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## Magnetic inversion modeling of subsurface geologic structures for mineral deposits mapping in southeastern Nigeria

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Research Article

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Aeromagnetic data,  
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Optimization (PSO),  
Minerals, Depths.

### ABSTRACT

Magnetic inversion techniques have been implemented to infer the extension and geometry of magnetic structures and also evaluate its influence on mineralization within Abakaliki and its environs, southeastern Nigeria. The modeling approach considers the techniques of three-dimensional (3D) magnetic data inversion, Euler deconvolution, analytic signal inversion, Enhanced Local Wavenumber (ELW) Technique and Particle Swarm Optimization (PSO) to estimate source parameters and compare results. Model solutions were interpreted to represent possible geologic units with varying trends, housing mineralization within the study region. Results from inversion computation over some active mine locations show subsurface bodies with magnetic susceptibilities  $>0.00188$  SI. Model results also show structural sources with almost 5.5 km depth extension, stretching 18 km in the EW direction at Ngbo – Ekerigwe location. This could imply significant mineral deposits at the location. Inversion of both magnetic anomaly and analytical signal enabled derivation of the actual subsurface structures in the region, with most of the structures appearing as dykes with depths ranging from 0.2 – 1.8 km at most of the mining sites. Location and depths of some of the modeled intrusions have been corroborated with the active on-site mines. The delineation of mineralization structures by this study would guide systematic exploration in the region.

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## 1. Introduction

Quantitative explanation of a potential field data includes assessment of depth, horizontal location, sources geometry as well as differences in the physical attributes (Essa and Abo-Ezz, 2021; Essa et al., 2021; Ganguli et al., 2021; Eshaghzadeh et al., 2020; Abraham and Alile, 2019; Essa et al., 2018; Aboud et al., 2018; Srivastava and Agarwal, 2010; Abdelrahman et al., 2003; Büyüksaraç et al., 1998, 2005). Modeling anomalies from a local magnetic field, and in particular, three - dimensional (3D) voxel-based modeling, is a contemporary and

important tool in exploration targeting (MacLeod and Ellis, 2013). Inversion for a physical property involves the subdivision of the causative sources into a collection of rectangular cells, whose density or magnetization contrasts are to be appraised to explain the true distribution of the geological sources (Yao, 2007). 3D magnetic inversion allows total use of information in magnetic anomalies, estimating a 3D discrete physical property distribution that can describe the discerned geophysical field data (Li and Sun, 2016; Mahmoodi et al., 2016). In oil exploration, credible appraisals of depth to magnetic basement are

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needed for improved comprehending of the crucial first-order basin examination parameters (Srivastava and Agarwal, 2010; Li, 2003). Magnetic inversion technique can resolve magnetic bodies possibly associated with zones having abundance of magnetite and other magnetic minerals, rendering structural knowledge regarding these magnetic bodies and in numerous occasions, about the structural system of the mineralization (Couto et al., 2017). 3D inversions have assisted interpretations just as magnetic data aids the characterization of ore bodies (Leão-Santos et al., 2015; Büyüksaraç et al., 1998). On a regional scale, a cross-plot of density and susceptibility has been used (Melo et al., 2015; Kowalczyk et al., 2010) to define the classes of different lithologies and identify rock types. This approach can thus offer useful exploration information in areas with a paucity of geological information. Melo et al. (2015) used a comparable approach to demonstrate copper mineralization guided by the trend in the cross-plot of susceptibility and conductivity.

Various geophysical studies have been conducted around Abakaliki and environs. These include using Vertical Electrical Sounding (VES) technique to determine aquifer parameters, estimation of depth to magnetic source in a location closer to Abakaliki (Ugwu and Alasi, 2016), assessment of Curie Point Depth (CPD) (Abraham et al., 2018), hydrocarbon and mineral exploration prospect determination (Ezema et al., 2014) using aeromagnetic data and investigating the sequence of deposition of sedimentary strata in the region using seismic refraction and VES techniques (Agha and Arua, 2014). However, no three-dimensional (3D) inversion of magnetic data has been undertaken within the region towards the delineation of geological structures housing mineralization in the region. Inversion of magnetic survey data can offer restrictions on subsurface susceptibility allotments (Büyüksaraç et al., 2005; Lelievre, 2003). Abakaliki region is a mineralized province and has been documented to house great mineral potentials that include Lead, Zinc, Sodium Chloride, Silver, and Limestone (Abraham et al., 2018; Ugwu and Alasi, 2016; Ezema et al., 2014). This has been substantiated by mining activities (mostly local/small scale) ongoing in the region. Given the economic relevance

of these minerals and the need to quantify the deposits for productive, extensive, and sustainable mining, the Nigerian government authorized an airborne magnetic and radiometric survey in the region between 2005 and 2009. A close relationship exists between the proportion of magnetic minerals and magnetic susceptibility in rocks. Iron oxides; pyrrhotite, cobalt, nickel, and metallic iron are noteworthy. As these minerals, to the greatest extent, go with economic mineral deposits, we could analyze magnetic survey data to gain information on potential drilling targets (Lelievre, 2003). The creation of 2D and 3D models of geophysical inversion and mineral potential modeling has added to the large precompetitive data available to explorers (Büyüksaraç et al., 2005, 1998). The area of coverage by this study locates within geographic latitudes 6°00' and 6°30' N and geographic longitudes 8°00' and 8°30' E within the sedimentary terrain of southeastern Nigeria (Figure 1).

Our study seeks to carry out 2D and 3D magnetic inversion modeling, identify sources location, and perform depth analysis to geologic units bearing possible minerals in Abakaliki and environ. A credible depth appraisal to the top of causative source enhances budgeting as well as scheming of drill holes and other exploitation projects (Srivastava and Agarwal, 2010). We anticipate that the effect of this study will emphasize mineralized geologic units and structural positions and augments mining certainty in the region.

### 1.1. Geological Setting

Following a series of tectonic activities and recurrent sedimentation in the Cretaceous time, the Nigeria-Benue trough was formed. The split of the continents resulted in an abrupt rift (aulacogen) that has been stuffed with transgressive and regressive sedimentary lay downs (Ugwu and Alasi, 2016).

The lower Benue trough is supported below by a thick sedimentary succession set down in the Cretaceous era. Four geological formations which include the Nkporo Shale (Campanian), the Awgu Shale (Coniacian), the Asu River Group (Albian) and the Eze-Aku Shale (Turonian), constitutes the sediments that happened in the Abakaliki Anticlinorium (Figure 2). The sedimentary sequence was influenced by

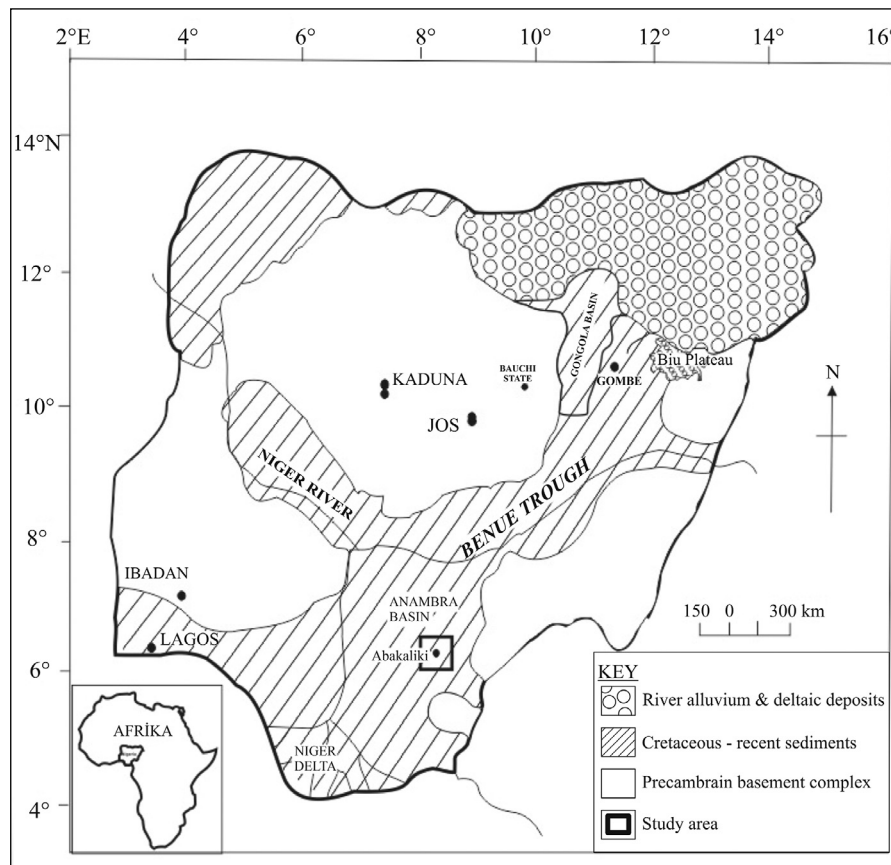


Figure 1- Map of Nigeria showing the general geology, location and coverage area of this study (modified from Abraham et al., 2018).

large-scale tectonic events that occur in two stages leading to folding of the sediments. Cenomanian and Santonian deformations affected the area with a large tectonic imprint (Nwachukwu, 1972; Olade, 1975; Ezema et al., 2014).

A general NE-SW trending fold characterized the Santonian deformation. The folding influenced the development of the Abakaliki Anticlinorium, a compressive structure marked with asymmetry and reversed faults. Benkhelil (1988) described the orogenic cycle of the anticlinorium to include sedimentation, magmatism, metamorphism, and compressive tectonism. Numerous intrusive bodies within the shale are due to magmatism that affected the Eze-Aku and Asu River Group (Figure 2). Majority of these intrusive has been concealed by the shale formation (general superficial geology) of the region as observed in the geology. This study offers supplemental information on the intrusive bodies including estimates of their respective depths.

Intermediate intrusive appear on the surface and could be seen in parts of the study area like the Abakaliki town. This intrusive appears as sills (Ezema et al., 2014; Ofoegbu, 1985; Eze and Mamah, 1985). The Abakaliki shale (Asu River Group) is of Albian age, dark gray, blocky and non-micaceous in most locations. The Asu River Group is predominantly shale and localized incidences of sandstone, siltstone, and limestone intercalations. Eze-Aku formation comprises of a succession of calcareous sandstones.

Figure 3 shows the lithostratigraphic section (Obarezi and Nwosu, 2013) of the two main geologic units recognized in the study area. The lithostratigraphic section was erected from acquired and logged geologic core data. The interpreted data shows the trend and structure that controls mineralization, mineralogy, and the sequence of deformation. Figure 4 displays images of the current open cast mining of lead-zinc (Pb-Zn) minerals by the locals within the study region. Current mining operations at these regions are largely done by

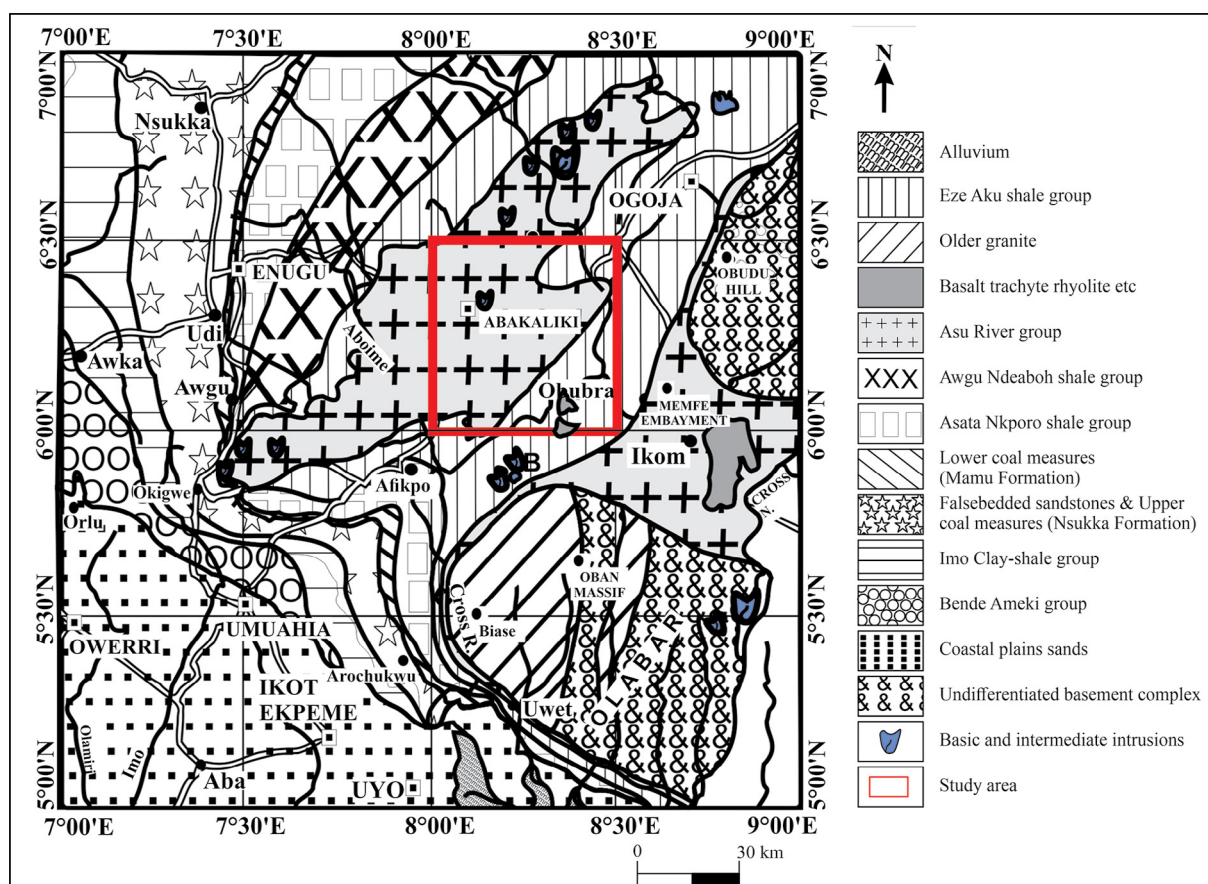


Figure 2- Detail geological map of southeastern Nigeria depicting the study area. The inserted red square represents the study area coverage in Figure 1 (modified from Abraham et al., 2018).

locals with crude tools and haphazard exploitation. Most of the mining is not mechanized as crude tools and poor excavation methods are employed by the locals to exploit these minerals. The water accumulations in some of the mines are mine water and rain accumulations.

## 2. Methods

Our study area is covered by a high-resolution digital aeromagnetic map sheet number 303 – Abakaliki, (Figure 5) spanning an area of approximately 3025 km<sup>2</sup>. The airborne data was acquired for the Nigerian Geological Survey Agency (NGSA) in 2005 and 2009. The entire data include approximately 2 km line of magnetic as well as radiometric surveys carried out at 500 m line spacing using 80 m terrain clearance. The regional field and diurnal magnetic effects were removed from the data. We applied the Reduction to Equator (RTE) correction (Leu, 1981; Jain, 1988; Abraham et al., 2018; Ganguli et al., 2021) assuming

a magnetic declination of  $-2.15^\circ$  and an inclination of  $-13.91^\circ$  for the study area utilizing the fast Fourier transform operator. Strong variations in magnetic intensities, suggesting different magnetic properties, could be discerned from the map.

Positive anomalies with higher values (90 – 94 nT) are observed at Onyen, Obubra, Ngbo, Abba Omega, and part of Enyigba localities. The positive anomalies at Obubra and Onyen regions may be due to intrusions of basalt, trachyte, Rhyolite and other intrusions within the region. This region locates within the Eze Aku Shale Group, largely notable for higher magnetic anomaly values (70 – 110 nT) (Figure 6). We note lower magnetic values around FUNAI, Ezzagu, and Egudenago localities between 19 nT and 40 nT. Within the Enyigba – FUNAI region, the notable lower magnetic anomaly unit observed, falls within the Asu River Group (Figure 6) and may be due to an intrusion within the Asu River shale formation. This



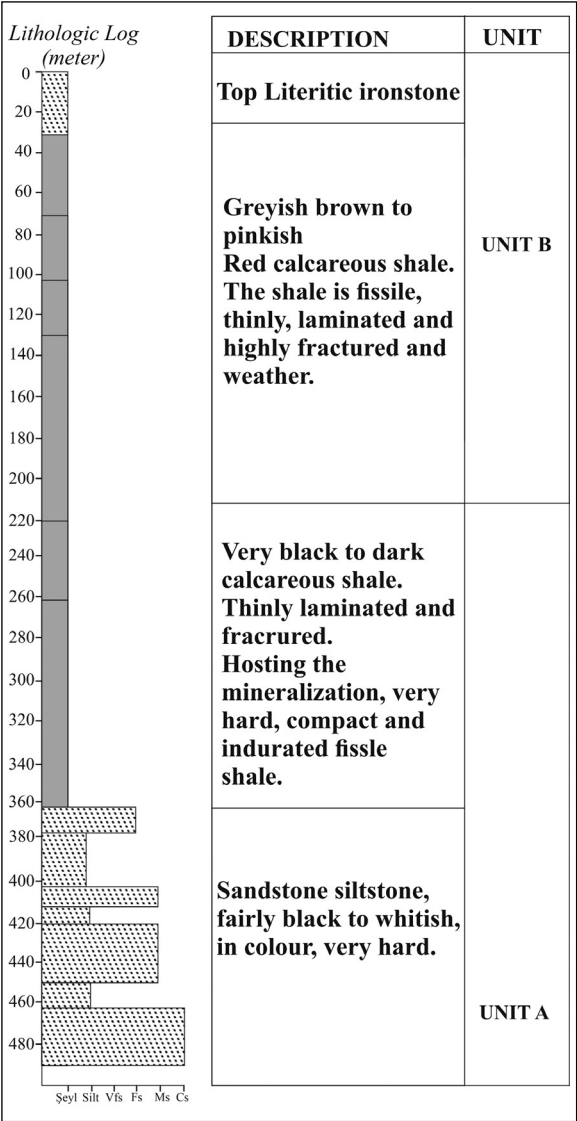


Figure 3- Lithostratigraphic section of the geologic units in the study area (modified from Obarezi and Nwosu, 2013)

may be true given the current exploitation of some mineral deposits from the region. A conspicuous E-W trending lower magnetic anomaly streak observed at northern region may be due to a lower magnetic susceptibility sill-like deposition located deeply in this region. The variation of magnetic strength (Total Field values) across the study area indicates the difference in susceptibility of the geological bodies, including mineralization and structures.

2.1. Magnetic Inversion

We present a brief theoretical insight into our adopted method for the 3D inversion. Pilkington

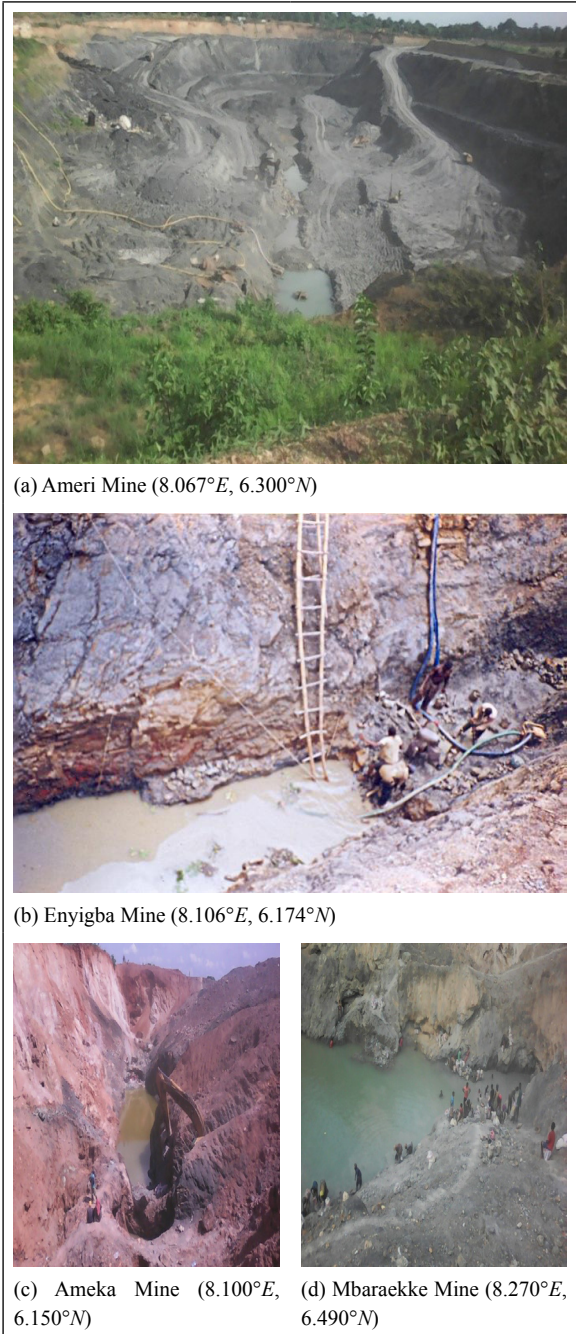


Figure 4- Images of some of the mines location in which current mining of lead-zinc minerals is ongoing by the locals (as could be seen in the pictures).

(2009) used the Cauchy norm (Sacchi and Ulrych, 1995) to solve the 3D magnetic inverse problem for sparse models, i.e. those models in which the number of nonzero values that fit the data is minimized. The derived inversion is therefore regarded as geologically unconstrained, in comparison with constrained inversions in which hard geologic constraints like

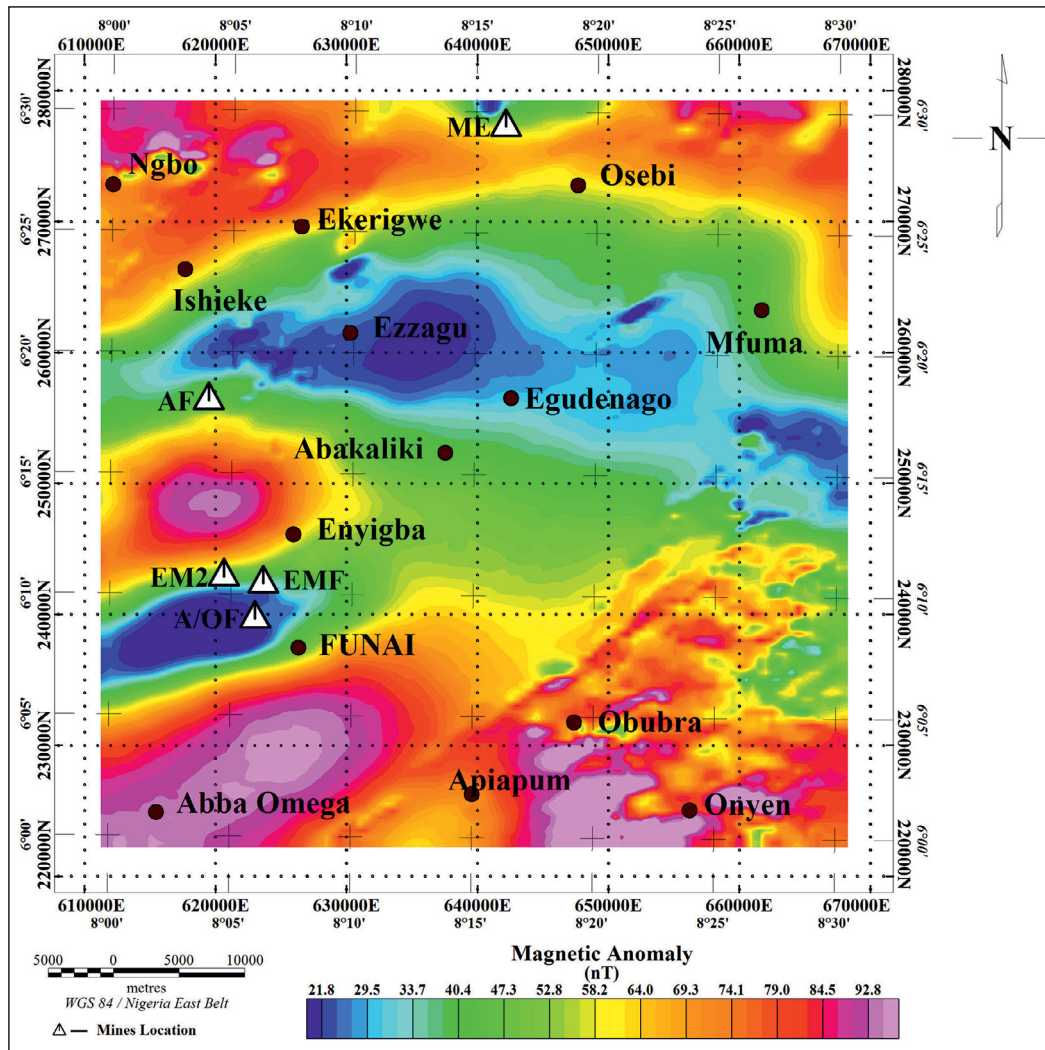


Figure 5- Aeromagnetic Anomaly map covering the region of study. Current and active mines (white triangles) are located on the map which includes the Ameri Mine Field (AF), Enyigba Mine Field (EMF), Ameka/Ohankwu Field (A/OF), Mkpuma-Ekwaokuko Field (ME) and Enyigba Mine Field 2 (EM2).

for example drill hole intersections are included (Pilkington, 2009).

For our computations, we assumed that all sources are magnetized by induction, having a susceptibility range starting from 0.0001 SI, an inclination of  $-13^\circ$ , and declination  $-2^\circ$ . We inverted the entire dataset to produce a 3D voxel susceptibility model using Pilkington and Bardossy (2015) implementation in the GEOSOFT program.

## 2.2. 3D Euler Deconvolution

Among the goals for performing the 3D Euler, the process includes outputting a map that exposes the depths of the geologic sources perceived in a 2D

grid and their corresponding locations (Eshaghzadeh et al., 2020; Whitehead and Musselman, 2005). The standard 3D Euler technique is founded on Euler's homogeneity equation – an equation relating the magnetic or gravity field along with its gradient constituents to source position, with structural index, SI (the degree of homogeneity N) (Thompson, 1982). An exponential factor analogous to the ratio by which the potential field falls off with distance when a source with a given geometry is taken into account. For our computations, we adopted the standard 3D design of Euler's equation (Reid et al., 1990) as implemented by GEOSOFT Oasis Montaj software as:

$$x \frac{\partial T}{\partial x} + y \frac{\partial T}{\partial y} + z \frac{\partial T}{\partial z} + \eta T = x_o \frac{\partial T}{\partial x} + y_o \frac{\partial T}{\partial y} + z_o \frac{\partial T}{\partial z} + \eta b \quad (1)$$



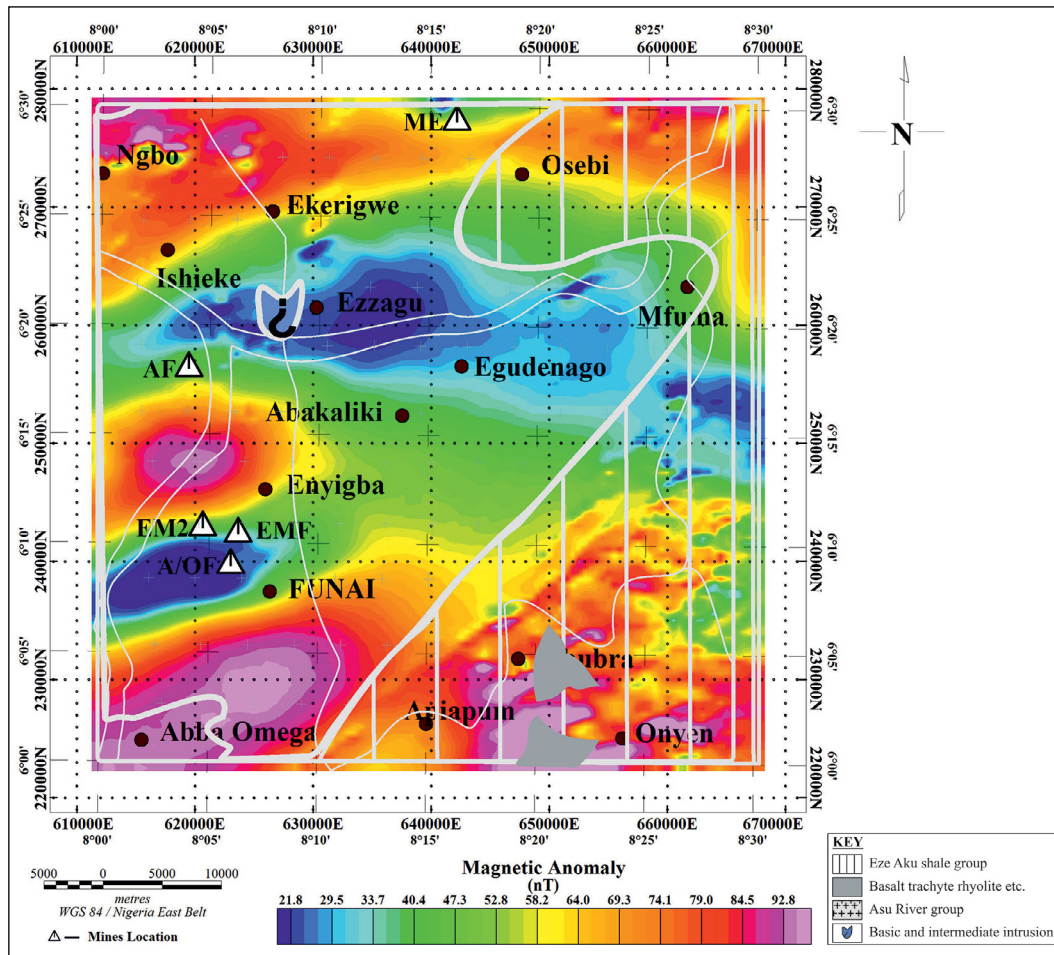


Figure 6- Aeromagnetic anomaly map with superimposed geology map of the study area.

where  $x$ ,  $y$  and  $z$  represents coordinates of a measuring point,  $x_0$ ,  $y_0$  and  $z_0$  represents coordinates of the source position of which the total field is discerned at  $x$ ,  $y$  and  $z$ ,  $b$  represent a base level,  $\eta$  represent the structural index (SI) and  $T$ , Total magnetic field. The source body type of interest determines the value of SI (Whitehead and Musselman, 2005). As an example (Kumar et al., 2020; Ganguli et al., 2019; Abraham and Alile, 2019; Thompson, 1982; Reid et al., 1990) proposes  $\eta = 0$  for a contact,  $\eta = 1$  (vertical dyke or the edge of a sill),  $\eta = 2$  (centre of a horizontal or vertical cylinder), and  $\eta = 3$  (centre of a magnetic orb or dipole). Euler's equation for magnetic data possesses a significant advantage because it is indifferent to magnetic inclination, declination, and remanence which constitute a constant, in the anomaly function of any given model. As we are interested in locating source contact/faults with depths, to model geological units influencing mineralization in Abakaliki and

environs, we adopted an SI of 0 (Reid and Thurston, 2014) and a window size  $\geq 10$  at 15% depth tolerance, for our computations.

### 2.3. Enhanced Local Wavenumber (ELW) Technique

Following the concept of local phase 2-D analytic signal of any constituents of the Earth's magnetic field assessments, an equation (autonomous of the causative source geometries) was obtained by Thurston and Smith (Thurston and Smith, 1997) utilizing second-order vertical and horizontal derivatives of magnetic anomalies. This includes the contact, thin sheet, pole and dipole, involving unknown parameters of location and depth only. Having known the horizontal position as well as depth parameters, the source geometry was further determined (Srivastava and Agarwal, 2010). For this study, we utilized a FORTRAN code developed by Agarwal and Srivastava (2008) to analyze field anomalies.



## 2.4. 3D Analytic Signal

Horizontal displacement regarding sources has always complicated the elucidation of observed magnetic anomalies. The non-vertical direction of the induced magnetization and geomagnetic field, results in displacement or skewness. To verify if the magnetic anomalies in the area were brought about by intrusions, we calculated the analytic signal response of the geomagnetic field. The 3D Analytic Signal amplitude is shown as (Roest et al., 1992; Riedel, 2008):

$$A(x, y) = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \quad (2)$$

where  $T$  represents the observed field at  $x$  and  $y$ .

Despite this function not being a measurable parameter, it is highly fascinating in the context of interpretation, as it retains its independence in terms of the direction of magnetization, as well as the direction of the inducing field. This implies that all bodies with the same geometry have the same analytic signal. Maxima are displayed over magnetization contrasts and are independent of the ambient magnetic field including sources magnetization directions. These maxima thus outline the magnetic sources from their locations. The analytic signal is useful in identifying the edges of the magnetic source bodies, where remanence and/or low magnetic latitude (as in this study) makes interpretation difficult (Whitehead and Musselman, 2005).

## 2.5. Particle Swarm Optimization (PSO) and 2D Analytic Signal

To model the subsurface structure from the analytical signal and magnetic anomalies, we adopted the particle swarm optimization (PSO) technique. PSO results appear to be stable to a greater degree than other optimization techniques (Essa and Elhussein, 2020; Essa and Munsch, 2019; Srivastava and Agarwal, 2010). PSO (Srivastava et al., 2020; Srivardhan et al., 2016; Kennedy and Eberhart, 1995) is a global optimization method and is one of the accepted naturally influenced metaheuristic algorithms founded on the conduct of bird flocks as well as fish schools looking for food (Pallero et al., 2015). The purpose

of a geophysical inverse problem is to discover a best reasonable model explaining a collection of observed data like an  $M$ -dimensional optimization problem (Srivastava and Agarwal, 2010). Following Srivastava and Agarwal (2010), we take into account the mapping,  $g$  betwixt the ‘model space vector’,  $\mathbf{m}$  together with the ‘data space vector’,  $\mathbf{d}$  as

$$\mathbf{d} = g(\mathbf{m}), \quad (3)$$

Also, take into account that the model  $\mathbf{m}_{true}$  produces the observed data,  $\mathbf{d}_{obs}$ :

$$\mathbf{d}_{obs} = g(\mathbf{m}_{true}) \quad (4)$$

The objective function is defined as

$$E(\mathbf{m}) = [\mathbf{d}_{obs} - g(\mathbf{m})]^T [\mathbf{d}_{obs} - g(\mathbf{m})], \quad (5)$$

The superscript  $T$  represents the matrix transpose. When the appraised model  $\mathbf{m}$  comes near to the true model,  $\mathbf{m}_{true}$ , the objective function  $E(\mathbf{m})$  tends to minimum.

For the PSO, a swarm of particles is chosen by chance from the  $M$ -dimensional model space vector in order that the position of each particle matches to a could be model. A particle  $i$  possesses the next attributes at the  $k$ th iteration (flight): (1) current location,  $\mathbf{m}_i^k$  (2) the best location accomplished so far  $\mathbf{m}_i^n$  and (3) velocity,  $\mathbf{V}_i^k$ . A velocity adaptation of the particle is resolved together by the previous best position filled by the particle as well as the best position of the swarm for each of the iterations. Computation of a new position on account of the particle is performed utilizing the new velocity. The part of the velocity adaptation resolved by the individual’s previous best position is known as the ‘cognition’, and the part impacted by the best in the population is known as the ‘social’ part. The swarm, from the other point of view, possess but one characteristic, particularly, the best locations  $\mathbf{m}_i^g$ , obtained up to the  $k$ th iteration. The cognitive and social knowledge determines the direction of each particle in the swarm. In mathematical form, this is described as (Srivastava and Agarwal, 2010):

$$\mathbf{m}_i^{k+1} = \mathbf{m}_i^k + a[\mathbf{V}_i^k + b \text{ran}(\cdot)(\mathbf{m}_i^n - \mathbf{m}_i^k) + c \text{ran}(\cdot)(\mathbf{m}_i^g - \mathbf{m}_i^k)] \quad (6)$$

Parameters  $b$  and  $c$  stands for the learning rates controlling the cognition as well as the social knowledge, correspondingly. The parameter  $a$

represents the constriction factor established by (Clerc, 1999) and is nearly connected to the inertia factor while  $\text{ran}(\cdot)$  represents a random number generator (Press et al., 1994) picked in a uniform manner in the open interval (0, 1).

The amplitude of the Analytic Signal over a 2D source (AS) is a symmetrical function with peak almost agreeing with the upper corners of the causative source (Mehanee et al., 2021; Nabighian, 1972). Some researchers (Salem et al., 2005; Srivastava and Agarwal, 2010) demonstrated that AS of distinctive source geometries is capable of being approximated by a generalized equation following the form:

$$|A(x)| = \frac{K}{[(x - x_0)^2 + z_0^2]^q} \quad (7)$$

The amplitude factor,  $K$ , is connected to the physical characteristics of the source. The horizontal location and depth of the source is represented as  $x_0$  and  $z_0$ , correspondingly, and the shape factor is represented as  $q$ . Equation (7) attains a maximum at  $x = x_0$ . PSO was used to invert AS to resolve horizontal location and depth, amplitude factor ( $K$ ) and shape factor ( $q$ ) for every corner of the adopted model. These parameters are determined by designating search spaces for constant  $K$ , shape factor  $q$ , as well as the horizontal location and depth (in connection with data spacing). The amplitude of analytic signal AS of a 2D magnetic source model as approached by an  $m$ -sided polygon

is the sum of the  $m$  symmetric bell-shaped functions (equation 7) nearly centered atop corners of a polygon (Srivastava and Agarwal, 2010; Huang and Guan, 1998).

For the PSO implementation, we performed 10 independent runs utilizing 100 particles to achieve the optimum model parameters. Values 1, 2, and 2 were allocated for the inertia factor ( $a$ ) as well as the cognitive and social scaling factors ( $b$  and  $c$ ), correspondingly (Thompson, 1982). The variation in shape factor from 0.2 – 1.5 was considered to incorporate various types of source geometries. Results obtained from PSO were compared with those from ELW technique (Agarwal and Srivastava, 2008).

We computed a synthetic magnetic field data using a MATLAB program (Stocco et al., 2009). The code of the inversion routine is established on a weighted-damped least-squares algorithm, following a standard of balancing the weight of the data inaccuracies as well as the compactness of the solution.

### 3. Results

The best 3D susceptibility model was achieved at the 230<sup>th</sup> iteration on the magnetic anomalies with a root-mean-square (rms) error of 1.129485 nT and results displayed in Figure 7. Figure 8 displays the model result after clipping susceptibilities lower than 0.00113 SI. Figure 9 displays model result with superimposed magnetic data respectively.

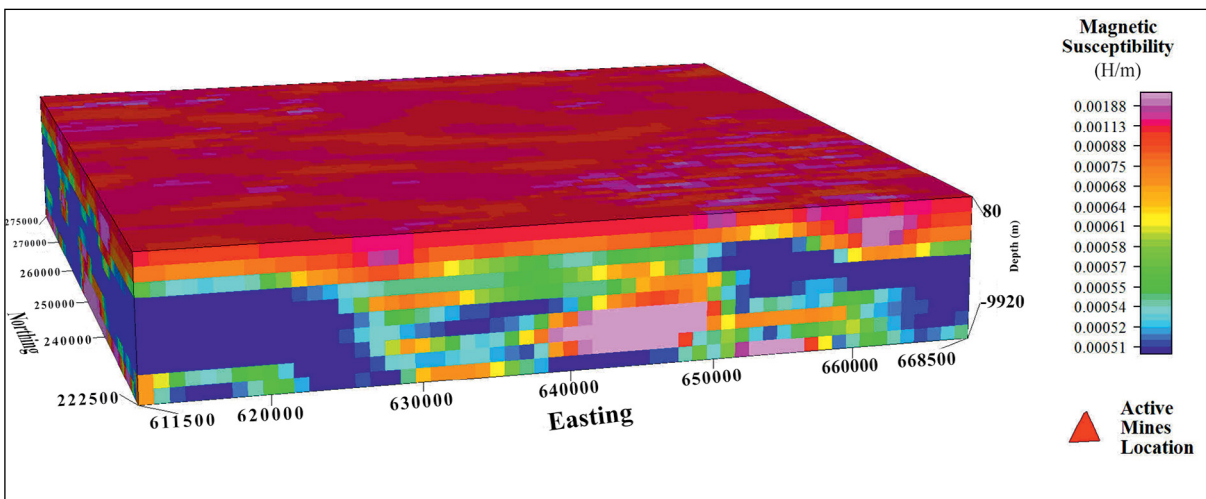


Figure 7- 3D model results from the inversion of magnetic data. The conspicuous contrast between the intruding structures and the host environment could be seen in the model with susceptibilities  $\geq 0.00113$  SI.

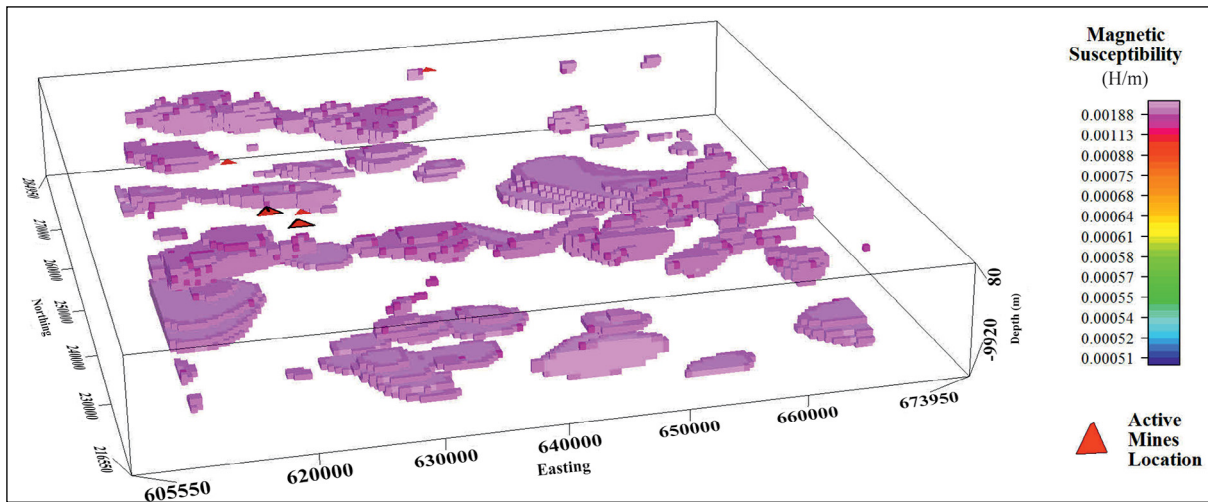


Figure 8- Model results after clipping susceptibilities lower than 0.00113 SI (Figure 7). A depth slice at -100 m was taken and the inversion model was constrained using information from Figure 2 (Geology) and 3 (Lithostratigraphic section) of Enyigba, in addition to Dobrin and Savit (1988).

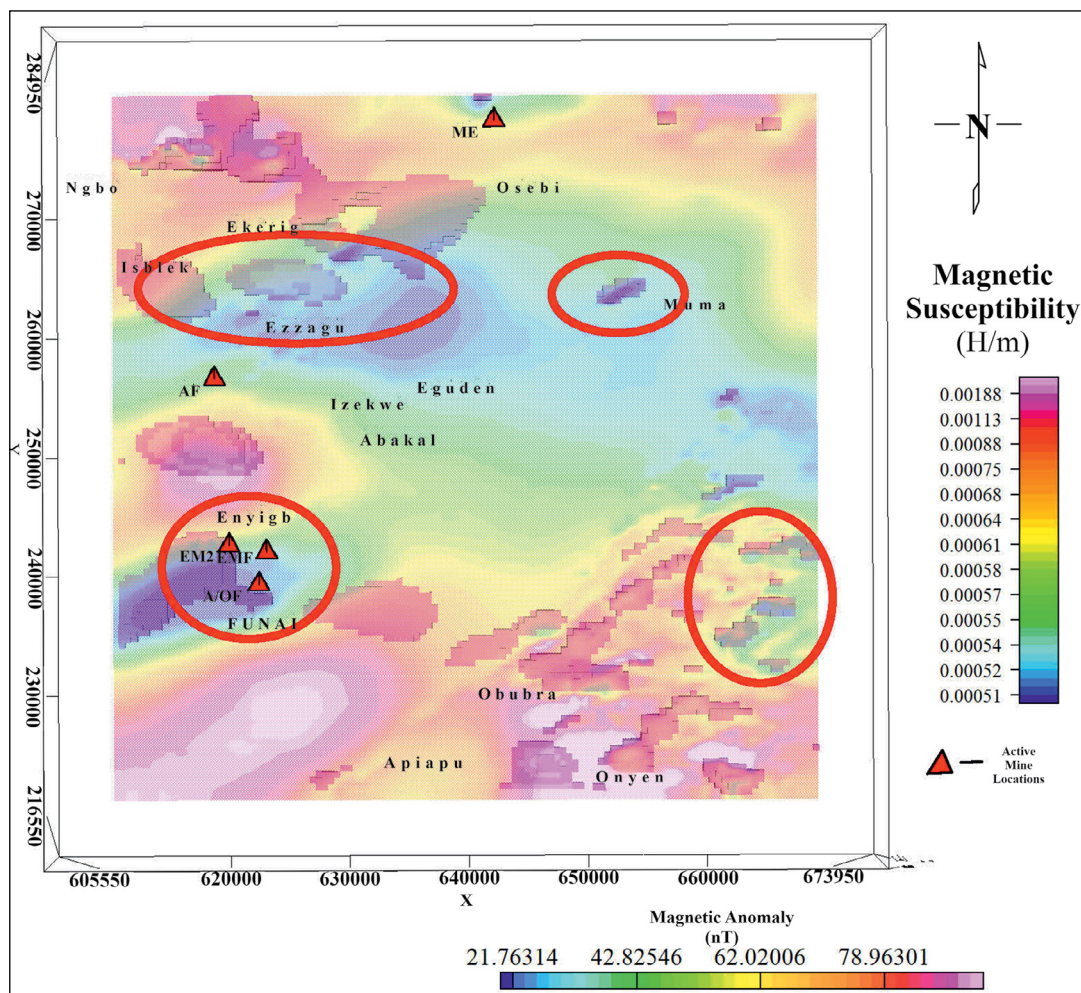


Figure 9- Plan view of the magnetic field anomaly (watermarked at 59% transparency) superimposed on the outlines of the model bodies. We noticed that some largely lower magnetic anomalies locate over high susceptibility units in the model (circled).



Results from 3D Euler deconvolution is presented in Figure 10. The presented result is a map showing Euler depth solutions superimposed on combined 3D susceptibility solutions (Plan view) map and magnetic anomaly data (with 59% transparency effect to enable see-through to some of the susceptibility solutions in the background).

The effect of the structural trends of possible subsurface geologic contacts mapped with the Euler deconvolution could be seen on the distribution of the model solutions from the inversion results (Figure 10). Parallel geologic structures trending NE–SW directions (inserted white lines), which may

be faults structures ‘sandwich’ the mines clusters at Enyigba – FUNAI enclave and appears to control the existence of the mineral deposits in the region. A similar structural network is also noticed at the Ameri Mine Field (AF), above the Enyigba town. These are observed on individual examination of the Plan View display of model solutions. Figure 11 shows a map of the Analytic Signal computation. The profiles on the map possesses various parameters as summarized in Table 1.

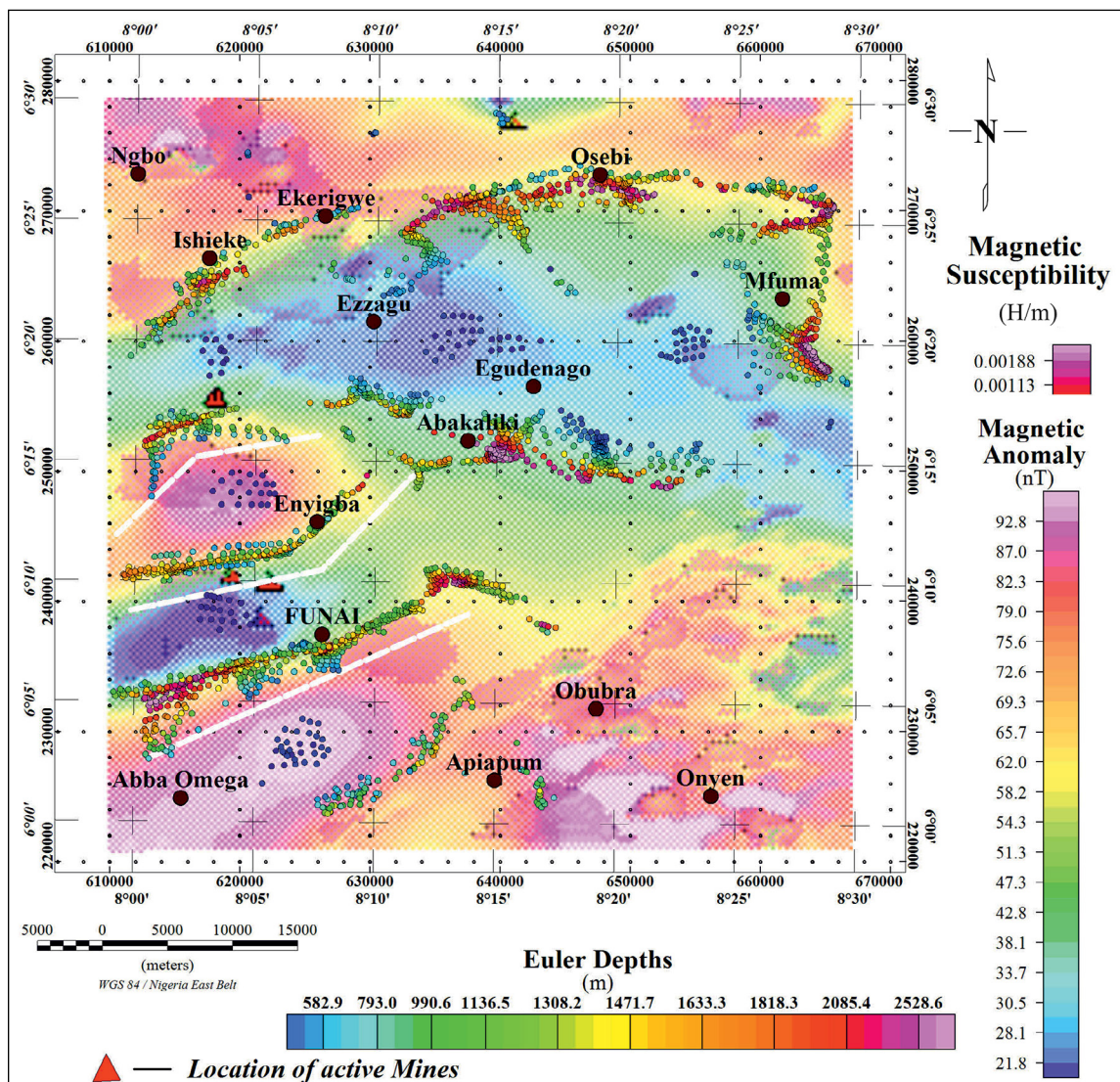


Figure 10- 3D Euler depths solutions overlain on the magnetic anomaly data (at 59% transparency) and 3D susceptibility model solutions.



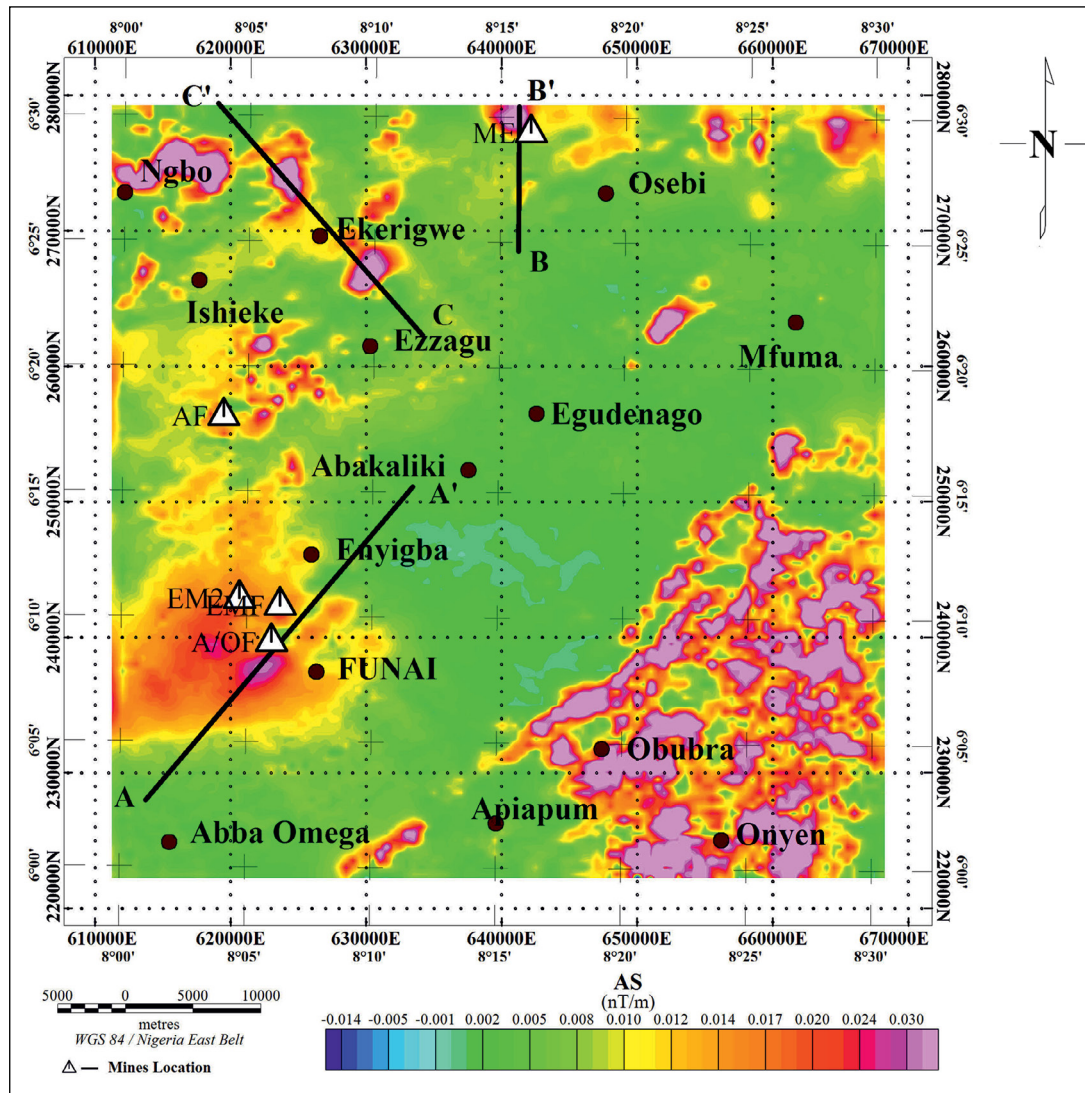


Figure 11- Analytic signal results of the study area. Various maxima observed on the map captures sources with strong magnetization contrast and provide information on their respective locations. Profiles  $AA'$ ,  $BB'$  and  $CC'$  are taken on suspected anomalies especially at current mining sites. These were inverted and analyze to derive the actual subsurface structures at these sites

Table 1- Profile parameters to include longitude, latitude, length and azimuth.

	Longitude (°)	Latitude (°)	Length (km)	Azimuth (°)
Profile AA'	8.02	6.04	104.60	49.81
	8.19	6.26		
Profile BB'	8.26	6.41	103.38	90.00
	8.26	6.51		
Profile CC'	8.20	6.35	23.24	138.81
	8.06	6.51		

The synthetic dyke model (Figure 12) was assigned a susceptibility of 0.005981 SI. The number of data points (101), profile length (100m), thickness (2m), depth to top of anomaly (4m) and depth to bottom (8m). 5% and 10% random noise was added to the

synthetic dataset and 2D analytic signal was computed from the noise corrupted synthetic anomalies using a frequency domain filtering undertaking as depicted by Agarwal and Srivastava (2008).

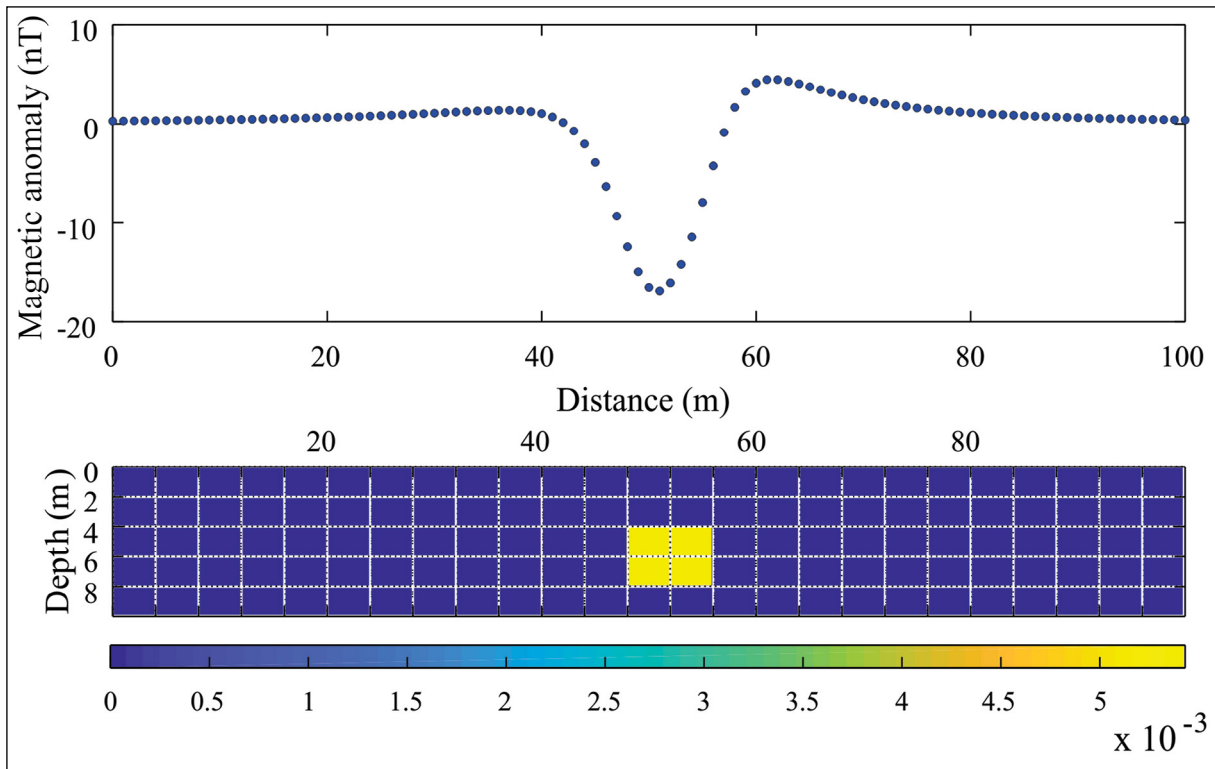


Figure 12- Synthetic anomaly with a dyke-like structure of 0.005982 magnetic susceptibility. Field intensity 33,000nT, inclination  $-10^\circ$ .

The PSO program was tested with parameters from the synthetic data before application to the anomaly profiles taken from our study region. Figure 13 shows a plot of the initial computation (at 0% noise data) and Table 2 displays model parameters reckoned from PSO for the single dyke structure with various noise percentages and the r.m.s. error. The computed amplitude of analytic (AS) of the synthetic magnetic

data is also shown on Figure 13. Model parameters were also computed with random noise addition of 5% and 10% successively.

We present the search spaces and computed/interpreted model parameters from PSO for profiles *AA'*, *BB'* and *CC'* on Tables 3, 4, and 5. Table 6 shows a comparison of interpreted model parameters from

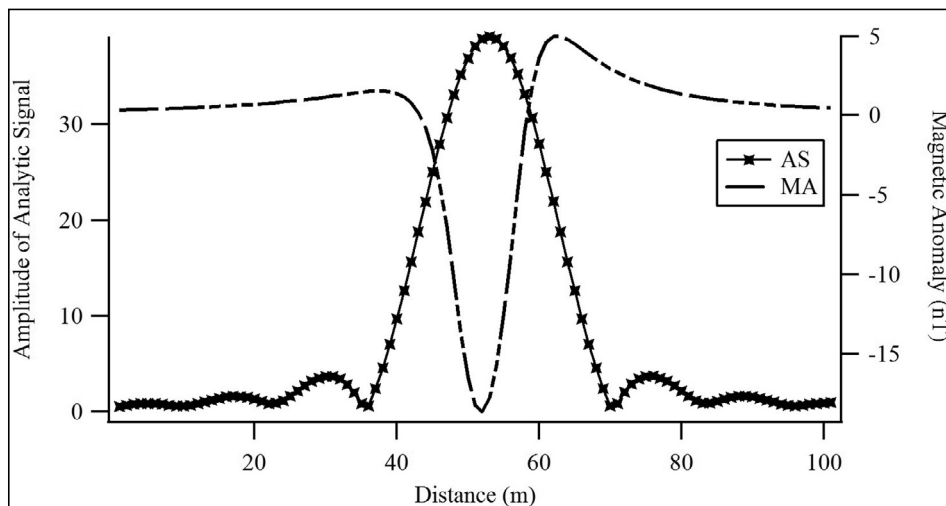


Figure 13- Synthetic Magnetic Anomaly data (0% noise) and its computed analytic signal.

Table 2- Model Parameters calculated from PSO for a single dyke with various noise percentages and their r.m.s. error.  $x_0$  and  $z_0$  are the coordinates of the source location in the unit of data spacing.

		Model space		Computed model parameters with random noise percentage		
	True model	Minimum	Maximum	0%	5%	10%
Amplitude	470	10	5000	490	515	520
$x_0$	55	10	100	56	56	58
$z_0$	4	1	12	4.5	4.5	4.8
$q$	1	0.2	1.5	1.0	1.0	0.9
rms Error				0.03	0.24	1.05

Data spacing = 1m

Table 3- Search space for profile  $AA'$  taken across a mine site within the region of study with computed PSO parameters.  $x_0$  and  $z_0$  are the coordinates of the source location in the unit of data spacing.

	Model space		Computed parameters from PSO
	Minimum	Maximum	
Amplitude	10	3000	355
$x_0$	1	20	12.5
$z_0$	0.1	10	1.8
$q$	0.2	1.5	0.9
r.m.s. error			0.1012

Data spacing = 0.5 km

Table 4- Search space for profile  $BB'$  taken across a mine site within the region of study with computed PSO parameters.  $x_0$  and  $z_0$  are the coordinate of the source location in the unit of data spacing.

	Model space		Computed parameters from PSO
	Minimum	Maximum	
Amplitude	10	5000	420
$x_0$	7	20	9
$z_0$	0.1	10	0.2
$q$	0.2	1.5	0.8
r.m.s. error			0.0682

Data spacing = 0.5 km

Table 5- Search space for profile  $CC'$  taken across two notable sources and the computed PSO parameters.  $x_0$  and  $z_0$  are the coordinates of the source location in the unit of data spacing.

Bell 1				Bell 2		
	Model space		Computed parameters	Model space		Computed parameters
	Minimum	Maximum		Minimum	Maximum	
Amplitude	10	5000	590	10	5000	1120
$x_0$	2	10	6	10	30	16.1
$z_0$	0.1	10	0.4	0.1	10	0.29
$q$	0.2	1.5	0.9	0.2	1.5	0.88
	r.m.s. error		0.1663			0.1882

Data spacing = 0.5 km

ELW and PSO computations for the respective profiles under consideration.

A plot of magnetic anomalies (MA), amplitude of analytic signal (AS) from measured magnetic anomalies and amplitude of analytic signal calculated by utilizing interpreted model parameters from profiles  $AA'$ ,  $BB'$  and  $CC'$  is shown in Figures 14, 15 and 16.

#### 4. Discussion

Tests on synthetic and field data (Pilkington, 2009) have shown that a more focused solution is produced from sparse inversion compared with a standard model – space, least-squares inversion. Our modeling results depicted in Figures 7 and 8 were realized from the modeling data of Figure 5. Figure 7 shows unit features embedded in the region. Various subsurface intrusions could be observed which contrasted with

Table 6- Interpreted model parameters from ELW and PSO modeling for profiles taken from the study region.

	Amplitude	Location (km)	Depth (km)	Structural Index
<b>Profile AA'</b>				
ELW	-	13.22	1.77	0.3
PSO	355	12.5	1.8	0.8
<b>Profile BB'</b>				
ELW	-	8.11	0.12	-0.35
PSO	420	9	0.2	0.8
<b>Profile CC' (S1)</b>				
ELW	-	5.28	0.38	0.85
PSO	590	6	0.4	0.9
<b>Profile CC' (S2)</b>				
ELW	-	15.34	0.27	1.02
PSO	1120	16.1	0.29	0.88

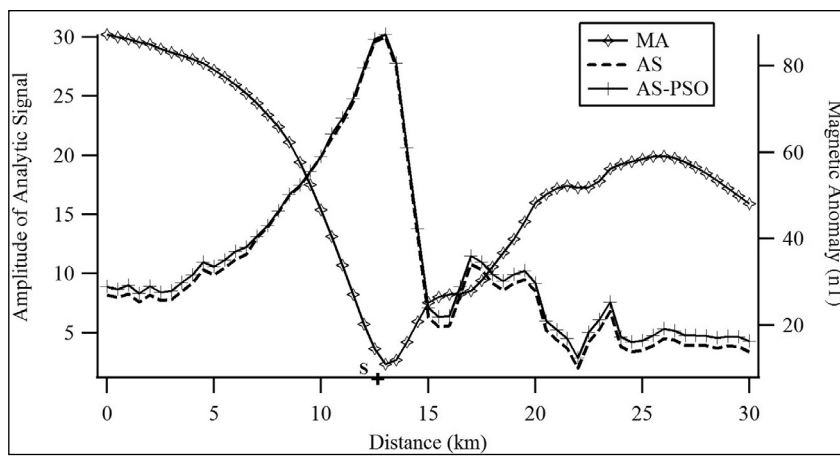


Figure 14- Magnetic anomaly (MA) over a source in profile *AA'* across the Enyigba mine site. AS, amplitude of 2D analytic signal from measured anomaly, AS-PSO, amplitude of analytic signal calculated by utilizing interpreted model parameters from PSO. The '+' sign indicate the horizontal position of the source.

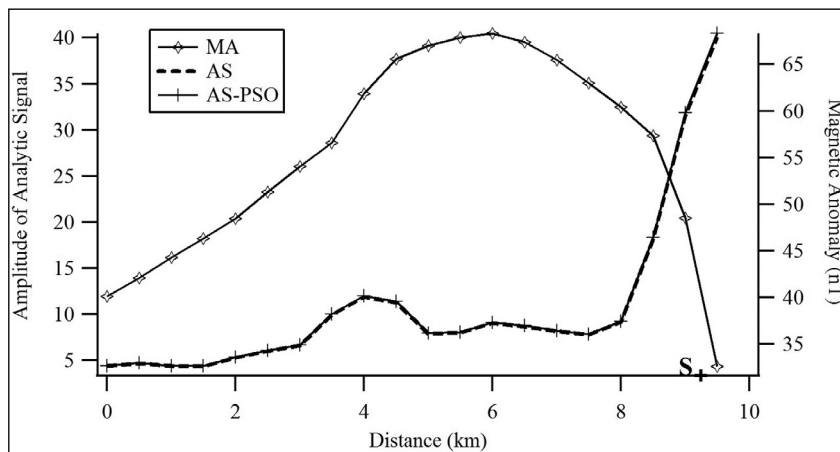


Figure 15- Magnetic anomaly (MA) over a source in profile *BB'* at Mkpuma-Ekwaokuko mine site. AS, amplitude of 2D analytic signal from measured anomaly, AS-PSO, amplitude of analytic signal calculated by utilizing interpreted model parameters from PSO. The '+' sign indicate the horizontal position of the source.



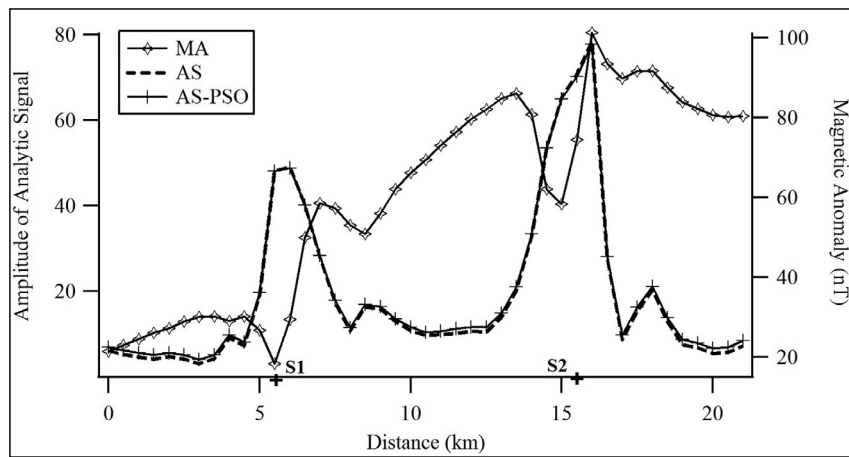


Figure 16- Magnetic anomaly (MA) over sources in profile CC'. AS, amplitude of 2D analytic signal from measured anomaly, AS-PSO, amplitude of analytic signal calculated by utilizing interpreted model parameters from PSO. The '+' sign indicates the horizontal position of the sources.

the background susceptibilities. We pegged the model susceptibility at 0.0005 SI due to the predominant background geology of the region (shale and sandstone with susceptibilities of 0.00065 and 0.0004 SI) (Dobrin and Savit, 1988; NGA, 2004) (Figure 7). We then clipped susceptibilities less than 0.00113 SI to bring out the contrasting bodies in the model.

Figure 8 displays various subsurface geologic features domiciled in the region. We interpret these features as geological units controlling mineralization in the region. To enable comparison and confirmation using the various locations of active mining activities in the region, we took a plan views of the modeled result (Figures 9 and 10). The model results capture most of the active mining locations in the region. The Enyigba mines location (Figure 9) indicates units with magnetic susceptibilities  $>0.00188$  SI. Some of the lower magnetic anomalies locates over high susceptibility units (as indicated within the drawn circles). The geometry of the resolved units (Figures 9) implies the union of magnetic anomaly with a metamorphic rock enveloped by the predominant shale formation in the region. The mining of rocks with lead-zinc (Pb-Zn) mineralization at Enyigba, ilmenite, and pyroclastic rocks at Abakaliki confirms this deduction. We also spotted an intrusion around Abba Omega that we identified as representing units bearing copper (Cu) or barite minerals (GSNA, 2004). Intrusions observed at Obubra are directly associated with traced volcanic

rocks mapped as basalts, trachytes, and rhyolites (Figure 2) and that of the surrounding areas of Obubra (Eja and Ogurude localities) has an imposing record of lead (Pb) ore deposits. The inversion result at Ngbo – Ekerigwe area shows a significant magnetic body connected with intense remnant magnetization. The dimensions of the magnetic mass are almost 3.5 km in-depth extension and 18 km stretch in the northern E – W direction (Ngbo – Ekerigwe). This magnetic body has great prospectivity importance because of its structural and positional emplacement and could contribute to the metallogenic as well as structural comprehension of mineralization in the Asu River formation. Further integration with other geophysical data from the area could provide more information regarding the association of these magnetic bodies and yet to be discovered minerals in the region. Our modeling study has shown even more possible geological units hosting economically viable mineral resources yet recorded within the study region, showing subsurface extensions and their possible boundaries.

The Euler deconvolution map (Figure 10) shows derived source positions represented as circles and depth information proportional to their respective colour representations. We achieved good clustering of the solutions and they show definite magnetic trends aligning in the E–W, NW–SE, and NE–SW directions within the study region. The dominant linear features

trending NE – SW (FUNAI, Enyigba, Ishieke and Apiapum regions) and E – W (Abakaliki and Osebi regions) directions show many clustering and could be interpreted as faults within the study region. The NE – SW trend corresponds to the orientation of the trend produced by the Santonian deformation which affected the Lower Benue Trough (Ezema et al., 2014). Epigenetic fractures striking E-W, NW-SE, and N-S generally host mineralization (lead-zinc-baryte) in an area (Ford, 1981; Omada and Ike, 1996; Oha and Onuoha, 2013). We observed similar trends of anomalies over Abakaliki–Ugep regions as Anyanwu and Mamah outo (2013) from their analysis of Landsat Thematic Mapper and airborne magnetic data. Magnetic edges – notable faults have been marked with good precision using a series of depth-labeled Euler trends (Pallero et al., 2015). The alignment of clusters from the 3D Euler solutions along the edges of contrasting magnetic intensities is also noted (Figure 10), with the structural contacts from Euler deconvolution aligning around the major solutions of the 3D model at the north-central region of the study area.

The analytic signal was evaluated to assess how well our modeling study matches the geological units in the region. We note that the model result agrees to some degree with obvious features realized from the analytic signal results (Figure 11). The AS assesses the amplitude of the gradient of magnetization; the closer we are to the magnetic sources, the higher the amplitude of that gradient. We observed that while the analytic signal computation was able to resolve the location of the present mines, the sparseness model could not resolve most of these anomalies. Nevertheless, the 3D model performed excellently in identifying deeper bodies (depths > 5000 m) with significant susceptibility contrast. Isolated and secluded maxima of the analytic signal results visible at the N-W, N-E and S-W regions of the study area were interpreted as stemming from subsurface intrusions at the respective locations. We observed matches of prominent anomaly features on the analytic signal map and the model solutions mainly with features located around the Ngbo, Ekerigwe, Mfuma, Obubra, and Onyen localities. The spread-out maximas notable at the S-E region could be due partly to some subsurface intrusions at the region, and also

to the shallow crustal deposition of gravels, basalt and trachytes within the Eze Aku Shale formation of that region (Ovat, 2015). Obande et al. (2014) adopted a similar interpretation approach in their study area with similar magnetization properties. We recall that Figure 2 showed the basaltic and rhyolitic intrusions at Obubra which may also influence the magnetic anomaly record for the region.

Analysis of the AS by PSO technique (Tables 3, 4 and 5) indicates that the structural index of the anomaly source identified from processing Profile AA' data (Figures 11 and 14) suggests the presence of an intruded dyke structure within the region. The index value from ELW computation (0.3) may also hint on a closed interaction of contact sources with the dyke structure at this location. This contact source interaction is clearly seen on the overlain magnetic anomaly data with the Euler and 3D model solutions (Figure 10). NE – SW trending geologic contact sources are mapped around the Enyigba – FUNAI region, sandwiching the Enyigba mine fields and also following the mapped out isolated region by the analytic signal results as seen in Figure 10. The present Pb-Zn mineral mining operations in the area is noted to extend vertically downwards in the open cast mining pits at this location and may confirm our dyke structure interpretation of the anomaly from this location. The extension of these anomalies within and around the Enyigba mine field (Figure 10) may also suggest capturing the edges of a sill structure around the region. Profile BB' was considered given the presence of the Mkpuma-Ekwaokuko mine field (ME) (Figures 5 and 11) and a notable maximum from the analytic signal at that location. This site is currently being exploited for Pb-Zn minerals by the locals. Examinations of the magnetic anomalies indicate similar magnetic features with the Enyigba mine field location. However, the limited data at the time of this study restricted the extent of our profile, therefore we located our profile from the center of the examined anomaly outwards (Figure 11). Table 4 shows model search space and computed parameters from PSO for profile BB'. A r.m.s. error of 0.0682 was also achieved from the computations. PSO computed a depth of 0.2 km at horizontal distance of 9.0 km for the location. Figure 15 shows a plot of the magnetic

anomaly over the source in profile *BB'*. Computations using the ELW technique presented a depth of 0.12 km at a horizontal distance of 8.11 km. The structural indices from the ELW and PSO techniques (Table 6) reveals an interaction of contact sources with the dyke structure within the subsurface at that location. The AS computed from Profile *CC'* data exhibits two peaks of significantly different amplitudes (Figures 11 and 16). In the absence of drill hole information at this location, the AS computation has clearly revealed the presence of the two distinct sources along this profile. Our inversion of the AS involved fitting two bells corresponding to the two peaks observed. Table 5 presents the model parameter search spaces and the realized computed parameters from PSO for both bells (Profile *CC'*). The r.m.s. error is also shown. The peaks analyzed in these results may indicate causative sources located at S1 and S2 to be vertical dyke structures separated by approximately 3 km. The structural indices from the ELW and PSO computations (Table 6) confirm that the causative sources are vertical dyke structures intruded at the location.

## 5. Conclusion

We have performed a 3D magnetic inversion modeling of geologic units representing mineralization structures in Abakaliki and environs. The 3D inversion results aligned with the analytic signal solution calculated from the same anomaly data. This region in the southeastern zone of Nigeria is known to host vast mineral deposits of economic significance. Good clustering of the Euler deconvolution solutions were obtained for the region and revealed definite magnetic trends aligning in the E–W, NW–SE, and NE–SW directions. The dominant linear features trending NE – SW around the Enyigba mine fields have been noted to play an active role in the mineralization of the region. The contact sources interact with the dyke structure identified in the region using analytic signal technique and a global optimization technique (PSO). In general, PSO results are comparable to those achieved by the ELW technique and indicate stability of solutions and reliability of results. Several other subsurface geologic units which possibly represent mineralization structures in the region have been recognized. Inversion of both magnetic anomaly

and analytical signal has enabled derivation of the actual subsurface structures in the region with most of the structures appearing as dykes with depths ranging from 0.2 – 1.8 km at most of the mining sites in the region. Structural indices computed for the region have also indicated interaction of contact sources (faults and fractures) with identified dyke structures. This study has confirmed most of the sites currently being excavated for these minerals and also show potential sites whose locations were hitherto unknown which could also be considered for further exploration. Results have contributed to the knowledge base of geologic units representative of the mineralization structures in southeastern Nigeria. Quantitative analysis provided by this study would enable informed geotechnical engineering decisions especially at potential mining sites.

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