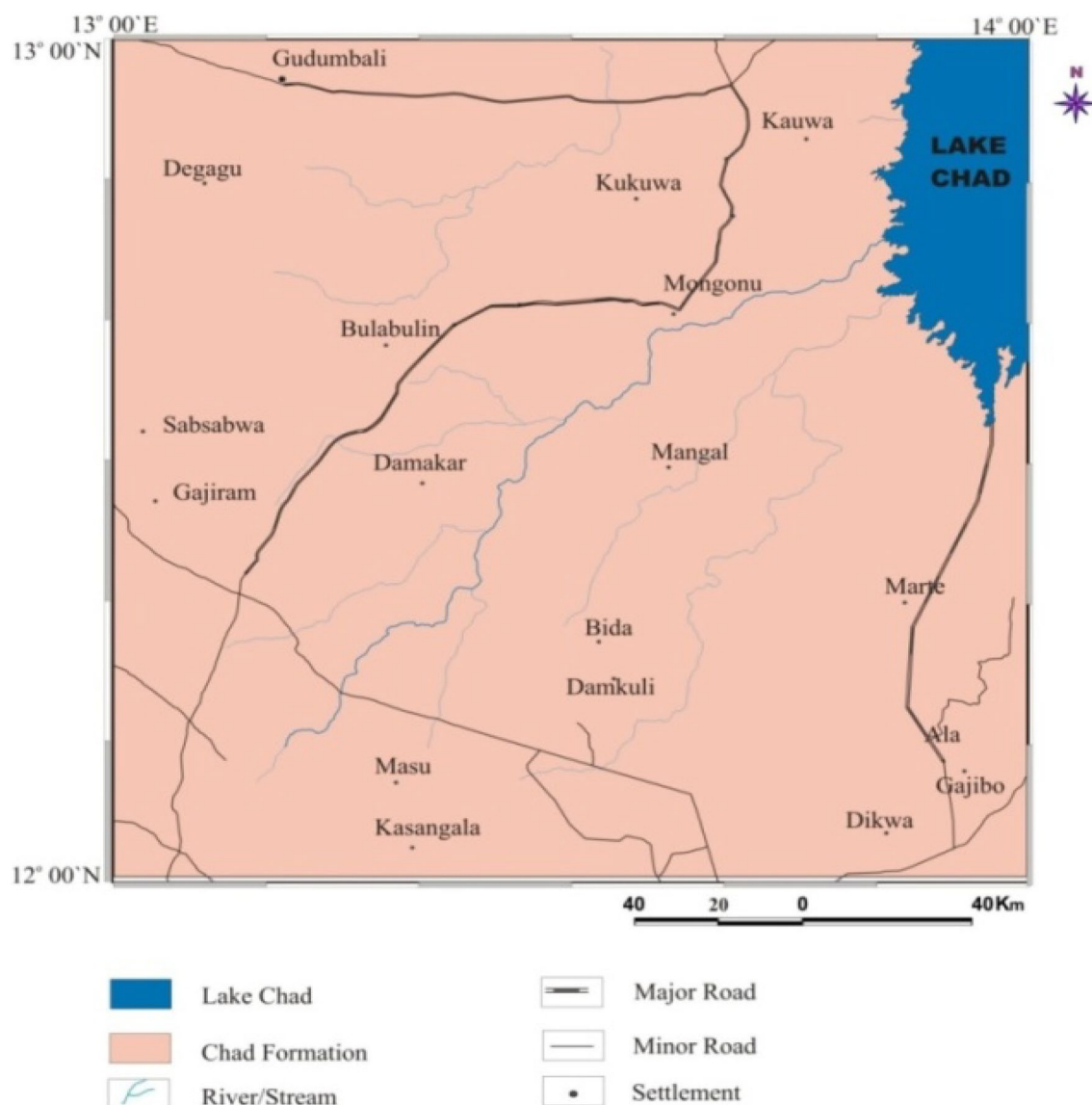


Fig. 3 Geological map of Masu (Modified after [19])












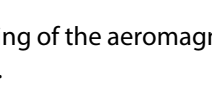

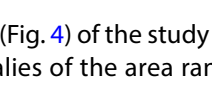
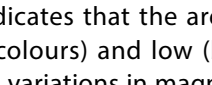
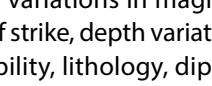
by the red curves and the observed field, which is represented by blue curves. This was achieved using Potent Q software. Points, P₁ and P₂ on the residual magnetic contour grid map, at the point where the observed values matched well with the calculated values produced magnetic susceptibility values of 0.0003 and 0.0250 with respective depths of 4300 and 1195 m, while points, P₁ and P₂ on the residual gravity grid map give the density values of 0.72 and 2.55 g/cm³ with respective depths of 6524 and 4312 m. These density and magnetic susceptibility values were further compared with the standard values of some subsurface material which include rocks, minerals and hydrocarbon [13, 32–34]. Hence, these indicate the presence of subsurface geologic materials like marble, limestones and petroleum.












5 Results and discussion

5.1 Results

Figures 4, 5, 6, 7, 8 and 9 present respectively, the maps of total magnetic field intensity (TMI), Bouguer gravity anomaly, residual magnetic field intensity, residual gravity anomaly, regional magnetic, regional gravity maps, while Figs. 10 and 11, respectively give the residual magnetic contour and residual gravity contour grids maps of Masu. In addition, the results of the forward and inverse models of magnetic modeled anomalies, P₁ and P₂ are shown in Figs. 12 and 13 respectively, while that for gravity modeled anomalies for P₁ and P₂ are given in Figs. 14 and 15 respectively. Finally, Tables 2 and 3 give the summarized results

Table 1 Generalized stratigraphic sequence of Nigerian sector of Chad Basin, [27]

Age	Formations	Lithology	Depositional Environment	Thickness (m)**
! Pliocene- Pleistocene	Chad		Continental (Lacustrine)	50 – 425
Paleocene	Kerri-Kerri	 	Continental	455 – 545
Maastric- htian	Gombe Sandstone	 	Deltaic, Estuarine	301 – 402
Turonian- Santonian	Fika Shale	   	Shallow marine	606 – 2012
Turonian	Gongila	   	Marine, Estuarine (Transitional)	226 – 1363
Albian- Cenomanian	Bima	 	Continental	408 – 1397
Pre-Cambrian			Crystalline Basement	

INDEX	
	Sand
	Clay
	Claystone
	Limestone
	Siltstone
	Coal
	Shale
	Sandstone
	Igneous sills
	Basement rocks
	Unconformity
** Thickness from well logs	

of the forward and inverse modeling of the aeromagnetic and aerogravity data respectively.

5.2 Discussion

The total magnetic intensity map (Fig. 4) of the study area has shown that magnetic anomalies of the area ranged from -42.4 to 237.6 nT. This indicates that the area is marked by high (red and pink colours) and low (blue colour) magnetic signatures. The variations in magnetic intensity could be due to degree of strike, depth variations, differences in magnetic susceptibility, lithology, dip and plunge [23].

On the other hand, it is noticed from the Bouguer gravity anomaly map (Fig. 5) that the Bouguer anomaly of the study area varies from -50.5 to -28.3 mGal. The negative

sign indicates that the area is mostly occupied by low density materials. Low gravity anomalies are observed in the north with its minimum value appearing in the southwest. This suggests the existence of sedimentary rocks which are low in density, since sedimentary rocks are characterized by low density values. Meanwhile, higher low Bouguer gravity anomalies are observed in the east with its maximum in southeast, small portion of it appears in the north-west and southwest. These anomalies could be attributed to intrusion of dense metamorphic rocks.

The 2D residual magnetic map (Fig. 6) of Masu reveals magnetic anomalies ranging from -42.1 to 103.6 nT. This indicates the area as predominantly of high residual magnetic anomalies and small area of low residual magnetic anomalies. This means that the area is more of intrusive bodies. High residual magnetic anomaly is observed in the

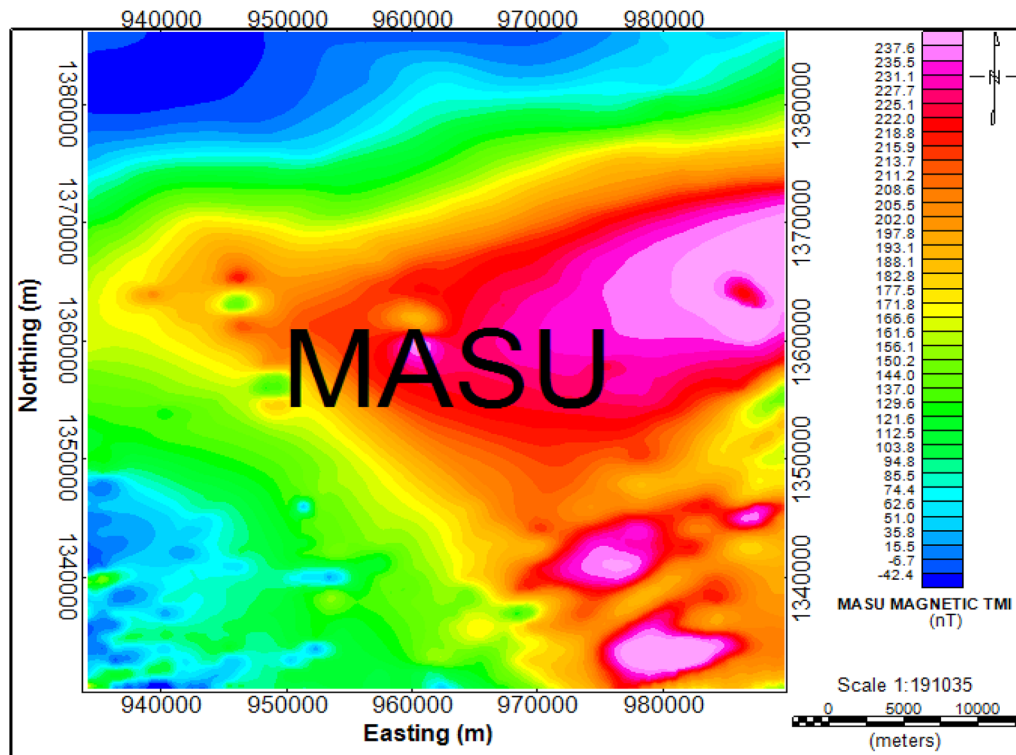


Fig. 4 Total magnetic intensity map

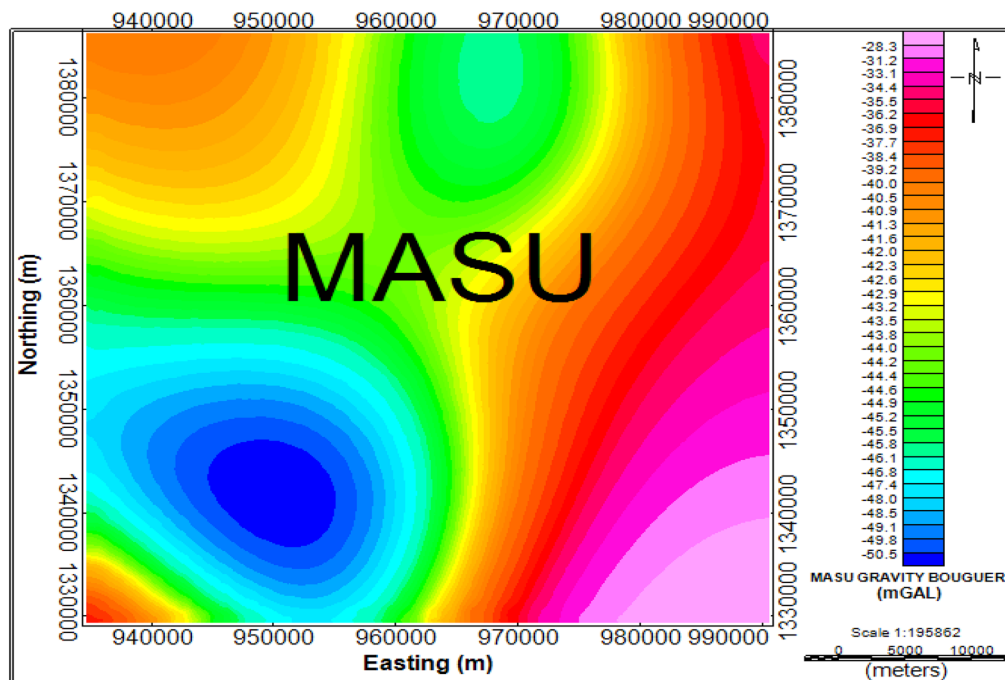


Fig. 5 Bouguer gravity anomaly map

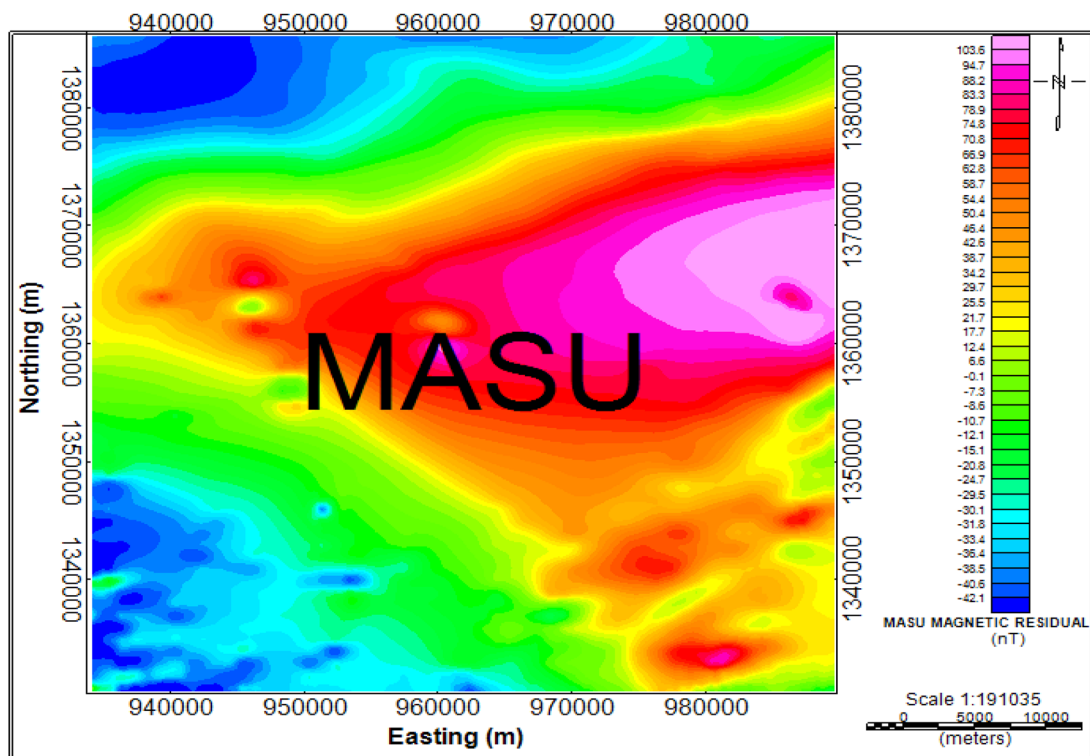


Fig. 6 Residual magnetic intensity map

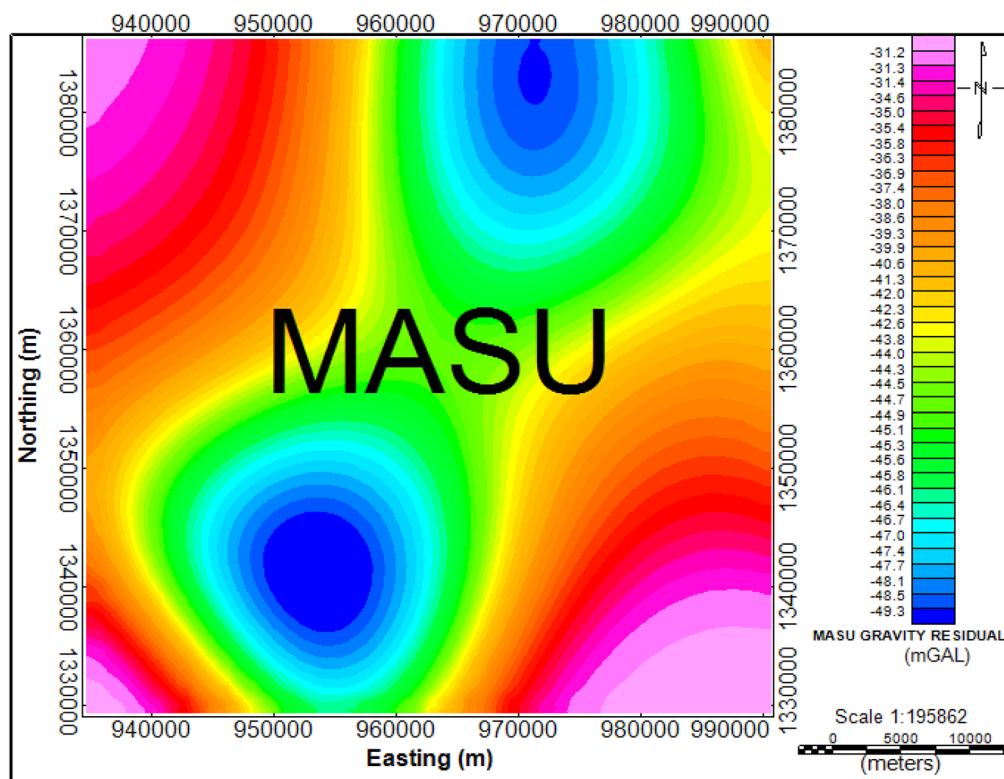


Fig. 7 Residual gravity anomaly map

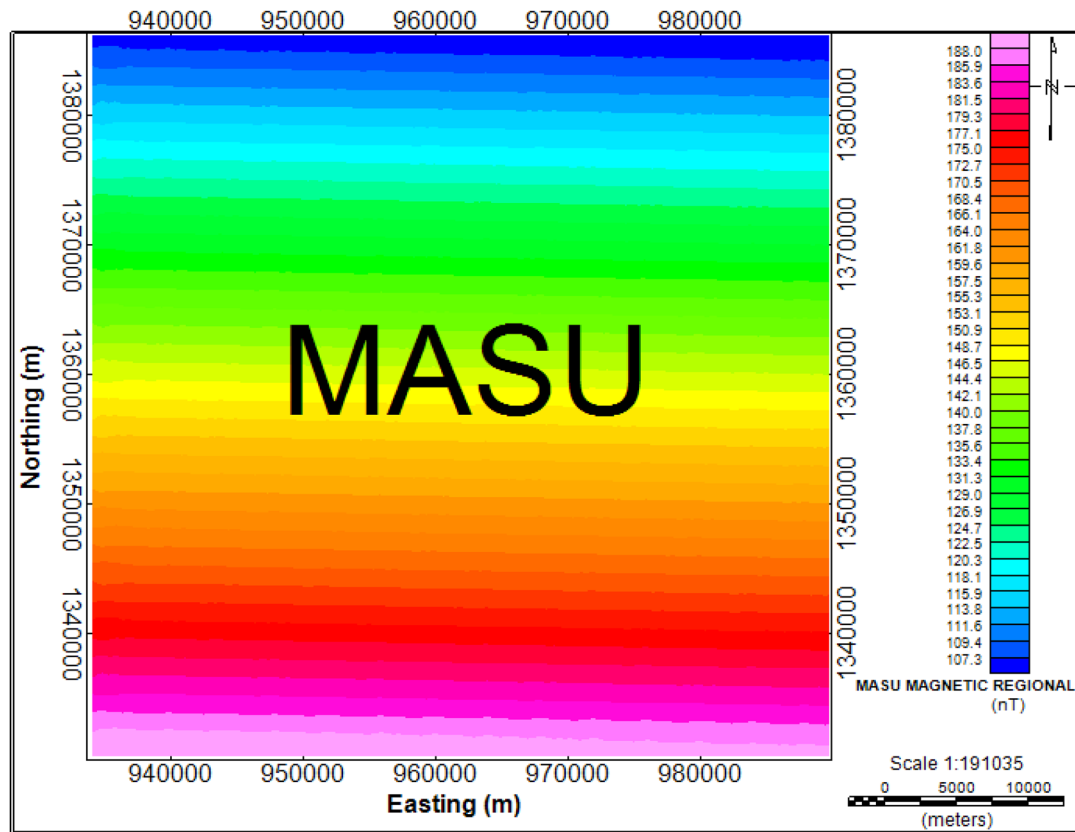


Fig. 8 Regional magnetic map

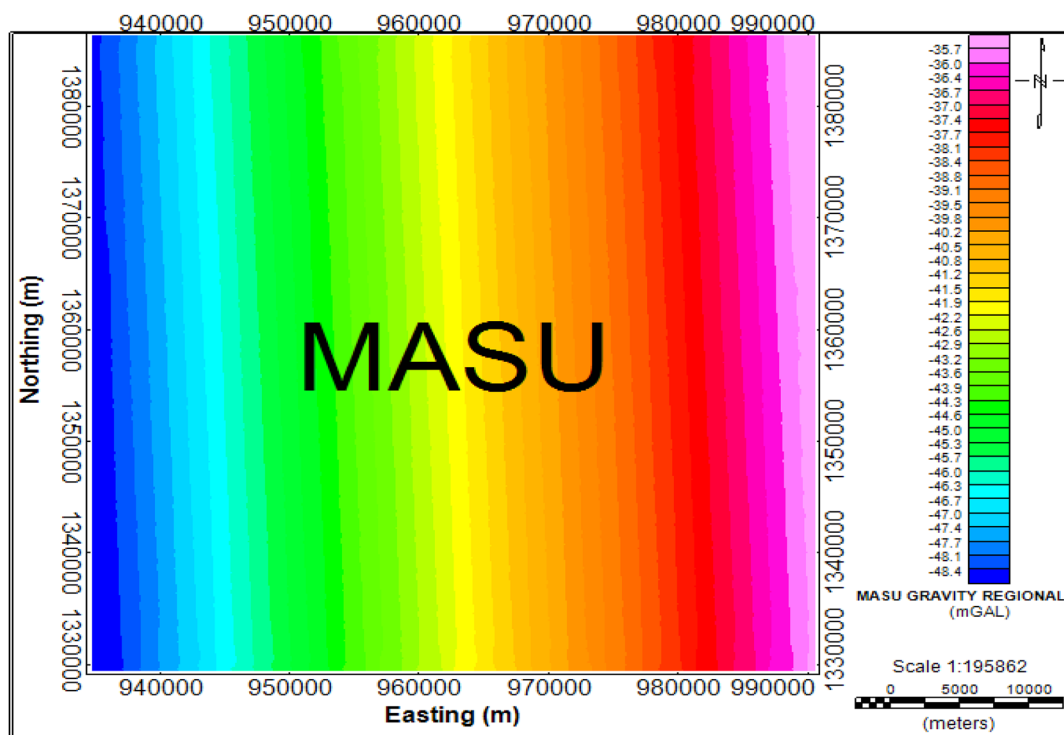


Fig. 9 Regional gravity map

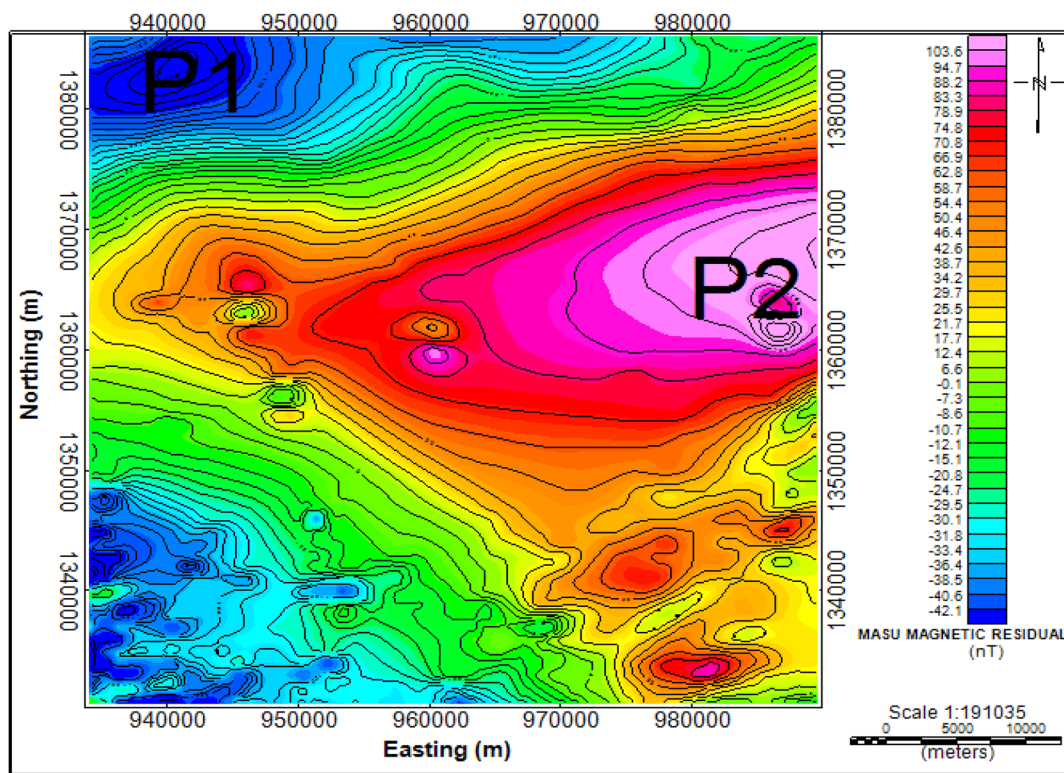


Fig. 10 Residual magnetic contour map showing two modeled points (P1 and P2)

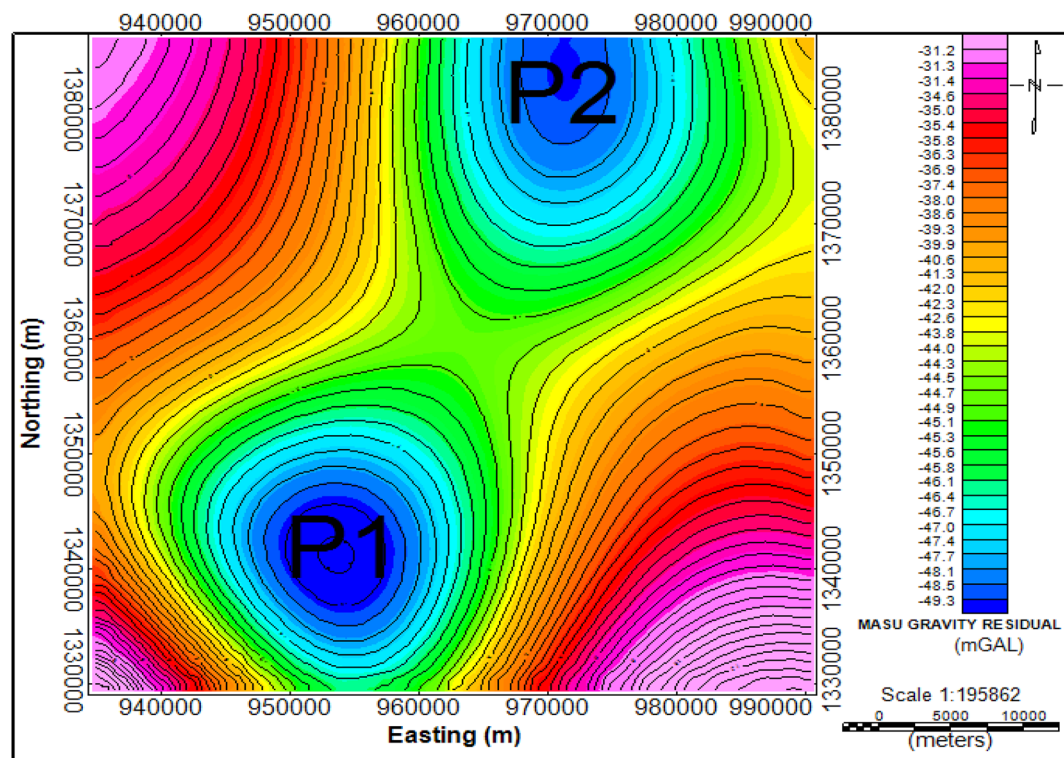


Fig. 11 Residual gravity contour map showing two modeled points (P1 and P2)

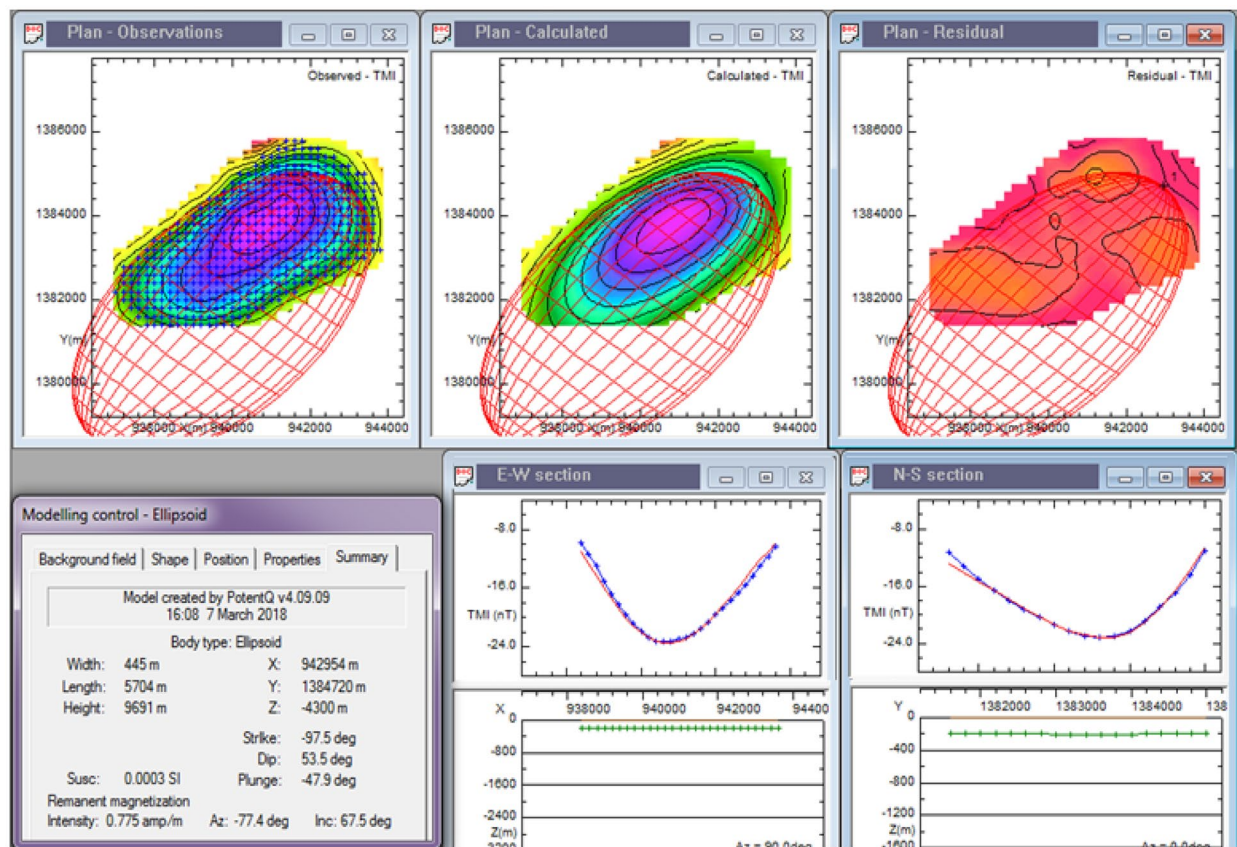


Fig. 12 Modeled magnetic anomaly for P1

east and decreases towards the northwest and the southwest axes. This could be due to near surface rocks containing large magnetic response. Low residual magnetic anomaly values appear in the northwest and southwest of the area. This could likely be due to the presence of sedimentary rocks (likely to be sandstones and limestone) or weak magnetic bodies in the area. This agrees with the work of [25] who observed that high residual magnetic intensity in most part of Chad basin are caused by near surface rocks. The residual magnetic map exhibit similar features with the total magnetic intensity map, which shows that the area is more of residual magnetic anomalies than the regional magnetic anomalies.

The residual gravity map (Fig. 7) shows that the residual gravity anomalies of Masu vary from -49.3 to -31.2 mGal. High gravity anomaly which corresponds to region with

high density contrast beneath the surface is seen in the northwest, southwest and southeast, while low gravity anomalies which correspond to regions of low density contrast are observed in the southwest and northeast. The high gravity anomaly in the area could be attributed to intrusion of metamorphic rock (likely marble), while low gravity anomalies could be attributed to sediments in the study area.

The regional magnetic intensity of Masu decreases from the south to the northern parts of the region (Fig. 8). This indicates there is more of sediment infill in the north than in the southern parts of Masu. The presence of high regional magnetic anomaly in the southern area of the map signifies the existence of deep seated magnetic body, which is suspected to be marble, while the low regional magnetic anomaly in the northern part of the region

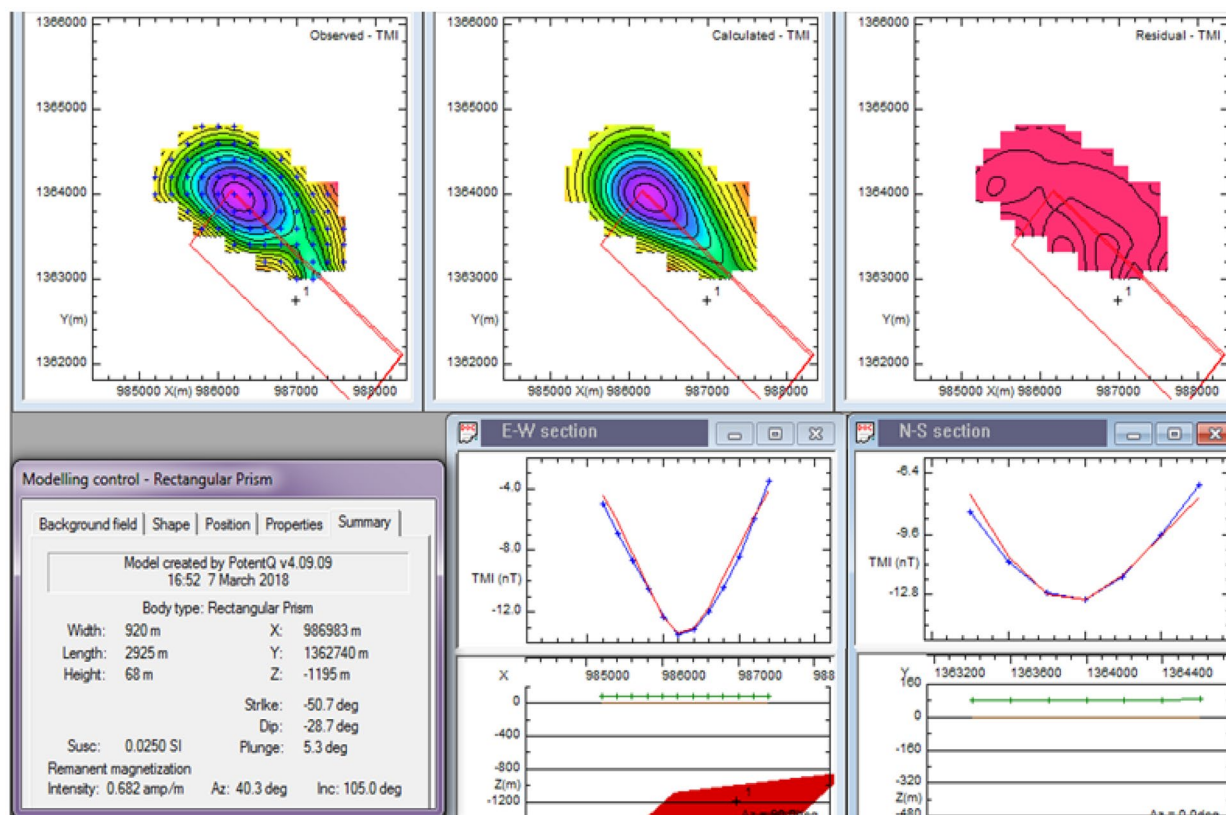


Fig. 13 Modeled magnetic anomaly for P2

indicates the presence of sediments (likely sand stone and limestone).

The regional gravity map of the area on the other hand, shows a regional decrease in gravity from the east to the western parts of the region (Fig. 9). This indicates a sediment infill in the western part of Masu. The high regional gravity anomaly exhibits in the eastern part of Masu indicates the presence of high density basement rocks (likely marble), while the low regional gravity anomaly in the western parts of the area may be associated with the infilling of this area by light sediments. This is in agreement with the work of [12] who also observed highest gravity anomaly.

The results of the aeromagnetic forward and inverse modeling as shown in Figs. 12 and 13 summarized on

Table 2 reveal that the estimated depths to geologic features are 4300 and 1195 m with susceptibility values of 0.0003 and 0.025 for P1 and P2 respectively. These indicate dominance of minerals like limestone and marble as could be ascertained from standard values of magnetic susceptibilities and densities of some rocks and minerals [32, 34]. Similarly, the estimated depths from the forward and inverse modeling of aerogravity data as shown in Figs. 14 and 15 and summarized on Table 3 are 6524 and 4312 m with density values of 0.72 and 2.55 g/cm³ respectively. These indicate the presence of petroleum and limestone respectively as could also be ascertained from the standard values of magnetic susceptibilities and densities of some rocks and minerals [32, 34].

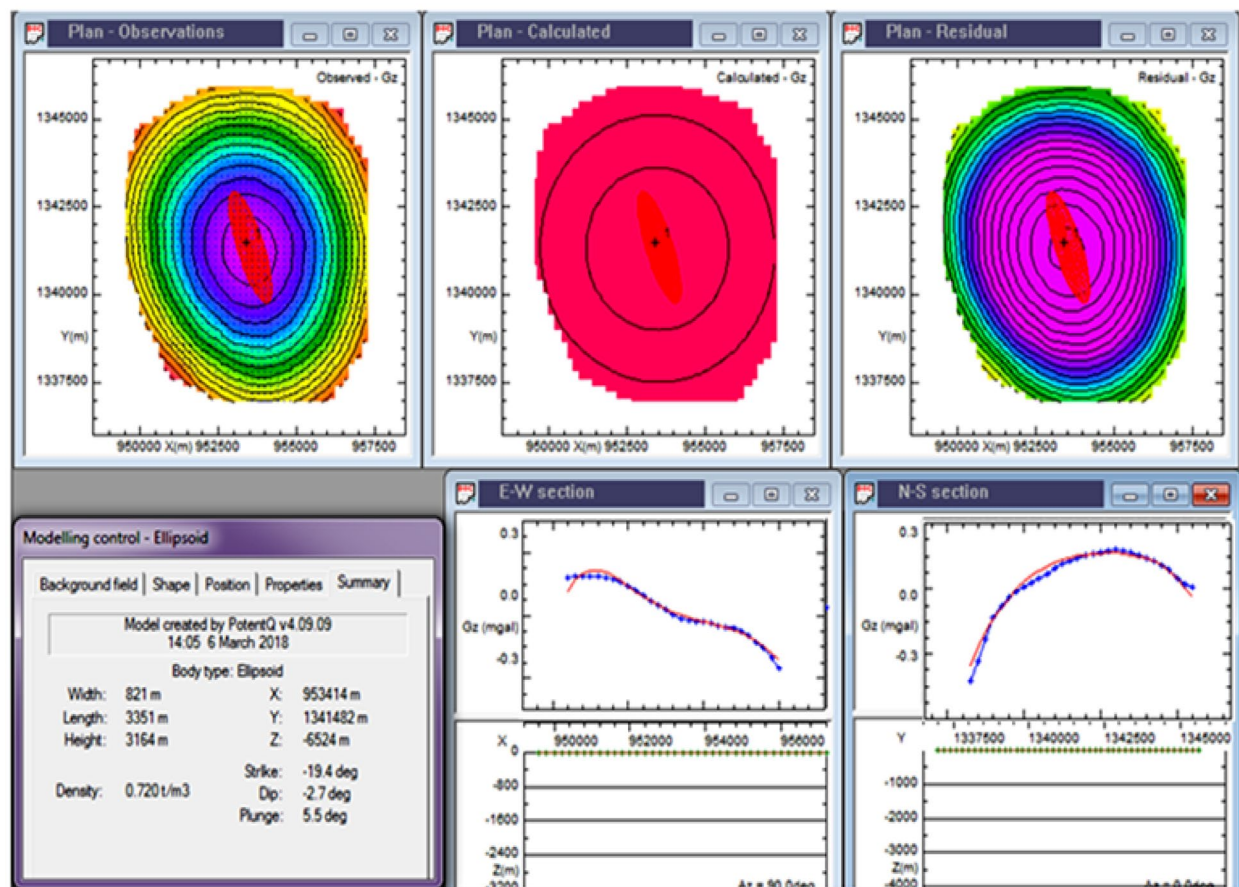


Fig. 14 Modeled gravity anomaly for P1

6 Conclusion

The qualitative and quantitative interpretation of aeromagnetic and aerogravity data covering Masu in the Nigerian area of Chad Basin have been carried out. The qualitative interpretation reveals the existence of intrusive bodies in the eastern part of Masu. The estimated depths for aeromagnetic forward and inverse modeling for profiles P1 and P2 are 4300 and 1195 m, with respective susceptibility values of 0.0003 and 0.025. These indicate dominance of mineral like limestone and marble respectively. Similarly,

the estimated depths from the forward and inverse modeling of aerogravity are 6524 and 4312 m for P1 and P2 respectively with density values of 0.72 and 2.55 g/cm³, which indicate the presence of petroleum and limestone respectively. These results indicate that Masu in the Nigerian sector of Chad Basin is suitable for sitting of industries such as cement factory and petroleum exploration companies. This will provide employment opportunity in the area. Similarly, it will generate revenue, which will in turn boost the nation's economy.

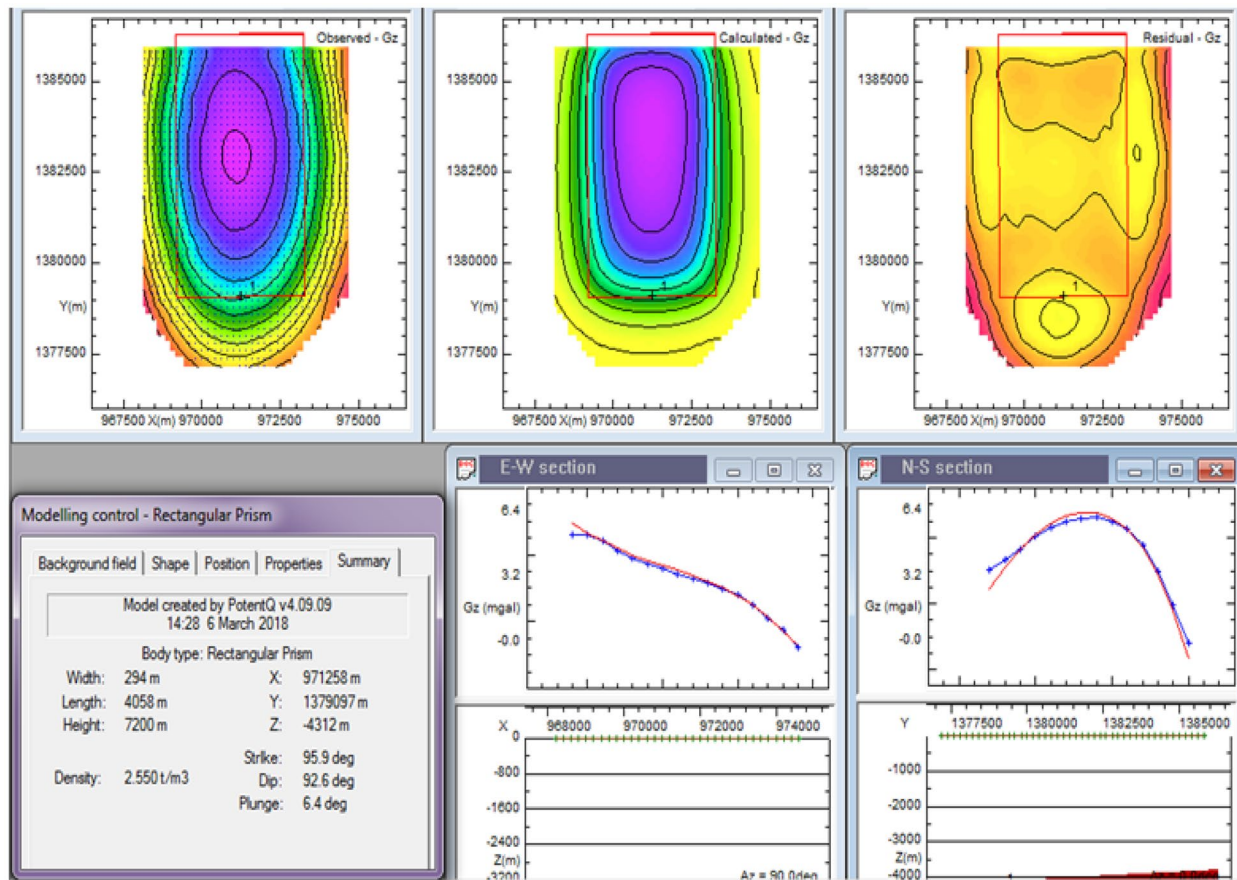


Fig. 15 Modeled gravity anomaly for P2

Table 2 Summary of aeromagnetic forward and inverse modeling results of Masu

Model	Model shape	X (m)	Y (m)	Depth (m)	Plunge (deg)	Dip (deg)	Strike (deg)	K-value (SI)	Possible cause of anomaly
P1	Ellipsoid	942,954	1,384,720	4300	−47.9	53.5	−97.5	0.0003	Limestone
P2	Rectangular Prism	986,983	1,362,740	1195	5.3	−28.7	−50.7	0.025	Marble

Table 3 Summary of aerogravity forward and inverse modeling results of Masu

Model	Model shape	X (m)	Y (m)	Depth (m)	Plunge (deg)	Dip (deg)	Strike (deg)	Density value (g/cm ³)	Possible cause of anomaly
P1	Ellipsoid	953,414	1,341,482	6524	5.5	−2.7	−19.4	0.72	Petroleum
P2	Rectangular prism	971,258	1,379,097	4312	6.4	92.6	95.9	2.55	Limestone

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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