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Full Length Research

Delineation of subsurface geological structures within Lower Benue Trough, Nigeria for possible mineral exploration targets using Airborne Magnetic Data

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ABSTRACT: A set of secondary airborne magnetic data of some parts of the lower Benue Trough, Nigeria, was analysed and interpreted to delineate subsurface structures that may harbour economic minerals for economic development. The interpretation is aimed at determining the viability of the area's mineral potential for possible harnessing. The data was subjected to various enhancement techniques such as reduction to the equator (RTE), first vertical derivative (FVD), analytical signal and centre for exploration targeting (CET). The results of the first vertical derivative (FVD), analytical signal and centre for exploration targeting (CET) enhanced and identified the magnetic signatures that represent the geological structures (lineament) of the area, as revealed by the rose diagram, suggesting major lineament at NE-SW, E-W, ENE-WSW and minor trends at N-S, NW-SE, NNE-SSW directions. These lineaments serve as traps and conduits for solid minerals that may be entrapped within the area. The most prolific areas detected by the enhancement techniques correspond to Okpom, Ogoja, Oju, Gboko, Tse-Agbera, Ikom, Boje, Ugep, Igumale, Abakaliki, Iboko, Effum, Isi-Uzo, Ankpa, and Otupko. If properly harnessed, these areas will contribute to the country's natural resource reserve.

Keywords*:* CET, lineaments, Lower Benue, magnetic data, mineral exploration.

INTRODUCTION

Solid mineral exploration is capable and efficient in sustaining economic growth and industrial development of any country. In the last five decades, Nigeria's economy has depended largely on oil and gas exports, why great opportunities for mining operations that have yet to be tapped, despite the abundance of solid mineral deposits in the country. Recently, it has been the goal of the present administration of the Nigerian government to key into solid mineral exploration to boost the country's economy so as to diversify from its current over-dependence on petroleum due to its fluctuations in price and reserves depletion.

Currently, there has been a global demand for base and precious metals, used by different companies around the world, and some of these metals have been known to occur in the lower Benue trough, Nigeria, such as lead, zinc, tin, pyrite, etc.

Mineral exploration requires interpretation of airborne geophysical data, which plays a vital role in broad regional exploration that is commonly employed by earth scientists in the early stages of exploration to quickly delineate broad, unknown, accessible, and inaccessible areas of interest (Nnaemeka *et al.,* 2023). These data can be used to assess the earth subsurface in order delineate possible rocks, zones and structures that serve as hosts for a variety of mineral deposits (Nnaemeka *et al.,* 2021). This is accomplished by taking measurements near or on the earth's surface in order to acquire data that may be examined to provide information about subsurface minerals and their host rocks.

The aeromagnetic methods used for this study have played a vital role in delineation of favourable spots for mineral deposits, by mapping geological features, such as contacts, faults, intrusions, folds and shear zones (Nnaemeka *et al*., 2021) and rock characterisation (Telford *et al.,* 1990).

The magnetic method uses the magnetic susceptibility of surface geology to identify the distribution of magnetic minerals and variations in lithology (Telford *et al.,* 1990). This susceptibility (magnetic content) varies depending on the type of rock and surroundings (Mariita, 2013). The recent advancements in technology have substantially improved the accuracy and resolution of this method, allowing it to provide useful enhanced information on lithology and geologic structures (Boadi *et al.,* 2013).

Previous studies on mineral prospecting in the Lower Benue Trough have been investigated using aeromagnetic data (Onyewuchi *et al.,* 2012; Goodhope and Mamah, 2013; Opara *et. al*., 2015; Ofoha, 2015; Nnaemeka *et al*., 2021; Nnaemeka *et al*., 2023; Ekwok *et al.,* 2024). The qualitative techniques of first and second vertical derivatives were mostly employed by the researchers in the area to map the structural architecture of the area, which these techniques only mapped the structurally deformed areas without delineating the proper direction and orientations of these structures. The works of Nnaemeka *et al*. (2021) and Nnaemeka *et al*. (2023) employed a similar technique to that of the current study and established solid mineral accumulation in the area, but not all the areas of the Lower Benue Trough were covered in their study. To that fact, the present study tends to further investigate the area using a unique and detailed structural analysis technique of the centre for exploration targeting (CET) that could reveal information on significant mineral-bearing sections, as well as the directions where this mineral entrapped can be found within the lower Benue Trough. This will help understand the shallow to deep-seated structures that will probably offer traps for solid mineral emplacement and migratory routes for hydrothermal fluids. This is because minerals are structurally controlled.

The study attempts to use airborne magnetic data to delineate the subsurface structures of the Lower Benue Trough, which are veins and entrapments of minerals that could guide possible solid mineral exploration within the area. These minerals, if exploited, will improve the country’s natural resources reserve.

Location and geology of the study area

The Lower Benue Trough lies between latitude 5°30' and 7°30' north and longitude 7°30' and 9°00′ east. It covers an estimated area of about 36,300 square kilometres. The Lower Benue Trough's sedimentary succession dates back to the separation of the African and South American plates during the early Cretaceous period (Fatoye and Gideon, 2013). The lower Benue Trough is made up of three primary components: the Anambra Basin, the Abakaliki Anticlinorium, and the Afikpo Syncline. The sequence is part of the Asu River Group's earliest sediment, which stands unconformably on top of a Precambrian basement complex composed of granitic and magmatic rocks (Ofoegbu and Onuoha, 1991). The Asu River Group reveals outcrops in Abakaliki that are Albian in age and have a thickness of approximately 2km (Ofoegbu, 1985). It is composed of argillaceous sandy shales, laminated sandstone strata, and tiny limestones with magnetic volcanics interspersed (Nwachukwu, 1972). The geology map of the Lower Benue Trough (Figure 1), produced within the coordinates of the study area, revealed ten (10) Cretaceous sedimentary strata, which include: the Ogwasi-Asaba formation, Bendi-Ameki group, Imo group, Ajali formation, Nsukka formations (upper and lower measures), Nkporo formation, Awgu Formation, Ezeaku Formation, Bima formation and Asu River Group. However, the display of lithological compositions of lignite, claystone, sands, shale, coal, mudstone, limestone, sandstone, sandy shale, black shale, siltstone, feldspathic sandstone, calcerious sandstone, shelly limestone, and sandstone intercalations was also revealed in the geology map. The map also exposed basement rocks of biotite and biotite hornblende granite, porphyritic granite, quartzite, biotite garnet gneiss schist, biotite/banded gneiss migmatite and migmatite gneiss that intruded the sedimentary beds as shown in Figure 1.

MATERIALS AND METHODS

Twelve (12) aeromagnetic data sheets of; Anka (269), Otukpo (270), Gkoko (271), Igumale (288), Ejekwe (289), Ogoja (290), Nkalagu (302), Abakaliki (303) Bansara (304), Afikpo (313), Ugep (314) and Ikom (315) utilized in this investigation were collected by Fugro Airborne Survey between the year 2005 to 2009 on behalf of the Nigeria Geological Survey Agency (NGSA) Abuja where this data was obtained. The airborne magnetic datasets were obtained with a 3X Scintrex CS3 Cesium Vapour Magnetometer. These airborne geophysical data were gathered at an interval of 0.1 sec, an altitude of 100 m along a flight line spacing of 500 m in NW-SE, a sensor mean terrain clearance of 80 m, and a tie line spacing of 2 km with a flight line trend of 125°, for a half-degree sheet. The maps were made at a scale of 1:100,000 and 55 km x 55 km, contoured mostly at 10nT intervals.

The first step of the data analysis was eliminating the geomagnetic gradient from the aeromagnetic data by using the January 2005 model of the International Geomagnetic Reference Field (IGRF) and referencing the 1984 World Geodetic System (WGS) ellipsoid.

The magnetic data interpretation generally involves the application of mathematical filters to observed data. The key objectives of these filters vary, depending on the situation. The general purpose is to enhance anomalies of

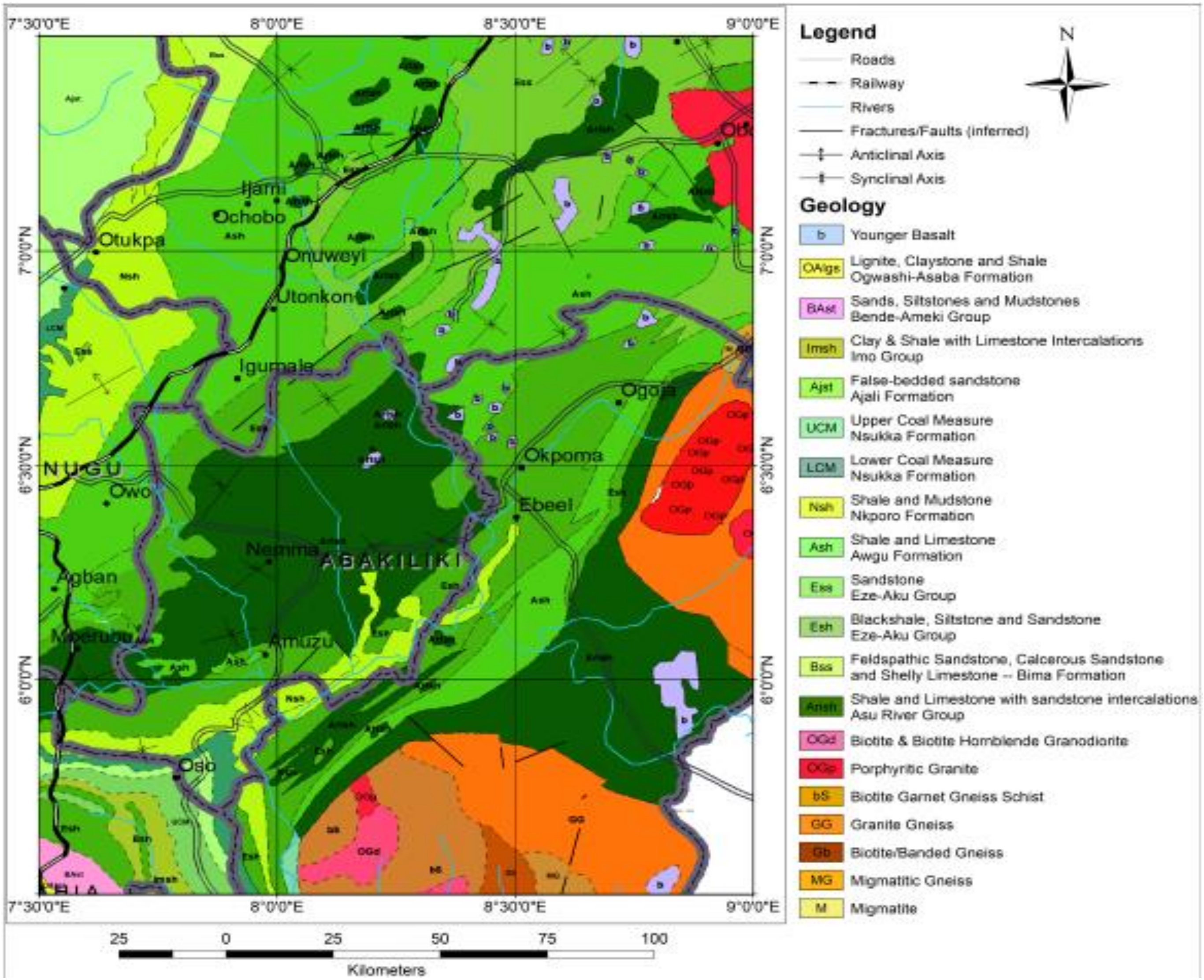

Figure 1. Geology map of the study area.

interest and/or to gain some preliminary information on source location or magnetisation.

The study area data sheets were knitted and used to produce the composite map of the total magnetic field (TMI) of the study area using a bi-directional gridding method. All the datasets used for this study were filtered, enhanced, and processed using the Oasis MontajTM software. The TMI gridded data were reduced to the magnetic equator (RTE-TMI) using geomagnetic inclination and declination of and employing amplitude corrections of inclination -13.9 and declination of - 1.9 as basic inputs, to ensure proper placement of the magnetic anomalies over their causative bodies. Hence, the TMI reduced to equator (RTE-TMI) data were further analysed via different structural magnetic analytical techniques, e.g., Regional and residual separation, first and second vertical derivative, Analytic Signal, and Centre for exploration targeting (CET) via Rose diagram to delineate the subsurface geological structures that might support mineral prospecting in the study area. These filtering and enhancement techniques are described briefly as follows.

Reduction to the Magnetic Equator

In areas of low magnetic latitudes, or geomagnetic inclination of less than 15˚, reduction to the equator of magnetic anomalies is usually carried out to get anomalies back in line with the structures that produce them.

The reduction to the magnetic equator (TMI-RTE) map was obtained by filtering the Total Magnetic Intensity map in accordance with the I.G.R.F of 2005 standard reduction method using equation (1) below and employing amplitude corrections of inclination -13.9 and declination of - 1.9 as basic inputs.

$$L(\theta) = \frac{[\sin(I) - i\cos(I).\cos(D-\theta)]^2 x\,(-\cos^2(D-\theta)]}{[\sin^2(Ia) + \cos^2(Ia).\cos^2(D-\theta) x\,[\sin^2(I) + \cos^2(I)\cos^2(D-\theta)]} \quad (1)$$

If $(/Ia/</I/)$, Ia=1

Where: $L(\theta)$= Residual reduced to the equator, I = geomagnetic inclination, Ia = inclination for amplitude correction (never less thanI), D = geomagnetic declination, Sin (I) = amplitude component and Icos(I)cos(D- θ) = phase components.

Polynomial fitting (Residual-Regional Separation)

The regional field was substituted from the total magnetic intensity field data to obtain residual data, using the polynomial fitting of the second order of the least square method. The generated residual map helped to enhance the high-frequency anomalies emanating from the shallow magnetic bodies while suppressing deep magnetic bodies. In mineral exploration, the importance of residual anomaly cannot be overemphasised. The equation (2) below was adopted as the algorithm for the removal of regional data (Ugwu *et al.,* 2013).

$$r = a_0 + a_1(X - X_{ref}) + a_2(Y - Y_{ref}) \quad (2)$$

Where r is the regional field, X_{ref} *and* Y_{ref} are the x and y coordinates of the geographic centre of the data set, respectively, and a_0 , a_1 *and* a_2 are the regional polynomial coefficients.

Vertical derivative

Vertical derivatives are widely used in total magnetic field data to improve the shallow geological sources and can be estimated in either the space or frequency domain. The first vertical derivative and second vertical derivative maps, specifically sharpen anomalies over bodies and reduce anomaly difficulties, allowing for more accurate imaging of causative structures. This technique was utilised in this study to delineate near-surface structures that may serve as paths/traps that will house mineral resources in the area. The first vertical derivatives (FVD) of the magnetic field are frequently calculated using the relation (Telford *et al.,* 1990).

$$FVD = \frac{\partial T(x,y,z)}{\partial z} \quad (3)$$

Where T is the total magnetic field at (x, y, z)

The second vertical derivatives (SVD) of the magnetic field can be calculated by the equation given below (Telford *et al*., 1990).

$$SVD = \frac{\partial^2 T(x,y,z)}{\partial^2 z} \quad (4)$$

Where T is the total magnetic field at (x, y, z)

Analytic Signal

The analytic signal filter produced a particular type of calculated magnetic anomaly enhanced map that defined the edges (boundaries) of the geological anomalous magnetisation distribution. It actually takes the magnitude of the square root of the vertical and horizontal components of the magnetic responses (Geosoft Inc, 1996). This technique was used in this study to clearly define areas of variable data resolution in the magnetic field as well as structures that may house prospective mineral resources in the area. The algorithm for the calculation of the analytic signal A of a potential field anomaly, as proposed by Nabighian (1984), can be defined in equation 5.

$$A(x,y,z) = \left[\frac{\partial M}{\partial x}\right]\hat{x} + \left[\frac{\partial M}{\partial y}\right]\hat{y} - j\left[\frac{\partial M}{\partial z}\right]\hat{z} \quad (5)$$

Where M = magnetic field.

The Centre for Exploration Targeting (CET)

The CET analysis is an extension of the Oasis Montaj software used in mineral exploration. The process adopts the following method of identifying linear structures within an area through consecutive maps byproduct forms of standard deviation, which estimates magnetic variations and for a window containing *N* cells, whose mean value is μ, the standard deviation σ of the cell values x_i is expressed in equation 6 (Kovesi, 1999). This was adopted for the study to infer directions/ orientation of the structures within the area via the rose diagram.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \quad (6)$$

RESULTS AND DISCUSSION

Total magnetic intensity

The total magnetic intensity map of the area (Figure 2) showed magnetic intensities ranging between -87.2 and 153.4, with variations of high, intermediate and low intensity signatures. The high magnetic signatures (pink-red colours) observed at the northwestern, north eastern, southwestern and some parts of the central portions of the study area are attributed to basement terrain areas that

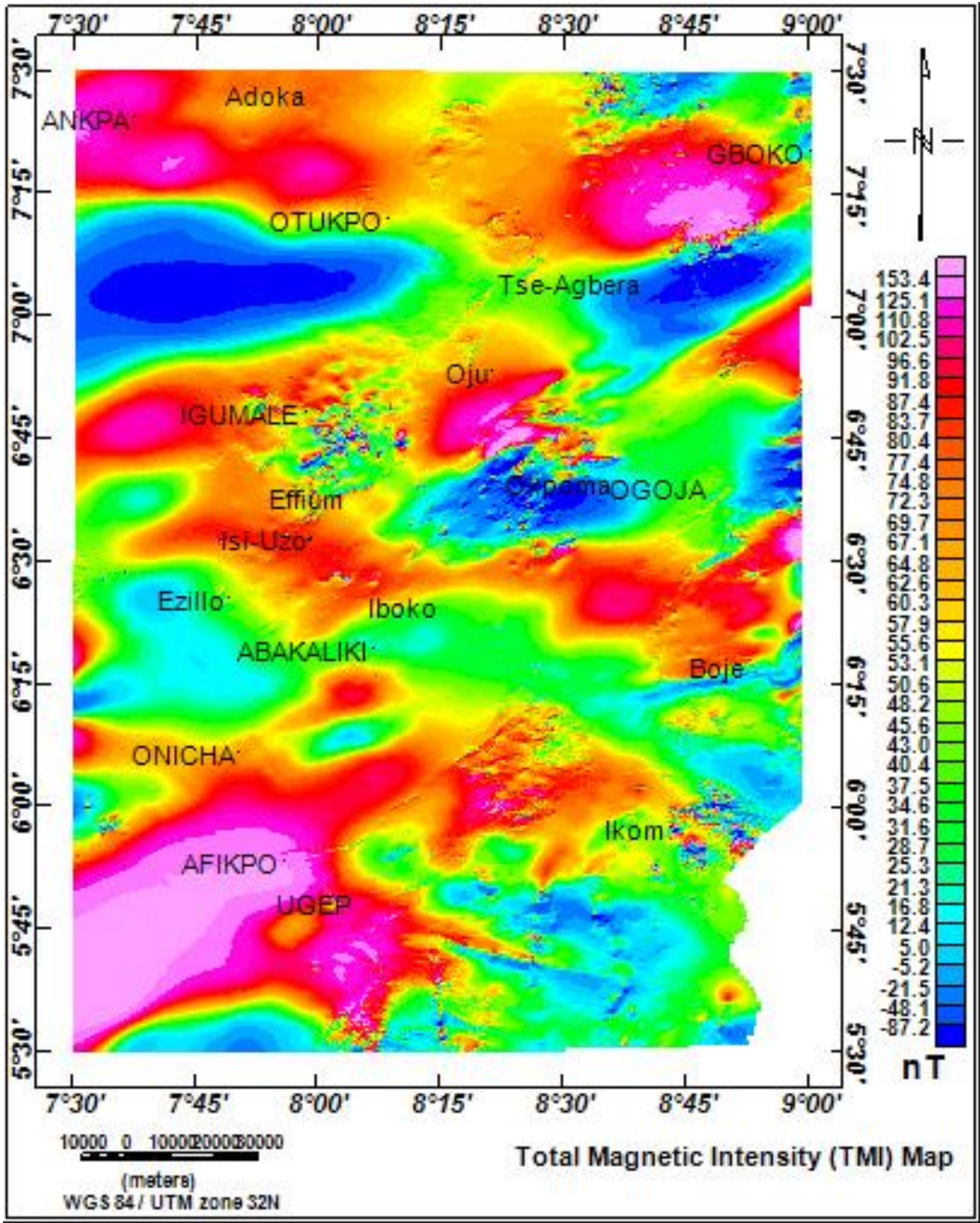

Figure 2. Total magnetic intensity map of the study area.

intruded the sedimentary beds. The lowest intensity signatures (green to blue) are seen in parts of the northwestern, north eastern, central portions and southeastern parts depicting sedimentary terrains. These areas were also depicted as sedimentary terrains from the studies of Nnaemeka *et al*. (2023).

Reduction to the Equator (TMI_RTE)

Reduction to the magnetic equator (Figure 3) revealed a resemblance of magnetic signatures with that of the total magnetic intensity map, but exposed magnetic intensities smoother and better than the TMI map. This is due to the

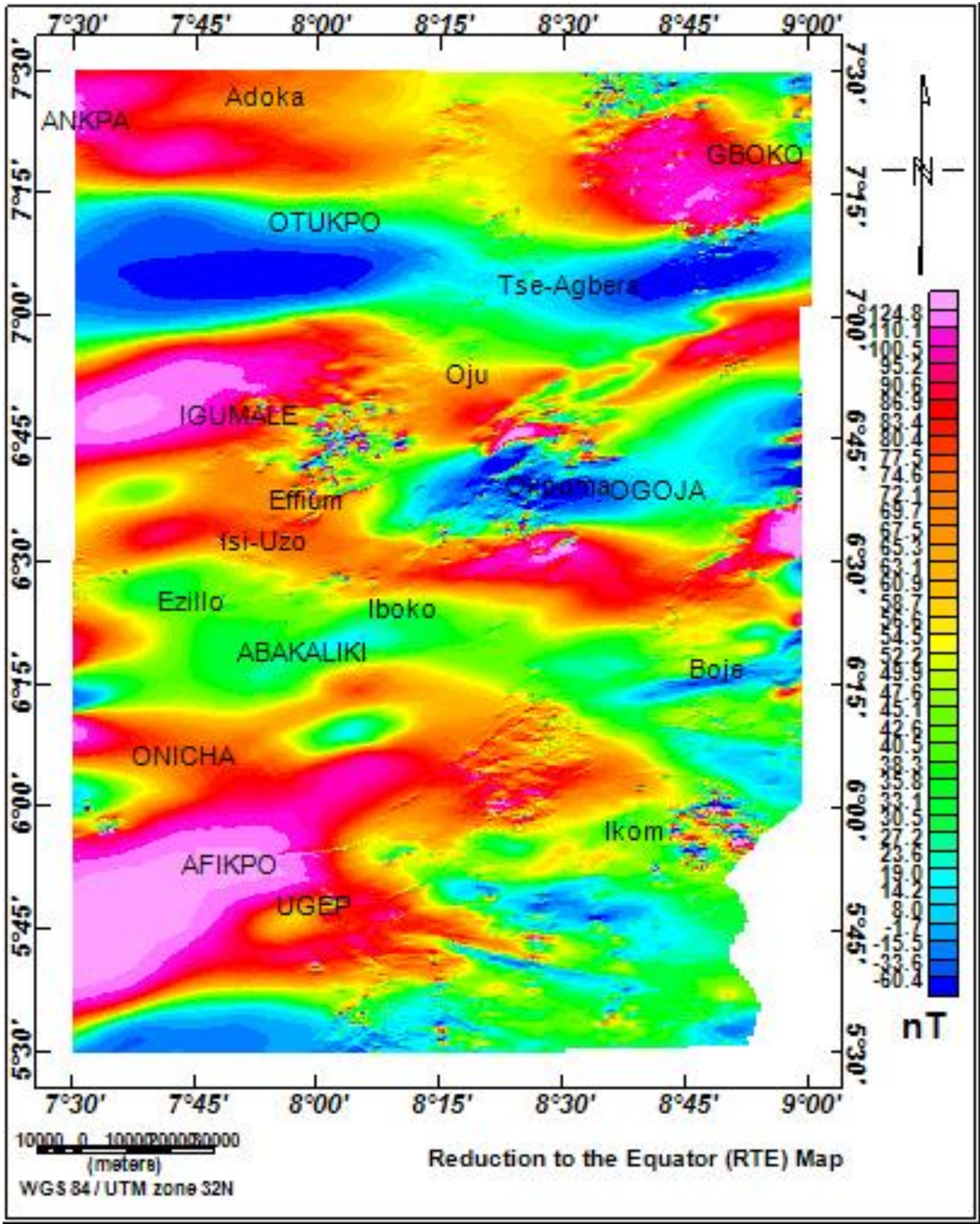

Figure 3. Reduction to the equator map of the study area.

reduction processes carried out on the TMI data. The TMI_RTE map showed magnetic intensities ranging between -60.4 and 124.8 nT. The high magnetic signatures (pink-red colours) are observed at the northwestern, north eastern, southwestern and some parts of the central portions of the study area, and the low intensity signatures (green to blue) are observed in parts of the northwestern, north eastern, central portions and southeastern parts of the area of study.

Vertical derivatives

The first vertical derivative and second vertical derivative maps (Figure 4a and 4b) revealed areas of geological structures trending majorly at NE-SW and N-S directions.

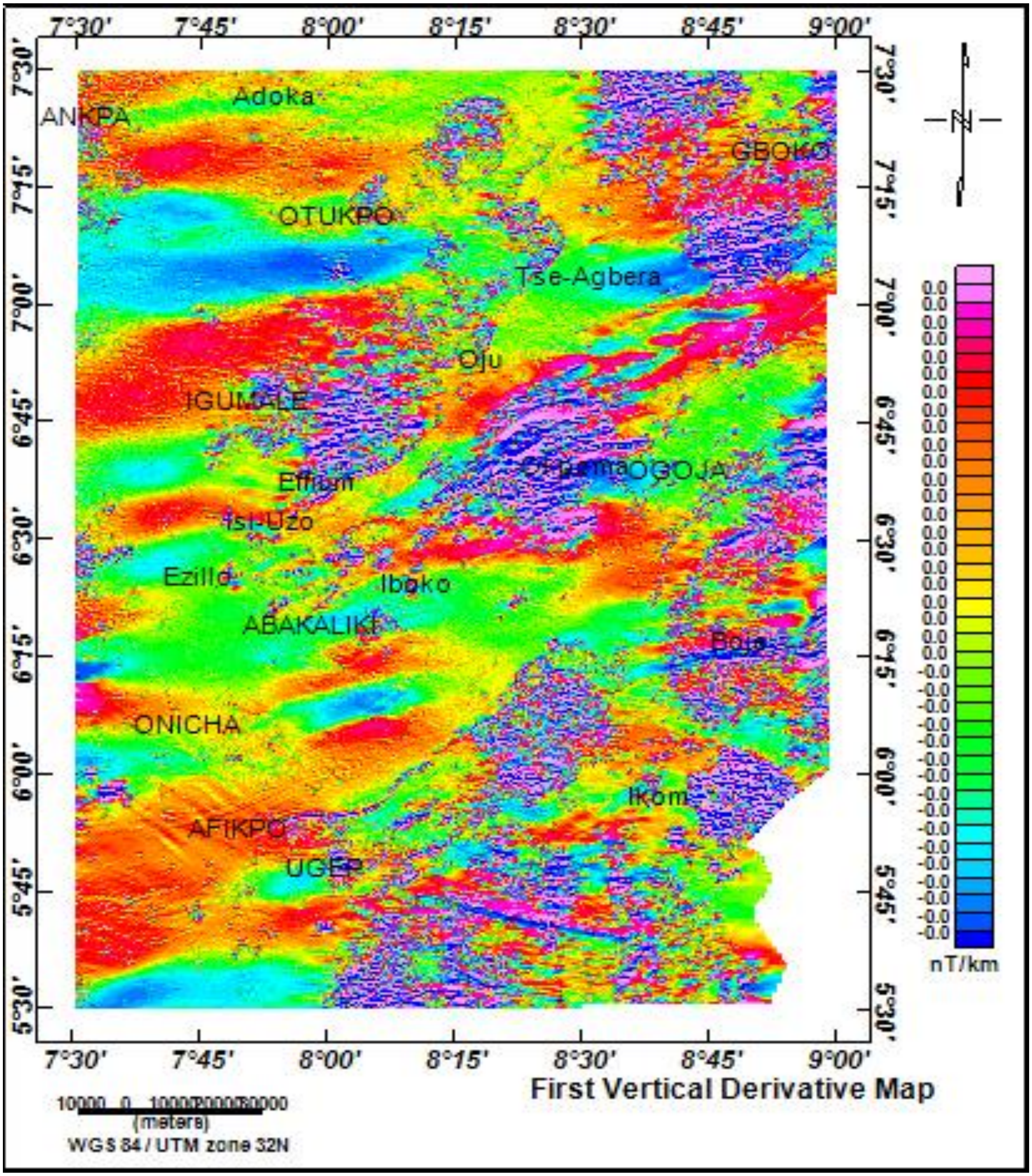

Figure 4a. First vertical derivative map of the area.

The second vertical derivative map exposed the areas with these structures more than the first vertical derivative map, and similar signatures of anomaly strike at the southeastern part were observed on both maps. These areas of intense geological structures or intrusions are considered to be shallow basement areas favourable for magnetic minerals exploration, because magnetic minerals are structurally controlled. This agrees with the work of Onyewuchi *et al.* (2012), Goodhope and Mamah (2013), Opara *et al*. (2015), Ofoha (2015), Nnaemeka *et al*. (2021), and Nnaemeka *et al*. (2023) on the structural orientation of the Lower Benue Trough.

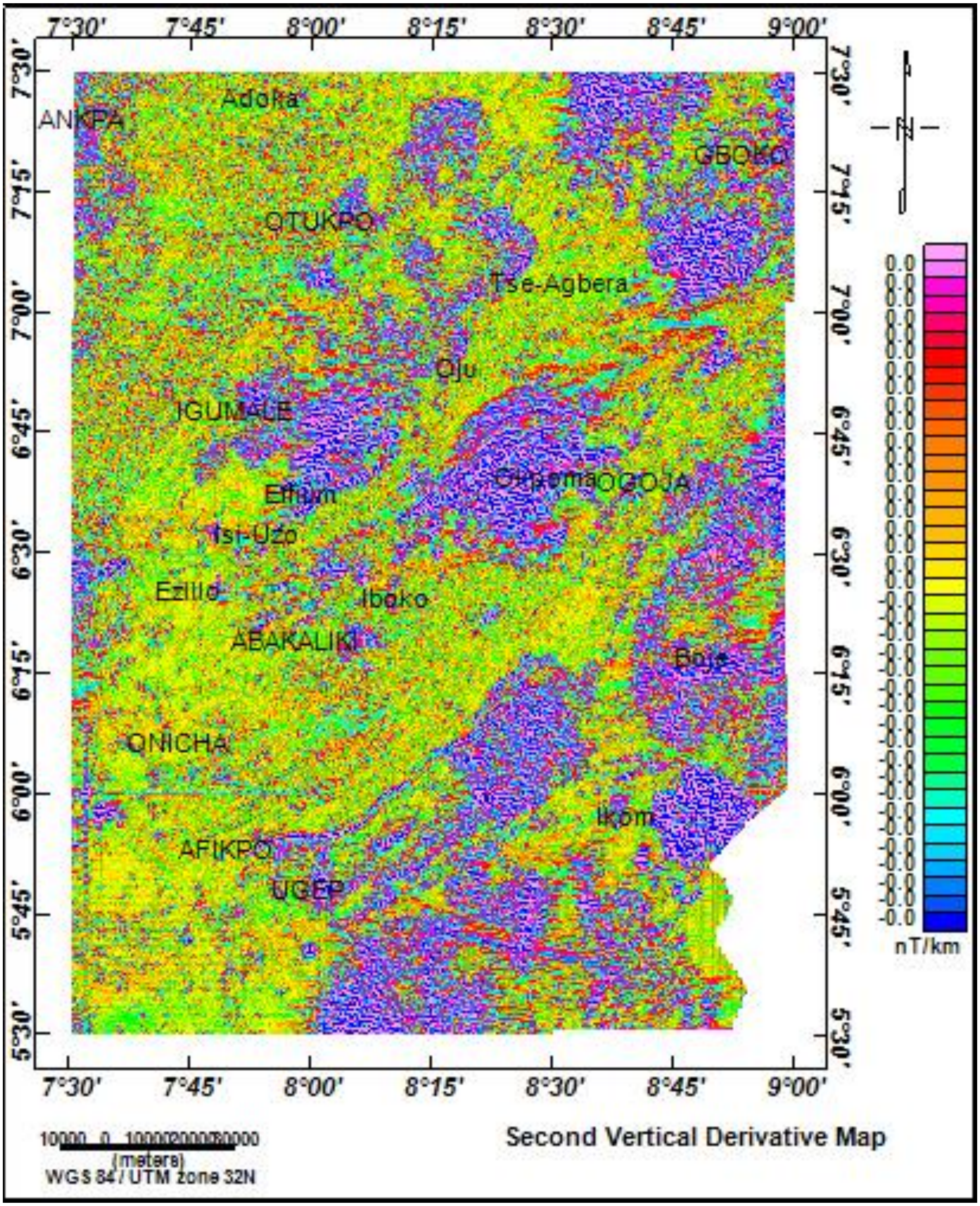

Figure 4b. Second vertical derivative map of the area.

Analytical Signal

The analytical signal map (Figure 5) clearly displayed the variations in the edge extent of the sources of geological anomalous magnetisation. The areas with high analytical signal amplitudes are observed at the southeastern, central portions, northeastern parts and spots at the northwestern, southwestern parts of the study area. This correlates well with the first and second vertical derivative maps of the study area, because areas of high analytical

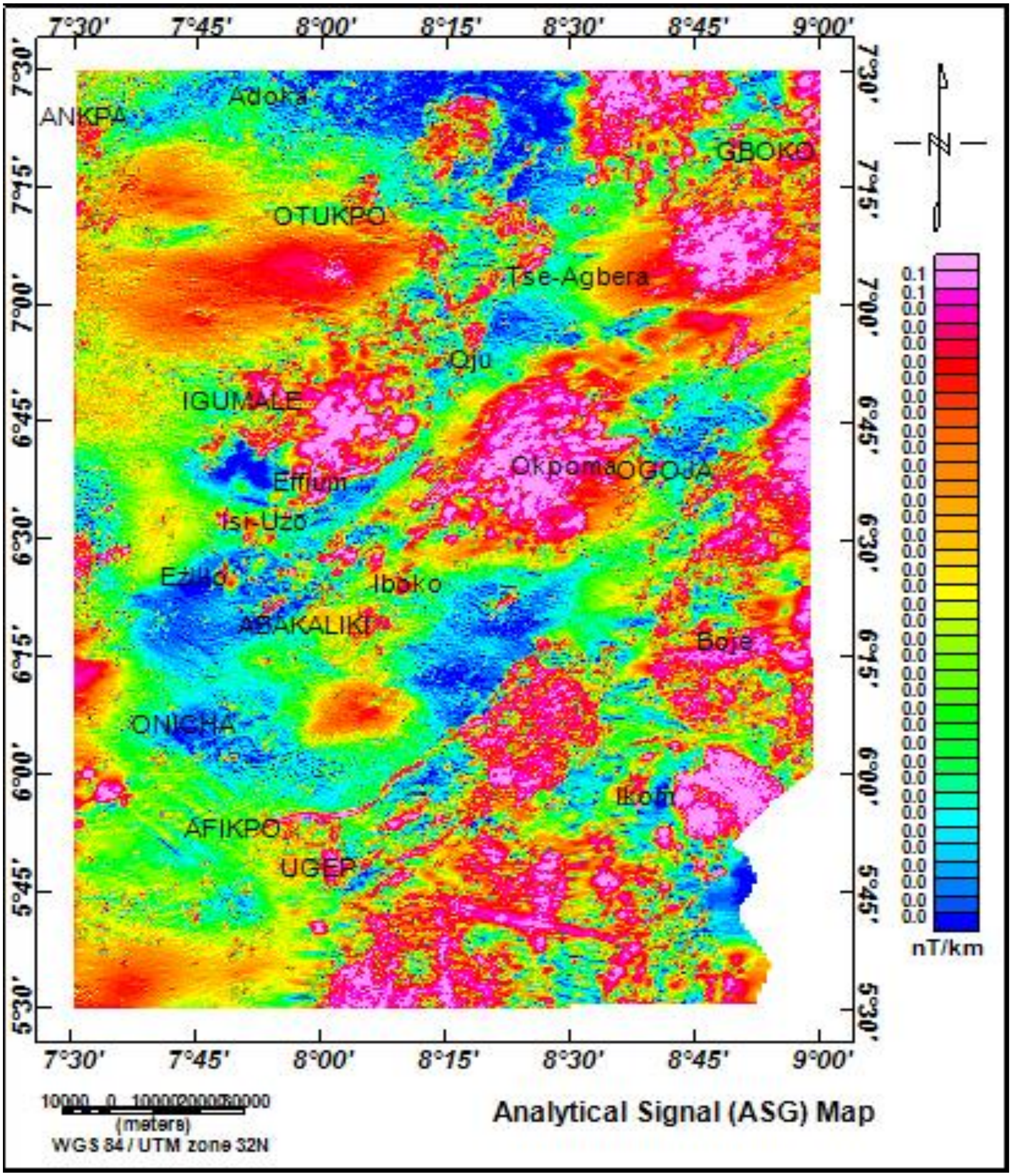

Figure 5. Analytical signal map of the study area.

signal amplitudes are recorded around significant areas of massive mineral deposits (Liu and Mackey, 1998; Nnaemeka *et al.,* 2021).

Centre for Exploration Targeting (CET)

The CET processes revealed geological structures (lineament) within the area, through the standard deviation map (Fig. 6a), structural map and the rose diagram (Figure 6b) that exposed the directions of the extracted lineaments, which reflect shallow and deeper tectonic trends in the area. These extracted structures are suggested as major lineaments at NE-SW, E-W, ENE-WSW and minor trends at N-S, NW-SE, and NNE-SSW directions. This orientation agrees with the works of

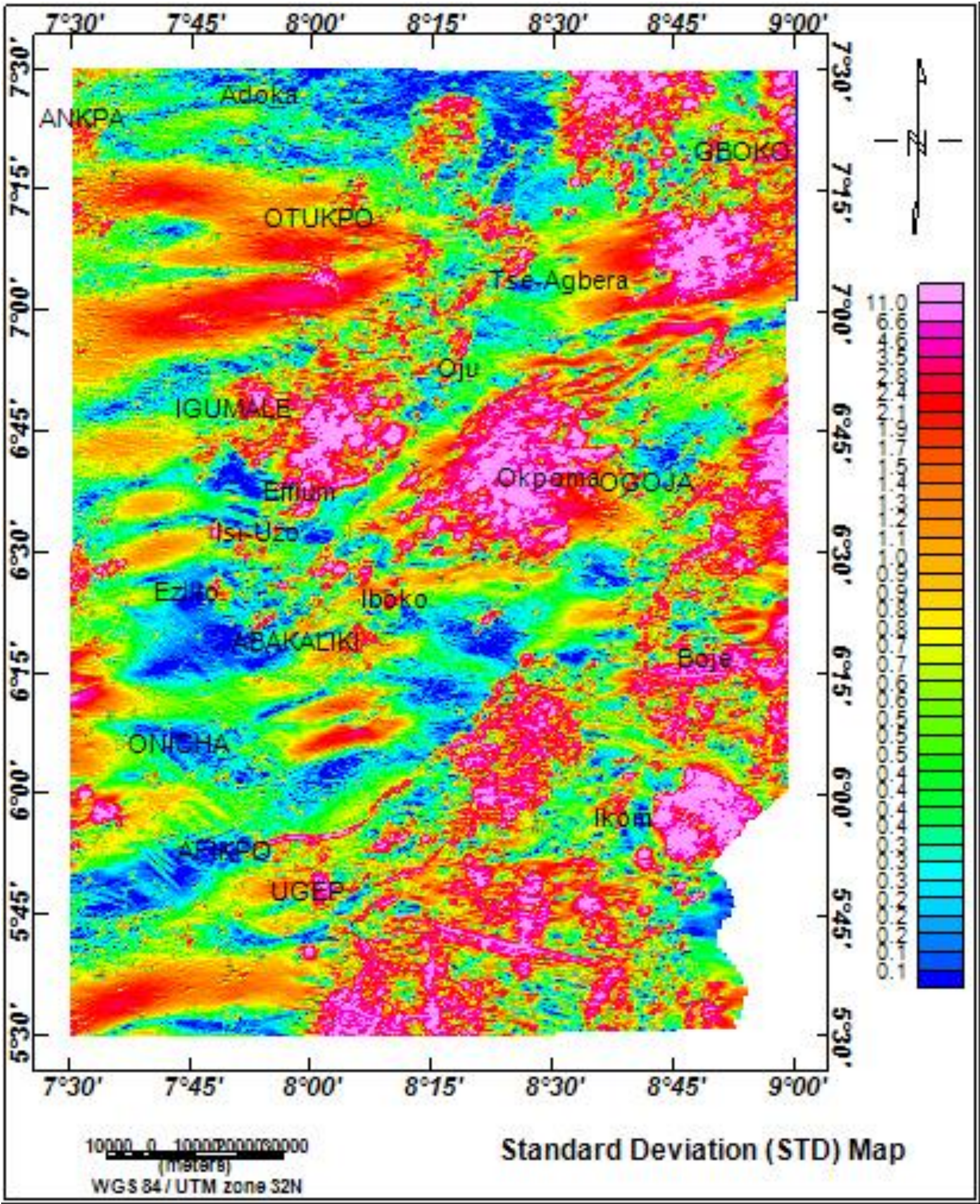

Figure 6a. Standard deviation map of the area.

Onyewuchi *et al.* (2012), Goodhope and Mamah (2013), Opara *et. al*. (2015), Ofoha (2015), Nnaemeka *et al*. (2021), and Nnaemeka *et al*. (2023) on the structural orientation of the lower Benue Trough and environs.

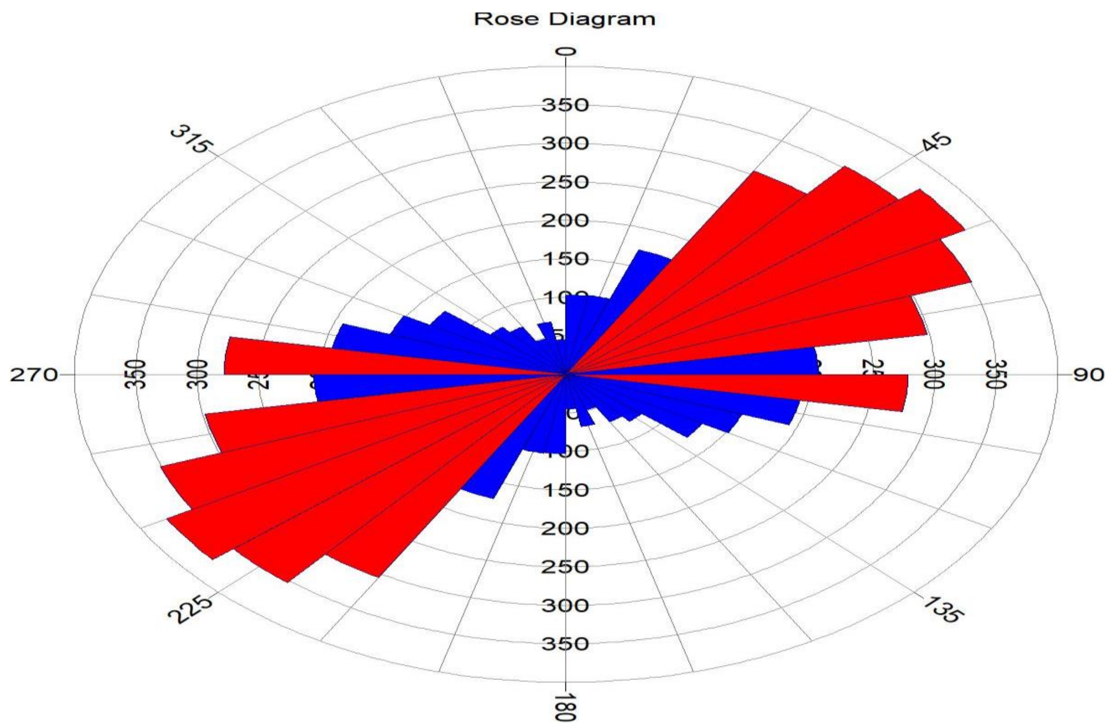

Figure 6b. Rose diagram from the lineaments of the study area.

Conclusion

The total magnetic intensity, reduced to the equator, showed areas with magnetic high zones, which may be due to shallow basements/ structures or areas of intrusions and areas with low magnetic anomalies, depicting deep structures or sedimentary terrains. The results of the vertical derivatives (FVD and SVD), analytical signal and centre for exploration targeting (CET) enhanced and identified the magnetic signatures that represent geological structures (lineament) of the area, which are aligned in the NE-SW, E-W, ENE-WSW, N-S, NW-SE and NNE-SSW directions. These lineaments mapped serve as traps and conduits for the minerals that might be entrapped within the areas with high potential for mineral deposits. These areas correspond to Okpom, Ogoja, Oju, Gboko, Tse-Agbera, Ikom, Boje, Ugep, Igumale, Abakaliki, Iboko, Effum, Isi-Uzo, Ankpa, Otupko, and, if harnessed, will add to the natural resource reserve of the country.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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