

RESEARCH ARTICLE

APPLICATION OF GROUND MAGNETIC METHOD FOR DELINEATION SUBSURFACE STRUCTURAL CONTROL ON SULPHIDE ORE DEPOSIT IN BENUE TROUGH; A CASE STUDY OF IKENYI IZZI

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ABSTRACT

The sulphide ore mineralization occurrence in the area is structurally controlled. However, wrong structural delineation has led to some recorded mine failures and revenue loss faced by investors and government. Therefore, subsurface structural mapping is crucial for the successful and reliable delineation of sulphide ore enrichment zone within the area. To this effect ground magnetic method was used to appraise the structural elements associated with the sulphide mineralization in Ikenyi IZZI area, part of Southern Benue Trough. The total magnetic field intensity (TMI) was recorded, corrected, and separated into regional and residual magnetic fields. The TMI varies from 33259.7–33329.7nT with an average field value of 33299.4nT. Whereas residual susceptibility value ranges from -36.3–25.7nT with significant magnetic closures which correspond to the areas of low and high susceptibility values. Three dominant structural geometries was identified in the area; NE-SW>NW-SE>N-S with few E-W structures. The NE-SW and some N-S structures characterized areas of high magnetic anomaly closures and are associated with the regional trends of the igneous intrusive rocks, whereas NW-SE structures host the ore deposit (Trending $\geq N300^\circ$) and dominantly associated with areas of low magnetic anomaly zones. The cross-cutting relationship of the NE-SW, N-S and NW-SE structures infers a close association of the intrusions and mineralization, which was validated by ground truthing. The residual susceptibility values of 1 to 10nT and $\geq 10nT$ were inferred as shale and intrusive rocks respectively. The implication of this study denotes that missing appropriate structural elements delineation could lead to abortive mines target.

KEYWORDS

Magnetic Anomalies, Subsurface structures, Igneous intrusions, Exploration, Sulphide Ore, Benue Trough

1. INTRODUCTION

Structural delineations are critical for successful mineral exploration, especially in areas deformed by several geodynamic processes such as that of Benue Trough (BT) in Nigeria. Structural delineation became significant in the area as many of the base metals mineralization patterns in the area is structurally controlled following the series of recorded tectono-magmatic events in the past across the trough. The Southern Benue Trough (SBT) hosts large lead-zinc lodes, However, its exploration has faced the critical challenge of delineating the structural control of the ore mineralization pattern. To overcome this challenge, ground magnetic method was employed in the structural delineation of the ore deposits. The ground magnetic method (GMS) is a dependable geophysical method for delineating mineral ore deposits (Gunn, and Dentith, 1997; Oha, et al., 2016; Adebisi, 2018; Offor, et al., 2022). As the geomagnetic field variations are often diagnostic in different rocks, and minerals; subsurface structures and minerals could be characterized based on their susceptibility. Magnetic method has proven useful in mineral exploration as a tool to detect ore-hosting structures and sediment thickness (depth to the anomaly sources), and also serves as a reconnaissance tool for basin modelling in hydrocarbon exploration (Essa et al., 2018; Telford et al., 1990; Kearey, 2002 Lowrie, 2007). The study area covers Ikenyi IZZI.

Geologically, it is part of the Southern Benue Trough, and the Asu River Group (ARG) underlain the area. The study area has latitudinal and longitudinal extent of $06^\circ 12' 30'' N$ to $06^\circ 17' 30'' N$ and $08^\circ 05' 30'' E$ to $08^\circ 17' 00'' E$ respectively. Southern Benue Trough host a significant quantity of lead-zinc lodes within the sedimentary deposit of the Asu River Group (ARG), which has been mapped to extend beyond 600 km from Ishiagu to the Gombe area (Farrington, 1952; Olade, 1975; Olade, 1980; Olade, and Morton, 1985; Orazulike, 1994; Oha et al., 2017; Offor, et al., 2020).

Contemporary development and improvement in software data processing and analysis accentuate GMS beyond the traditional mapping of magnetic minerals to the estimation and determination of the geometry of causative magnetic anomalous bodies at the subsurface for better inferring tectono-magmatic related mineral deposits (Chukwu and Obiora, 2018; Adejuwon, et al., 2021; Wang, et al., 2012; Wang, et al., 2015). The basin morphology, ore geometry, depth, width, shape, dip, lithologic boundaries, amplitude ratio, salt domes as well as position of the anomaly has been quantitatively and qualitatively defined by the application of one or more of the following filters on magnetic data; analytic signal vertical derivative, source parameter imaging, reduction to equator or pole, Werner and/or Euler deconvolutions, second moving average residual anomalies, combining deconvolution technique and

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simplex algorithm, gradients of the magnetic anomaly, upward/downward continuation, ant colony optimization, singular value decomposition, differential evolution algorithm and global nonlinear optimization (Ekinci et al., 2016; Balkaya et al., 2017; Biswas and Sharma, 2016; Debeglia and Corpel, 1997; Thurston and Smith, 1997; Milligan and Gunn, 1997; Adebayo, 1986; Jain, 1976; Adebayo, 1986; Reid et al., 1990; Abdelrahman and Essa, 2015; Abdelrahman et al., 2016; Tlas and Asfahani, 2015; Cooper, 2012; Abedi et al., 2013; Srivastava et al., 2014; Eshaghzadeh and Kalantary, 2016).

However, many rocks and minerals are non-magnetic such that their magnetic property is generally small in correspondence to the magnetic minerals in them, hence hard to delineate using magnetic survey (Telford, 1990; Kearey, 2002; Abdelrahman, 2015; Abo-Ezz and Essa, 2016; Essa and Elhussien, 2018; Arinze et al., 2019; Elem et al., 2022; Elem and Anakwuba, 2022). But all rock units have at least some infinitesimal degree of magnetization which may not be detectable with the magnetometer, this made the use of the magnetic method relatively hard (Offor, 2022; Gunn, P.J., 1997). Nevertheless, the method remained a useful tool for subsurface characterization, for example, aeromagnetic data was used to map the igneous intrusive in Southern Benue Trough and also applied in delineating linear structures through horizontal and first vertical derivatives enhancement technique extending it to the determination of the intrusions origin by applying spectral analysis filtering (Oha et al., 2016; Musa et al., 2021). Magnetic method has been extensively applied in sulphide ore mineral exploration (Offor, 2022; Adejuwon et al., 2021; Arinze et al., 2019; Salati et al., 2008; Okonkwo and Ezech, 2012; Obasi, et al., 2020; Martínez, et al., 2019). Though, the aeromagnetic approach performed poorly and hence relatively irrelevant for mapping micro shallow structures that is hosting ore loads in the study area, because the approach defines regional structures better and performs poorly in capturing local microstructures that host the deposit within the area (Adejuwon et al., 2021; Thurston and Smith, 1997; Luyendyk, 1997; Horsfall, 1997). This could be observed in the works of earlier researchers that adopted the aeromagnetic study approach (Oha et al., 2016; Offor et al., 2022; Adejuwon et al., 2021; Musa et al., 2021; Salati et al., 2008; Lawal et al., 2021). Also, works that used an aeromagnetic approach within the trough only documented anomalies sources from depths ≥ 300 m, a depth that is not benefiting for the exploration of ore minerals controlled by localized structures (Osazuwa et al., 1981; Ajakaiye et al., 1986; Ofoegbu, 1985; Ofoegbu and Onuoha, 1991; Nur, 2000; Onyedim, 2006; Obi et al., 2010; Lawal et al., 2021). This depth (≥ 300 m) is relatively undependent in the exploration of lead-zinc deposits within the Benue trough; since the depth of occurrence of the Pb-Zn deposit in the area is shallow and the deposits are hosted by microstructures rather than regional structures. The depth of the deposit in the area previously defined to 30 and 50 m for shallow and deep deposits respectively (Adejuwon et al., 2021).

The ground magnetic method is a reliable method for capturing local anomalies, especially when integrated with the induced polarization (IP) method. However, the use of GMS has attracted little or no interest in sulphide ore exploration in the area except the recent studies that recently applied the method, but they were unable to properly correlate their findings to target prioritization for lead-zinc exploration purposes (Offor, 2022; Adejuwon, 2021; Elem and Anakwuba, 2022). Although the magnetic method as a standalone geophysical approach cannot be used to confirm the presence or absence of lead-zinc deposit in the area, because of the non-magnetic nature of the ore deposit. However, the method remains a background concept for a meaningful Pb-Zn exploration program in the area due to its application in structural delineation capabilities. From this study, a measurable percentage of mine failure and economic waste faced by miners in connection to abortive mines are integral effects of wrong target definition at long structural elements. The paper emphasized the need to along the integrate ground magnetic method with intensive field measurements from geological mapping and electrical geophysical methods usually employ in delineating the structural elements associated with mineralized lodes. This approach (GMS) is one of the sure ways of minimizing investor's risk exposures and exploration errors in defining mineralized zones and target prioritization in the area. There is also a need to expand the application of GMS, as a reliable and effective tool in detecting structural patterns which will guide integrated resistivity and chargeability imaging profiles.

2. TECTONIC/MAGMATIC EVENTS IN THE AREA

There are many documentaries about the tectono- magmatic events within Benue Trough, which gave rise to the formation of the trough and sequent emplacement of igneous intrusive rocks, and structures that host the sulphide ore in the area (Oha et al., 2016; Lawal et al., 2021; Benkhelil, 1989; Obiora and Umeji, 2004; Obiora and Charan, 2010; Obiora and

Charan, 2011; Oha, 2014). The SBT has been characterized as part of the massive Central and West African Rift system (Chukwu and Obiora, 2021). The origin was linked to the crustal stretching of the African Plate which was contemporaneous to the opening of the equatorial and South Atlantic Ocean during the Jurassic–Early Cretaceous (Chukwu and Obiora, 2018; Chukwu and Obiora, 2021; Coulon et al., 1996; Fairhead and Binks, 1991; Maluski et al., 1995; Nwajide, 2013; Popoff, 1990). The mechanism of the triple junction rifting is the integration of mantle plume, crustal stretching and thinning, block faulting, and igneous activities (Olade, 1975; Bott, 1976; Chukwu and Obiora, 2014). This made the characterization of the trough a bit complex hence raising several models about the origin/formation of the trough, which has resulted in descriptive and understanding ambiguity about the processes of the Trough formation. The most related events and models attributed to formation of the trough include; mantle plume, block faulting, thinning, stretching, and emplacement of igneous intrusions within the lithosphere (Olade, 1975; Obiora and Charan, 2010; Bott, 1976; Fairhead and Okereke, 1986; Benkhelil, 1986). Large-scale wrenching leading to the formation of pull-apart basins is one of the most discussed geneses of BT formation (Benkhelil, 1989). Others proposed that rifting gave rise to tensional movement hence the formation of the Trough and that faulting resulted in graben and horst as the genesis of the Gulf of Guinea has been related to Cretaceous sediments (Chukwu and Obiora, 2021; Chukwu and Obiora, 2014; Cratchley and Jones, 1965; Kings, 1950; Stoneley, 1966).

However, magmatic/tectonic events in the SBT have been discussed under three folds of geodynamics in the area (Chukwu and Obiora, 2021; Coulon et al., 1996). Cenomanian tectonic, Santonian epeirogeny, and Tertiary events generated a series of fractures and emplacement mafic to intermediate intrusive rocks accompanied by hydrothermal fluid within the BT. The tectonic settings also initiated the alteration of genetic characteristics of the marine transgressive Albian deposit, with the first tectonic phase assigned Aptian – Santonian, and Albian – Santonian (Short and Stauble, 1967; Murat, 1970). This led to the brittle deformation creating secondary structures (fractures, folds, and faults) following stress and strain complexities, deforming the earlier sedimentary succession of the Trough. The Cretaceous sedimentary rocks became folded during the orogeny forming the Abakaliki anticlinorium and creating NW-SE faults and fractures which plunged southeast wards resulting in the younger formations overstepping the older beds (Oha, 2017). However, the fracture-filled materials are associated with pre or post-Santonian events cross-cutting the Albian deposit (Oha, 2016; Oha, 2017; Arinze, 2019).

The second tectonic phase (Santonian – Maastrichtian) led to the down-faulting of the former Anambra platform to form the inland basin (Anambra Basin) and the down warping in the Afikpo area creating Afikpo Syncline (synclinorium) (Oha, 2017; Nwajide, 2013; Amajor, 1985). This coincides with the structural deformation of the Abakaliki-Benue Trough, hence generating other sets of secondary structures on earlier deposited sediment of the Trough. Relatively, the third tectonic phase occurred towards the end of the Eocene giving rise to the Niger Delta Basin, as well as tertiary intrusive rocks in the eastern part of the anticlinorium (Afikpo Sub-basin) (Short and Stauble, 1967). These thermo-tectonic settings created structures for the mineralization of Pb-Zn ores in the area as structurally controlled by Santonian tectonism (Benkhelil, 1989; Wright, 1968). The magmatic evolutions within the Trough contributed as a key control of the precipitated base metals (Pb-Zn) mineralization, which filled some of the fractures (veins) in the area. Lead-zinc deposits are localized in Cretaceous sediments along a 600 km long belt within the Benue Trough, a sediment-filled intracratonic basin extending from Ishiagu (South of Abakaliki) north eastwards to Gombe (Oha, 2016; Farrington, 1952; Oha, 2017; Olade, 1980; Olade, 1976). The created structural complexities together with the sporadic occurrence of igneous intrusions and sulphide ore (base metal) mineralization have created vicious research interest amongst the geoscience community mostly as it relates to lead-zinc occurrence due to its economic potential.

2.1 Regional Stratigraphic Setting

The Trough tectonic uplift and magmatic events influence the sedimentation in the area, from an 'abandoned' rift basin or failed rift (aulacogen) during the Early Cretaceous resulting in the subsidence and accumulation of about 5,000 m of sedimentary and volcanic rocks (Olade, 1975; Olade, and Morton, 1985; Grant, 1978). The sedimentary fill of the SBT was controlled by marine transgressions and extensive deltaic sediments with thin layers of fine clastics regression cycles and several local tectonics characterizing carbonaceous shale deposition (Nwajide, 2013; Oha et al., 2021; Nworie et al., 2021). The study area is part of the Asu River Group (AGR) within SBT which represents the first marine transgression and oldest sedimentary deposit in Nigeria's sedimentary

basins, unconformably overlying the Precambrian rocks (Nwajide, 2013; Reyment, 1965; Obaje, 2009; Petters and Ekweozor, 1982; Okoro et al., 2016). The Abakaliki Formation of ARG is dominated by poorly bedded carbonaceous shale (figure. 1a and b) and subordinate alternating lenses of sandstones, siltstones, mudstones, limestone, volcanoclastic rocks, and several igneous intrusive rocks (figure. 2a and b) (Nwajide, 2013; Reyment, 1965). The general sequence of this formation from the oldest to the youngest units has been described (Umeji, 2000). The basal component of the group is sandstone-siltstone with inconsistent bands of limestone which is overlain by limestone alternating with siltstone-shale units (Oha, 2021; Umeji, 2000). Around the Ogoja-Abakaliki area, the sediment of the group was divided into Middle Albian sandy unit and Late Albian Abakaliki Shale, deposited in the environment ranging from hyposaline to marginal hypersaline lagoon (Nwajide, 2013; Oha et al., 2021; Umeji, 2000; Nwajide and Reijers, 1996; Ojoh, 1992). This sediment underwent minor folding during Cenomanian and a more major one during the Santonian accompanied by igneous intrusions (Simpson,

1954).

These Albian sediments are unconformably overlaid by the Turonian Eze Aka Group (EAG) on the east and western flanks of the Abakaliki Anticlinorium dominated by sandstone and limestone respectively. The Turonian deposit is bounded above by Santonian unconformity and below by Middle Cenomanian Unconformity (Okoro et al., 2016; Igwe, 2015). Lithofacies of the EAG comprises fossiliferous calcareous marine shale, limestone, siltstone, and sandstone, with the sandstone and limestone occasionally alternating with the calcareous shales (Oha, 2017; Nwajide, 2013; Reyment, 1965; Okoro et al., 2016). The sediment of this age has been mapped throughout the entire Benue Trough where it continued from Cenomanian into Turonian without a break in the stratigraphic sequence (Oha et al., 2017; Ojoh, 1992). The intervening Coniacian regression deposited the Awgu Formation within the Trough, which overlies the Turonian Eze-Aku Formation at the western flank of Abakaliki Anticlinorium (Petters, 1978).

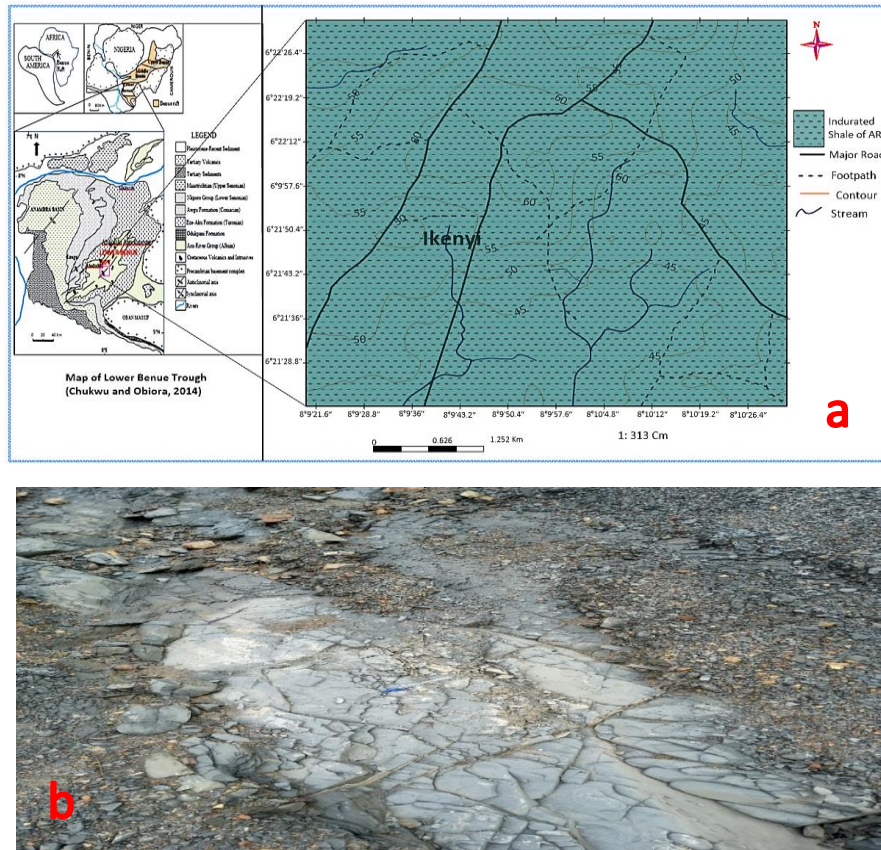


Figure 1: (a)Geology map of Ikenyi area covered by magnetic data acquisition, (b) Dark-gray baked shale of Abakaliki Formation

This transgressive phase was abruptly terminated by the Santonian tectonic episode, which resulted in the folding, faulting, and fracturing of the earlier deposited sediments hence part of the genesis of structural deformation, metallogenesis, and emplacement of igneous intrusions that characterized the Trough (Hoque and Nwajide, 1985; Murat, 1972). The

subsequent transgression and regression events deposited the Nkporo Group, unconformably overlying the folded pre-Santonian sediments consisting of marine mudstone/shales and fluvial-deltaic sand packages (Nwajide and Reijers, 1996; Murat, 1972; Odunze, 2013).

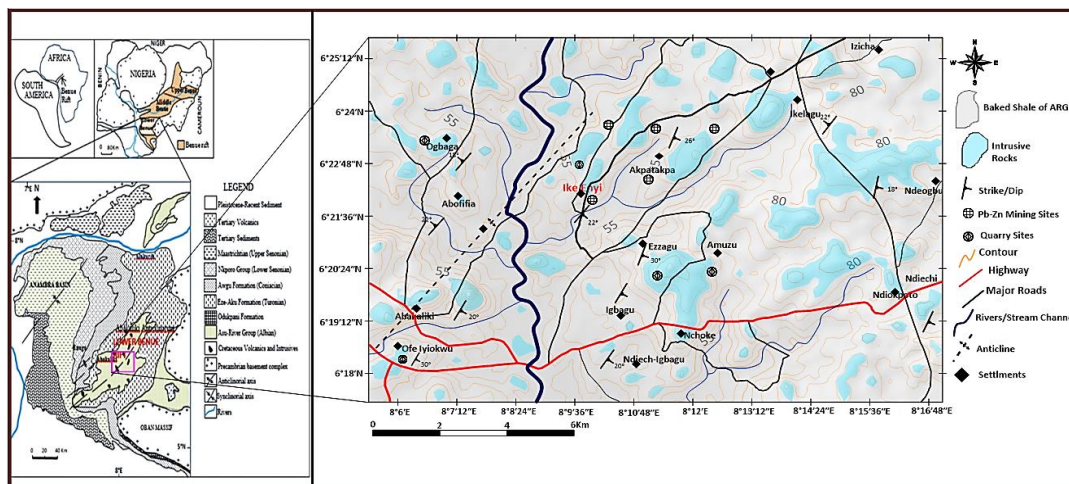


Figure 2a: Expanded geological map of Ikenyi and its adjoining areas

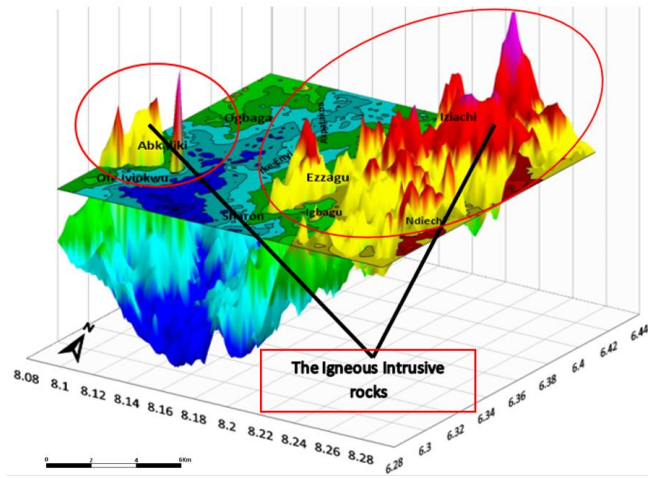


Figure 2b: The geospatial map delineating the trend of the igneous intrusion within the study area

3. MATERIALS AND METHOD

Ground magnetic field intensity was measured using a portable GEM-19 v7.0 Overhauser instrument, produced by GEM systems in Canada. The instrument has two basic components, a stationary magnetic recording machine at the base, and the rover which was moved from one point to another recording readings. It has an in-built Global Positioning System (GPS). The magnetic survey covered an area of about square 2 km with an inter-line profile spacing grid of 100 m (20 profile lines) covering the area in east-west trending profiles. The magnetometer was set to take a reading per second along the profile line. The base station was fixed outside the survey area (grided area) around the relatively middle of the grided survey area at a distance of about 50 m from the data acquisition area. The rover was moved around the survey area following the pre-determined interline grided lines. The magnetometer in-built GPS contemporaneously with recording field intensity recorded the coordinates of each measurement station, hence at least three different reading was recorded at each point. Every metal, magnetic object and electronic gadget, and related item that can cause a spike in the reading was removed from the survey area to avoid introducing noise into the measured values.

A diurnal correction was carried out between the based station reading and that of the rover. The resultant corrected data was downloaded into the computer for processing. The line-to-line errors were removed through decorrugation or micro leveling methods using cosine directional and butterworth filters. The second-order polynomial filtering (eq.1) was used to separate TMI into regional and residual fields from TMI (Indrawati, 2020). The geometry of geologic structures was achieved through modelling of the corrected data using Geosoft (Oasis montaj), afterward, the processed data were quantitatively and qualitatively interpreted; upon which inference was drawn based on the spectral band, magnetic susceptibility, anomaly signature, sources, shapes, and geology.

$$g_i = C_1 + C_2x_i + C_3y_i + C_4x_iy_i + C_5x_i^2 + C_6y_i^2 \quad (\text{Eq.1})$$

Where g_i = magnetic anomaly, $i = 1, 2, 3, \dots, n$; x_i and y_i = coordinates, C_1, \dots, C_6 are polynomial constants.

Data enhancement and subsurface inspection of the area were delineated through the application of various filtering approaches such as; the first vertical derivative (FVD), horizontal derivative, and analytic signal (ANSIG). These filters redefined the behaviour of the anomalies and visualization of shallow structures and edge enhancement of the anomalous causative structures/bodies. From these, inferences were drawn on both the geology and structural deformations of the area. This operation allowed each anomaly band to have different inclinations and declination and thus greater accuracy (Grauch et al., 2004). This improved data visualization and anomaly isolation, the filter approach very useful in structural identification, though this may cause little instability in the data against the actual trend of the anomalies (Musa et al., 2021; Cyril, 2019; Lu et al., 2003; Adewumi, and Salako, 2017; Nabighian, 1984.

3.1 Vertical Derivative (VD)

The First Vertical derivative (FVD) is one of the filtering approaches for enhancing signals arising from shallow geologic structures (short wavelength). Field magnetic measurement was recorded as the earth's

magnetic field intensity, visualization in the horizontal and vertical directions were achievable through this processing. The operation sharpens structures/anomalies hence reducing anomaly complexity for brighter imaging of the causative structure (Oha, 2016; Adewumi and Salako, 2017). The VD is usually applied on TMI which enhances and sharpens the anomalies over bodies and tends to reduce anomaly complexity for clearer imaging of a causing structure, as today it has become a basic necessity in magnetic data interpretation and can be calculated using Eq.2 (Thurston and Smith, 1997; Oha, 2016; Adewumi and Salako, 2017; Nabighian, 1984).

$$FVD = \frac{\delta M}{\delta z} \quad (\text{Eq.2})$$

M = magnetic field intensity.

3.2 Analytic Signal (ANSIG)

The analytic signal filter was used to sharpen the anomaly edges and enable its visualization at peaks of the anomaly sources. This filter simplifies the anomalous bodies clearer by applying the principle that every magnetic source has positive and negative peaks associated with it, which in many cases tend to mask the actual location such that it becomes difficult to determine the exact location of the causative body (Debeglia and Corpel, 1997; Adewumi and Salako, 2017; Nabighian, 1984; Geosoft Inc., OASIS Montaj Version 7.0., 1996; Nabighian, 1972). The mathematical expression for the calculation of ANSIG anomaly amplitude is given in Eq.3 (Debeglia and Corpel, 1997).

$$|A(x,y)| = \sqrt{\left(\frac{\delta M}{\delta x}\right)^2 + \left(\frac{\delta M}{\delta y}\right)^2 + \left(\frac{\delta M}{\delta z}\right)^2} \quad (\text{Eq.3})$$

M = magnetic field

4. RESULTS AND DISCUSSION

Visual inspection of the total magnetic field intensity (TMI) map of the area, presents a relatively complex magnetic susceptibility anomaly pattern comprising short and relatively long wavelengths (figure 3). The anomalies' amplitude variations suggested corresponding magnetic field intensities variations resulting from various causative anomaly sources (Telford, 1990; Adelusi et al., 2014; Adelusi et al., 2013). The TMI of the study area has high and relatively high magnetic susceptibility values around the southern and northern parts of the area respectively (figure 3), which sporadically extend to the central portion of the area. The central portion was dominated by moderate susceptibility except for the few portions with low and high susceptibility trending NE - SW and NW-SE. The susceptibility values range from 33104.7 to 33338.9 nT with an average of 33283 nT. The high anomalies (susceptibility) trends NE- SW, corresponding to the defined trend of regional structures in Southern Benue Trough which is an opposite of the low susceptibility value observed at Mkpuma-Ekwaoku (Adejuwon et al., 2021; Chukwu and Obiora, 2018; Adejuwon et al., 2021; Arinze et al., 2019). The alignment of the low susceptibility zone at the center abruptly terminates towards the northern and southern portions of the area (figure. 3).

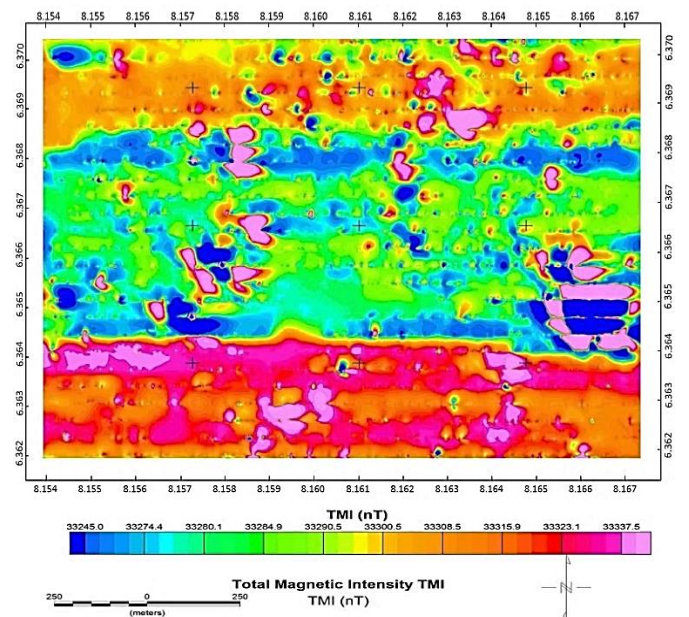


Figure 3: Total magnetic field intensity map of the area

The peak of high amplitude susceptibility is dominant at the southern central portion and there is an alignment of highest susceptibility anomalies in NE-SW. A trending that corresponds to the regional trend of igneous intrusive rocks around the study area (Chukwu and Obiora, 2018; Chukwu and Obiora, 2014). The low amplitude anomalies trend relatively N to S and NW – SE around the northeastern part whereas moderate amplitudes dominated the centre and northern portion of the mapped area. The separation of residual field intensity from the TMI produced regional field revealed occurrence of high susceptibility

in the southern, moderate in the northern region, and low to moderate susceptibility towards the center portion of the mapped area (figure. 4a). The susceptibility value ranges from 33259.661 to 33329.668 nT with an average field value of 33299.353 nT. The absence of recognizable anomaly signatures on the regional map (figure. 4a) and its resurgence on the residual map (figure. 4b) of the area suggested that the causative factor/body of the anomaly is localized and shallow rather than being a regional body.

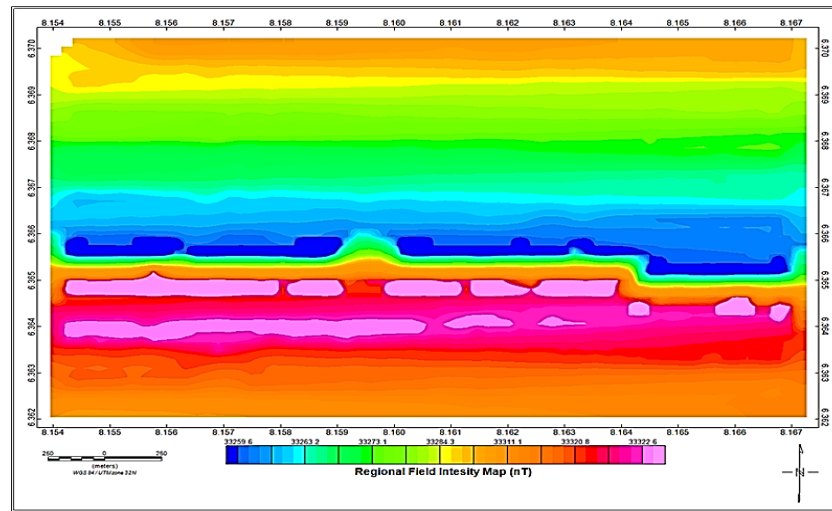


Figure 4a: Regional Field Magnetic Intensity Map of the Study Area.

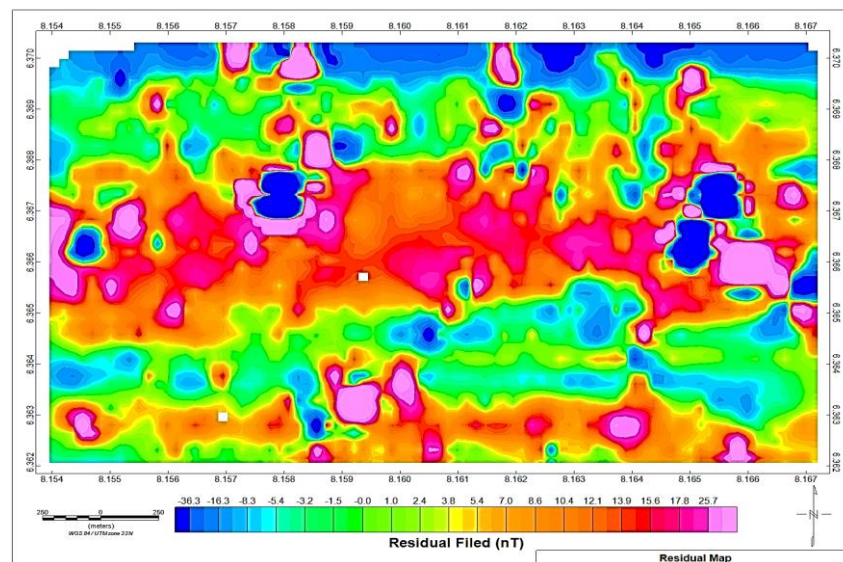


Figure 4b: Residual field magnetic anomaly map of the area

The regional map of the area indicated susceptibility value range of about 33259 to 33329 nT. The colour band is a function of susceptibility to regional field intensity indicating five layers with high magnetic intensity characterizing the southern portion, the low intensity at the central portion, and a bed with moderate susceptibility dominating the northern portion of the study area in terms of regional field anomaly (figure. 4a). The high magnetic field anomaly signals at the southern portion of the area result from deep-seated sources rather than shallow structures. This is evident in the TMI and regional anomaly map of the area but weakly represented in the residual anomaly map which defined the source to be more regional body/source than localized (figure. 3, 4a and 4b).

The residual magnetic susceptibility field (figure. 4b) shows more detailed information about the shallow subsurface structures across the area, unlike TMI and regional fields. The central and southwards portion has a bed with higher residual magnetic signatures, occurring like a conduit running E – W. There are defined contour closures aligned in NE – SW (dominantly), fewer N – S and NW – SE closures within this bed (figure. 5a). The trend of magnetic closures corresponds to the high elevation regions in the digital elevation map (DEM) of the area with high elevation values (figure. 5b), interpolating with structural lineaments map and outcrop joints and fracture azimuths depict similar trend (figure. 6a).

The structural model/lineament of the area indicated three basic structural trends in the area N – S, NE – SW, and NW – SE (figure. 5 and 6) which occur sporadically and correspond to the structural trend dominant in the Southern Benue Trough. This multi-faceted structural trend diversity characterizing the area is an indication of several episodes of geodynamics. The structure pattern (NW-SE) at eastern portion of the study area corresponds to the adjudged host structures for lead-zinc mineralization in Benue Trough (Emedo, 2022). The NW – SE were crosscut by N – S and NE – SW structures at the eastern portion (figure. 6a). Overlaying of the structural lineaments (figure. 6a) on the residual magnetic field anomaly map (figure. 6b) revealed the cross-cutting structures occurred around the low and high susceptibility zone, which result from materials of different magnetic character. These structural cross-cutting relationship (figure. 6) were supportive to trend of active and abandoned mining fields, the azimuths of surface geologic structures (fractures and quartz veins) (figure. 7) in and around the area. Also, for all the active mines visited, the host structures trends $\geq 300^\circ\text{N}$ and some N – S trends (figure. 7a). This could be used for selecting an area of further geophysical survey (like 2D electric resistivity tomography (ERT) and Induced polarization (IP)) in the area in sulphide ore exploration target prioritization.

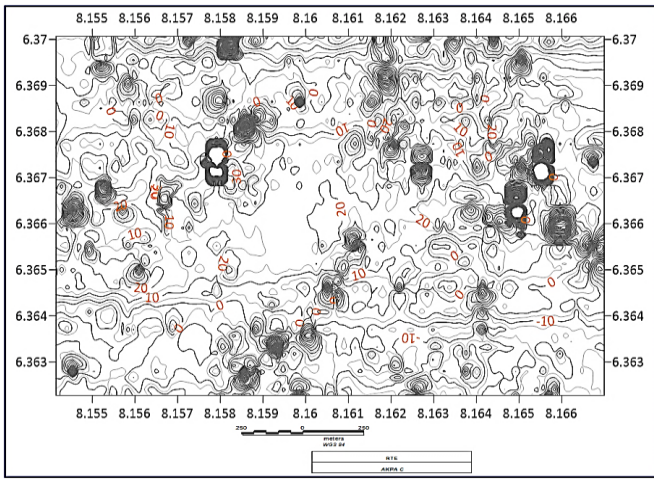


Figure 5a: Residual magnetic anomaly contour map of the study area

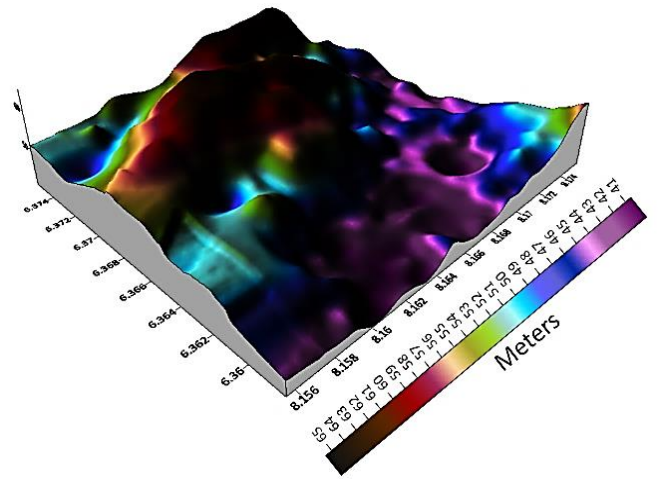


Figure 5b: Digital elevation model of the study area

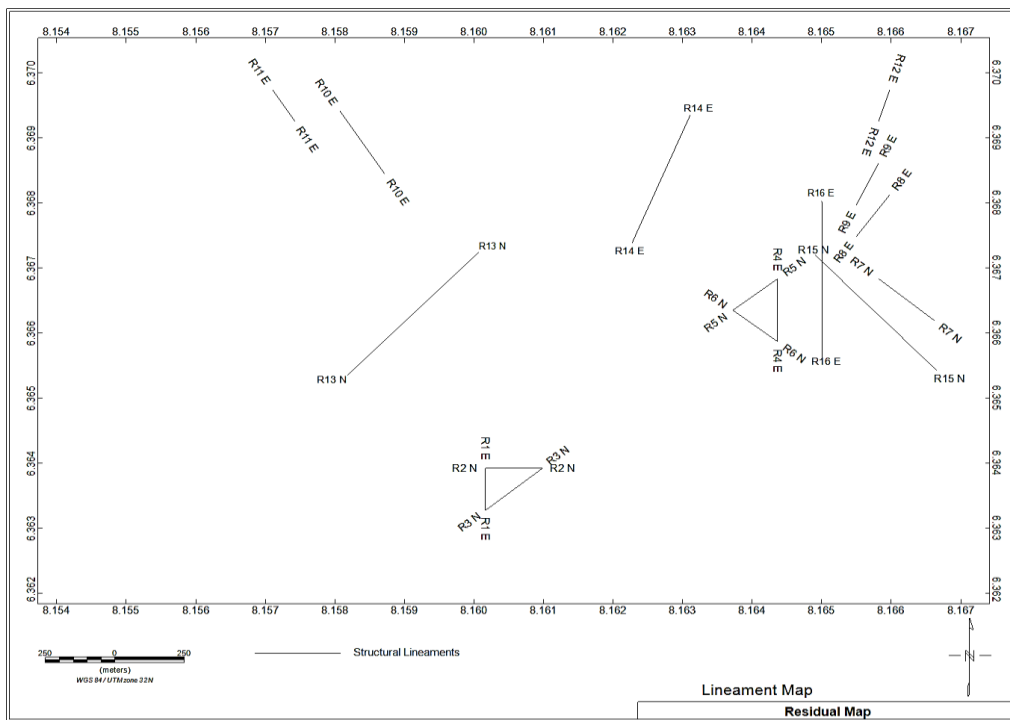


Figure 6a: Lineament Map of Some Shallow Structures in the Area.

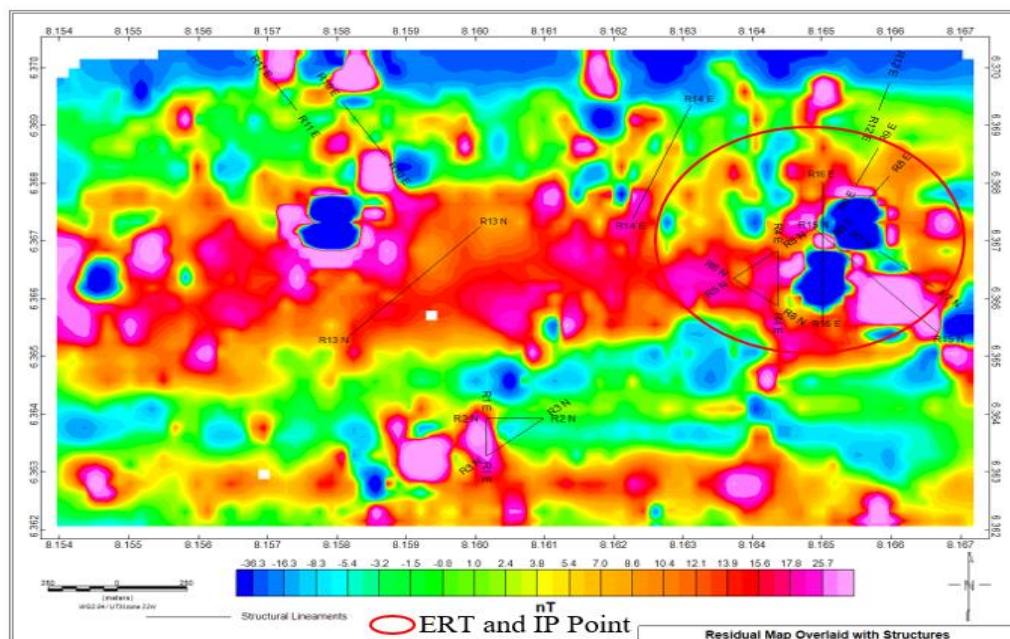


Figure 6b: Residual Field Anomaly map overlaid with Lineament Map

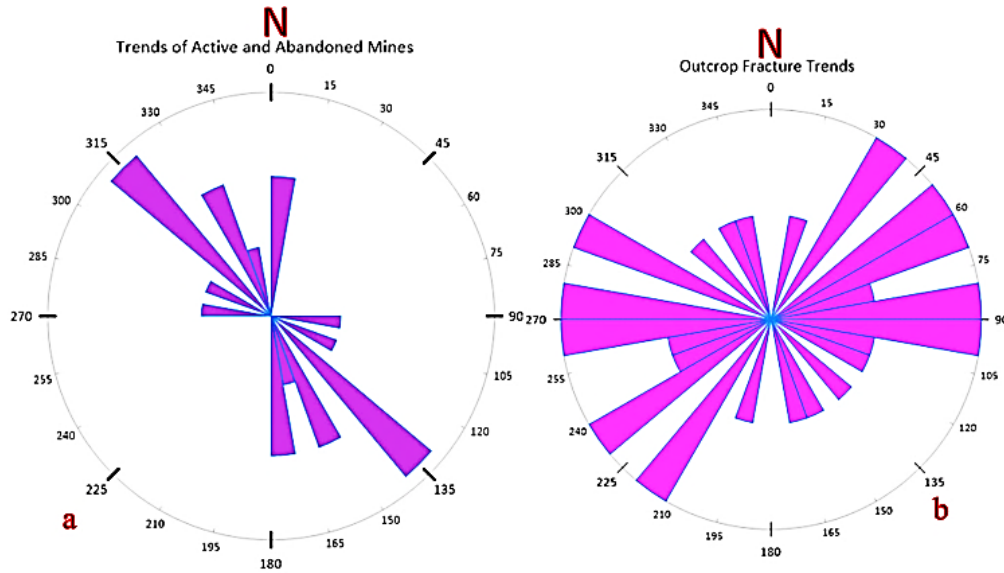


Figure 7: Rose diagram of structural azimuths (a) Mineralized fractures at mining fields (b) Fractures on outcrops; dominantly trending NE -SW profile line & NW – SE.

Application of FVD and HD enabled visualization and interpretation of the subsurface structures (fractures) in the vertical and horizontal directions (figure. 8a and 8b). These combined the relationship in susceptibility variation of vertical and horizontal directions, and created a shading image of the anomaly body and structure, through such marked the extent of the structures (figure. 8c). The FVD magnetic vector provides additional information about the directional variations of the whole magnetic field of the area (Nelson, 1998). It exposed the anomaly texture and emphasizes anomaly pattern discontinuities in the area, providing a significant guide map of linear structures in the study area (NE-SW), delivering an advanced resolution and accuracy at wider line spacing (Christensen and Dransfield, 2002).

The structural lineaments and their boundaries within the sedimentary sequence were clearly defined through edge sharpening (figure. 8). These orientations represent the stress patterns that accompanied the magmatism in the area which gave rise to brittle deformation as seen on outcrops in the area (figure. 1). The FVD subsurface structures trends were in agreement with the rose plot of outcrop mapped structures in the area and the trends azimuth of the active and abounded mine fields visited around the area (figure. 7).

The ANSIG closures indicated short wavelength (Shallow structures) anomalies (figure. 8c) which have a similar pattern revealed by FVD and HD with those of outcrop data, a similar observation has been made at other parts of Benue Trough . Figure 8c gave a relatively isolated view of each of the structural elements in the area.

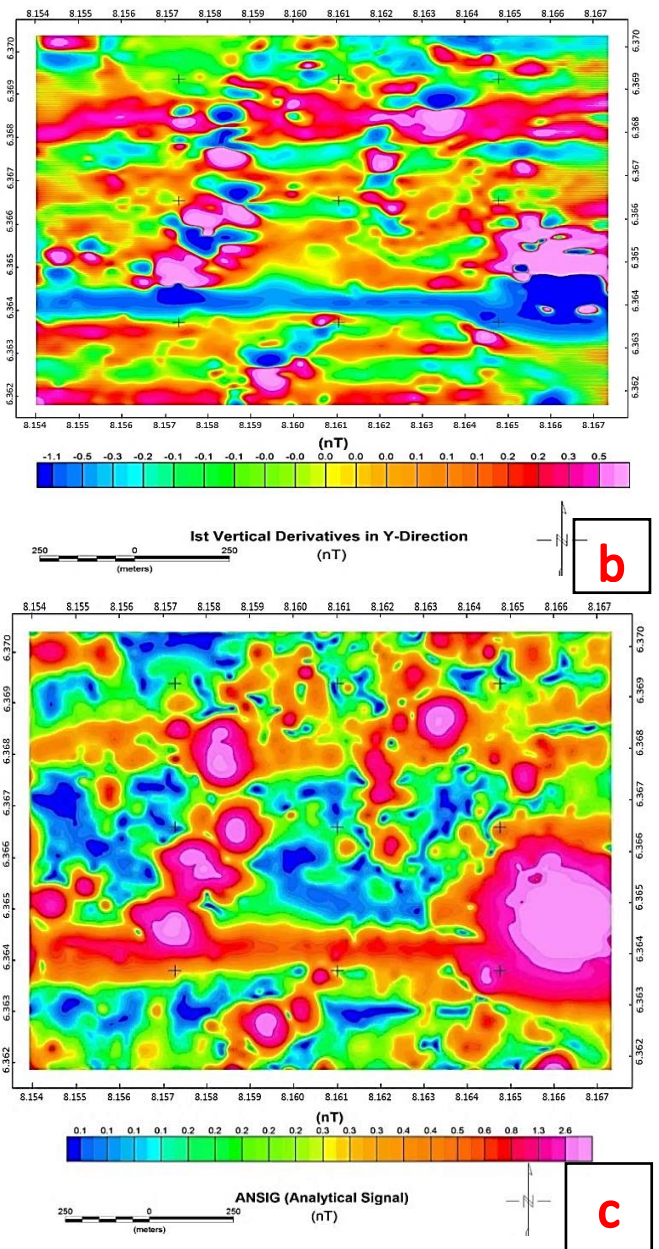
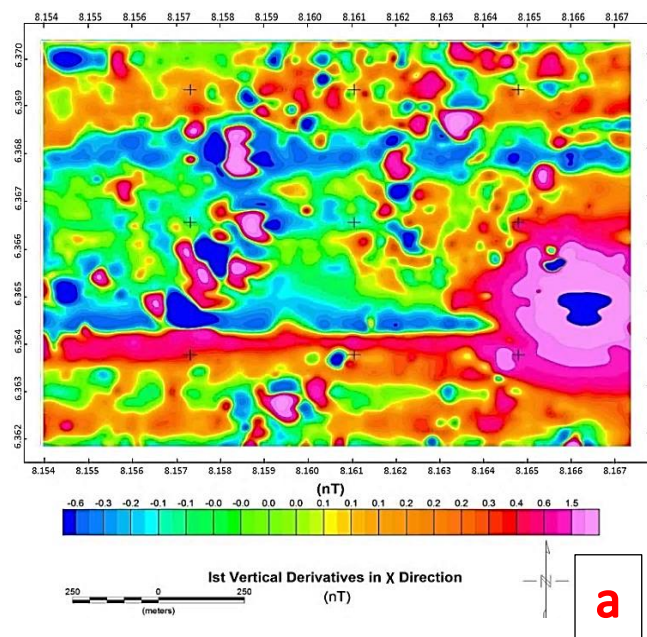


Figure 8(a): First vertical derivative in x – Direction, (b): First Vertical Derivative in Y – Direction, and (c): Analytic Signal Map of the Study Area.

The relative uniformity of the spectral band shown by FVD inferred that the area has relatively uniform sub-surface lithology; but with lots of shallow microstructures around the centre portion which trends dominantly, NE – SW, and NW- SE at an angle very close to N as signified by anomalies alignment (figure. 7 and 8a). The western portion has structures with low magnetic susceptibility unlike the NE part which is dominated by high to moderate signals, SW structures trend NE-SW with very few structures trending north, the displacement of this spectral band towards the southern and northern portion are indicative of bedding plane characterized by the material of slightly different magnetic character (figure. 8a and 8b). The ANSIG map presented three basic pieces of information, high amplitude areas (igneous intrusions), moderate amplitude ratio (indurated ARG shale), and low amplitude anomalies (possibly mineralized structures) which are less prominent in the area (figure. 8c). The sensitiveness of ANSIG towards anomaly sources, and structural and magnetization direction accentuated the edge delineation of the anomaly bodies, which it makes easier to directly delineate the subsurface anomalous causative source (Nabighian, 1972; Rao et al., 1981; Salem et al., 2005; Doo et al., 2007; Roest et al., 1992). The circular and/or elliptic high magnetic anomalies closures are associated with igneous intrusion processes (figure. 8). The adjacent low susceptibility delineates the juxtaposition of structural elements in the eastern part (figure. 6 and 8). These circular and elliptical anomalies may result from the emplacement of shallow igneous intrusions in form of boulders, producing structural closures revealed in the magnetic anomalies map (figure. 5, 6 and 8) (Reeckman et al., 1984).

Generally, ANSIG maps by extension serve as a lineament map being precise about the structures and lithologies distributions, defining the orientation of the structures in the area (figure. 8a-c). The high anomaly signals around the southeastern portion of Figure. 8, suggest a shallow seated volcanoclastic rock (pyroclastic) that was outcropping massively at Ezzagu the adjoining area of Ikenyi (See figure. 2). Previously, the magnetic peaks in the Abakaliki area have been defined to be associated with past magmatic events in the area which led to the emplacement of pyroclastic and other intrusive rocks in the area, high susceptibility values were traced to the pyroclastic and intrusive rocks in the area.

4.1 The 3D modelling of the Magnetic Field

This model aided in inferring definitive structure targets for minerals and has also inferred areas to carry out ERT and IP in the area targets in line with the appropriate structural trend(s). It further enhances understanding of the study area's regional geologic setting, modelling of sulphide ore-forming structural controls, metallogenesis, and important extraction of features representing criteria for selecting exploration and exploitation targets (figure. 9 and 10). The 3D spatial analysis buffer extraction ore body geometry along controlling structures and created the subsurface position of the mineralized structures inferring the location of the deposit in the area (figure. 9). The inverse distance weightage revealed that the eastern anomaly source in the area is shallower and more extensive (in terms of NW-SE subsurface structural elements) compare to the western anomaly (weightage is a function of $1/d$), which defined major two inferred mineralized portions in the area.

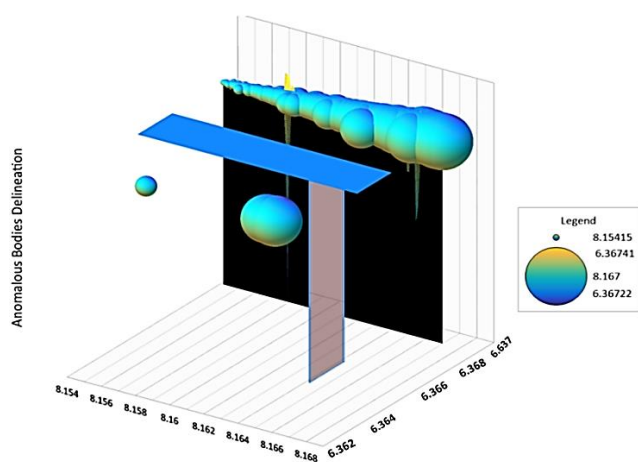


Figure 9: 3D Inverse Distance Weighting (IDW) Model of Mineralization from Residual Magnetic Field

Linking its deposit, the eastern portion of the area have a better reserve, more reliable and prolific in terms of reserve sustenance (figure. 9 and 10), it is also shallower and hence will be more economical for recovery. For the intrusive rocks, the 3D defined the shapes and orientation at the

point of occurrence recognizable by the peak (figure. 10a, b and c). The distance between the two main inferred ore hosting structures and the adjoining intrusive rock was calculated using the statistical tool kit of the Geosoft giving a distance of about 177.8 m and 976.7 m between the eastern peak anomalies and eastern to western peak anomalies in the area (x and y) respectively (figure. 10b). Composite evaluation of the 2D ANSIG and the enhanced 3D models defined clearly the shapes of the anomaly causative bodies giving insight of their sources and emplacement pattern as boulders within the sedimentary sequence, as the product of geological processes in the area (see regional geology description in section 2.0).

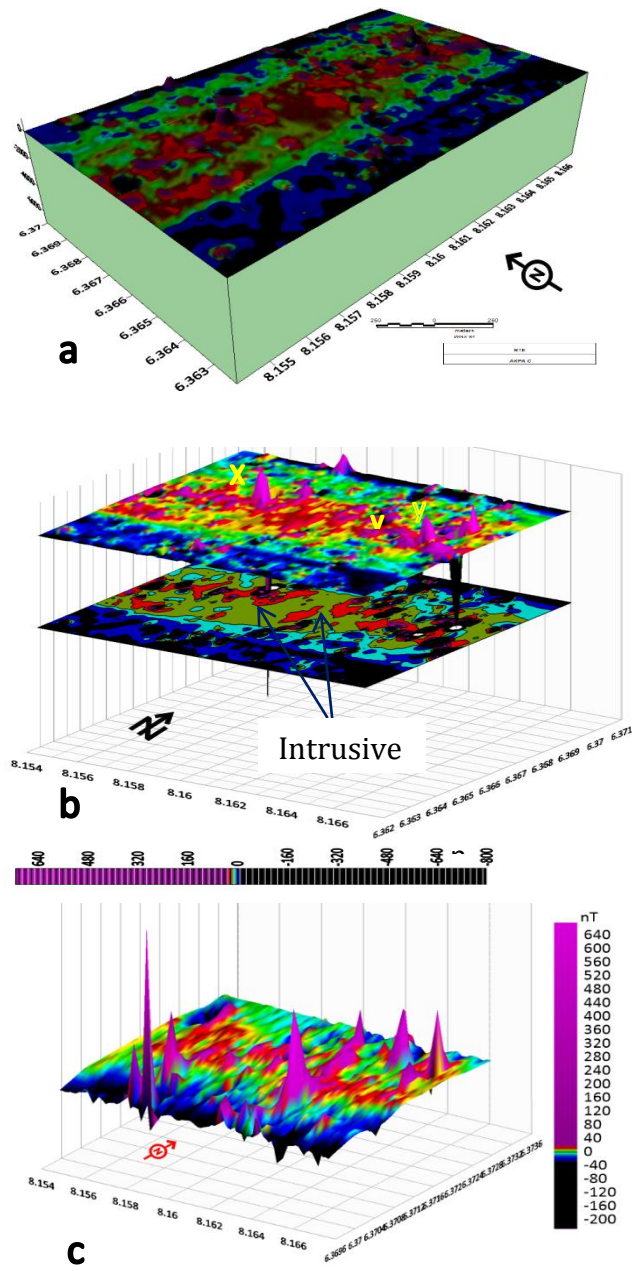


Figure 10: 3D Enhancement of the Analytic Signal of the magnetic field

The moderate susceptibility (0 to 10 nT) at the center stratum (figure. 8 and 10) differing from low susceptibility strata in N and S regions of the study area, is an indication of an induced magnetic field arising from the associated intrusive rocks (which was more of magmatic processes) within the sedimentary sequence. This correlatively guides the definition of targets for minerals and has also defined exploiting area targets in line with the appropriate structural trend(s) delineation. It further enhances understanding of the study area's regional geology setting, modelling of sulphide ore-forming structural controls, metallogenesis, and importantly extraction of features representing criteria for selecting exploration and exploitation targets (figure. 6, 9, and 10). The 3D spatial analysis buffer extracts delineation of possible ore body geometry along controlling structures, revealing the subsurface position of the deposit at the area (figure. 9). For the intrusions the 3D defined the orientation at the point of occurrence recognizable by the peak (figure. 10c). Application

of 3D approach in Molybdenum surface target prediction ore mineralized zones was possible, though acknowledged that the models cannot eliminate all the uncertainty in geological modelling and targeting of the subsurface mineral deposits and structures, but the error of estimation reserve/resource (as an index of uncertainty) between the exploration targets and the new exploitation targets can be calculated in a 3D environment. This can aid the estimation of the bulk volume reserve of the deposit (Wang and Huang, 2012).

4.2 Determination of depth to Anomalies Source

Depth to the anomaly source in the area was achieved by applying Peter's half slope method in potential field interpretation (figure. 11), which is based on the rule of thumb. He applied this mathematical expression in defining depth to the anomaly source of the vertical dyke noting that the distance of half the maximum slope (X) is approximately equal to 1.6 h; where h represents depth to the anomaly source. However, for X = 2.0 h and 1.2 h for bodies having large width ratio and small width ratio respectively (Ojo et al.,2014; Peters, 1949; Rao and Ram Babu, 1984; Mudge, 1994). Hence the depth $h = X/1.2$ (1.2 is the index value for small-width bodies). Eight profile lines were used to appraise the anomaly depth. Depth to causative magnetic anomaly sources in the area ranges from 14.25 to 96.59 m with an average of 44.27 m (Table 1). The depth value of 30 and 50 m for shallow and deeper ore bodies respectively at the adjoining Nkpuma-Ekwoku area has been inferred. These depth values indicate that the anomaly sources result from shallow sources, have short wavelengths, and are sporadically distributed in the area (figure. 10) against deep source defined by aeromagnetic survey in the area.

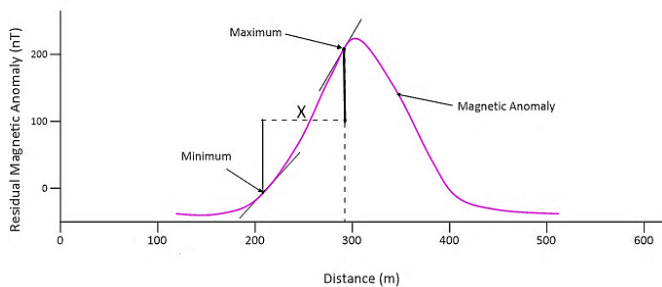


Figure 11: Peter's half-slope anomaly depth determination approach (modified after (Adegoke and Layade, 2014).

Table 1: Estimate depth of magnetic Anomalies Causative Sources	
Profile Lines	Depths (m) to Anomaly Sources along each profile line
1	96.59
2	57.97, 64.77, 15.15
3	70.70, 30.30, 25.25
4	17.81, 62.32, 14.25
5	47.22
6	65.79, 17.54
7 (8)	28.85, 54.49
8 (9)	48.65, 34.93

4.3 Igneous Intrusive Rocks, Structures, and Mineralization Relationship

The fractures on the outcrops, structures delineated from GMS, field trends of the ore veins, and 3D geometry of the subsurface ore body defined structural complexes in the area. The orientation of the igneous intrusions aligned themselves in the direction of the dominant deformative forces that characterized ARG arising from the past geodynamics; which enables the sporadic occurrence of the Pb-Zn mineralization in the area and their structural controls. The pattern of igneous intrusions can be informative about the structural morphologies and dissemination of magnetic minerals within a sedimentary basin. The dissemination of lead-zinc ore, and its associated minerals like pyrrhotite, pyrites, and also intrusions (in form of boulders) explained low, moderate, and high magnetic anomalies with the observed structural style in the eastern part of Figure. 6b and 10b. Pyrrhotite and ilmenites disseminated in shale could spike significant magnetic anomalies, but the anomaly may be weak at times (Mudge, 1994). Usually, relative to the horizontal magnetic sheet like in a bed of uniform magnetic characteristics, there exists structural relief that spikes magnetic anomalies, and more intense anomalies usually result from igneous intrusions as horizontal sheets can only give rise to anomalies at their edges.

From the residual magnetic field overlaid by the shallow structure lineaments within the study area, the cross-cutting of the mineralized structures (NW-SE) by the NE-SW structures indicated a close association with the genesis of igneous intrusions and the ore deposit within the carbonaceous shale of SBT. The field relationship of sulphide mineralized vein with the host rocks (figure. 12, 13, and 14) indicated them younger than the host rocks, having been introduced along fractures, a similar relationship portrayed by some igneous intrusions mapped within the area and those at mapped Ishiagu (Isabella, 2020). Though the NE - SW structural trend has been linked to lead-zinc mineralization at the EPL A40 mine filed at Ishiagu (Okonkwo and Eze, 2012), such could not be established in this work. However, the active and abandoned minefield visited have structures trending NNW - SSE, and N-S (usually ≥ 300 N, figure. 7). Around some active and abandoned mining fields in Mkpuma-Akpatakpa and Mkpuma Ekwaoku the igneous intrusion was found outcroppings like boulders about 300 to 800m from the mining pits (figure. 12) which corresponds to the high magnetic closure observed in residual and ANSIGN maps of the area.

The dominance of NW - SE structures indicated by the structural maps (figure. 6 and 10) suggested that the ore hosting structures were contemporaneous with the emplacement of the igneous intrusive rocks in the Trough, controlled by the operational geodynamics and prevailing force field at the period (tensional tectonic deformation of Cenomanian). The crosscutting relationship existing between the mineralized veins and intrusive rocks in the area establishes that some of the intrusive rocks are older than the deposit. In re-appraisal of the genesis of Ishiagu lead-zinc ore deposits, lead-zinc deposit was mapped in between dolerite sill at Greenfield mine 04 (figure. 14) (Isabella, 2020). Having not yet identified any mappable NE - SW structures hosting the ore deposit, it implies that the Aptian - Cenomanian magmatic vent may not be associated with the main mineralization phase outside possible structural creation. These shallow structural elements (joints and fractures) initiated by the Cenomanian-Santonian magmatic events in the Benue Trough are the main control of the base metal deposits in the area (Mbah et al., 2018). Hence the Santonian magmatic event has been adjudged the source that brought the ore deposition in the area. This conclusion was drawn from the absence of Pb-Zn mineral within post Santonian deposit characterized by tertiary intrusive rocks as well as their crosscutting relationship of ore veins and some intrusion rocks in some areas within the pre-santonian sediments. Clay cake, quartz, and sideritic crystals are strong pathfinders for Pb-Zn exploration which mostly occur in association along the NW-SE (figure. 12 and 13).

However, the restriction of Pb-Zn deposit to two fractures trending in NW-SE and N-S directions is suggestive of two mineralization episodes for the structurally controlled ore deposit and the deposit being an open space filling (Emedo et al., 2022; Ezepue and Dunham, 1983; Fatoye et al., 2014; Obarezi and Nwosu, 2013).



Figure 12: Field Photographs of Ore Veins and Intrusion (a) Indurated shale with quartz veins, Mining Field in Mkpuma-Akpatakpa (b) Mining Field at Mkpuma-Ekwoku, (c) Igneous Intrusive < 300 m from Pb-Zn Site (d) Old cored sample of Igneous Intrusive at (e) Pb-Zn veins trending NW-SE and N-S at Akpatakpa.

In line with local and regional geologic events of the area, the host structural architect/trend of the sulphide ore and intrusions, simplifies the understanding and subsurface visualization, effectively presenting possible co-occurrence of these bodies which is suggestive of having related origin and possibly the same source, but this awaits evaluation of the ore and intrusion using fluid inclusion studies and isotopic data. The Santonian tectonic events resulted in the refolding of the shale with contemporaneous emplacement of igneous intrusions, their thermal interactions usually resulted in the lead-zinc mineralization basically along the igneous intrusions mobile belt (Nwachukwu, 1972; Orajaka, 1965). Field evidence of the co-occurrence of the diorite sill and the lead-zinc ore body has been previously mapped in some parts of Benue Trough (Isabella, 2020; Okezie, 1957).

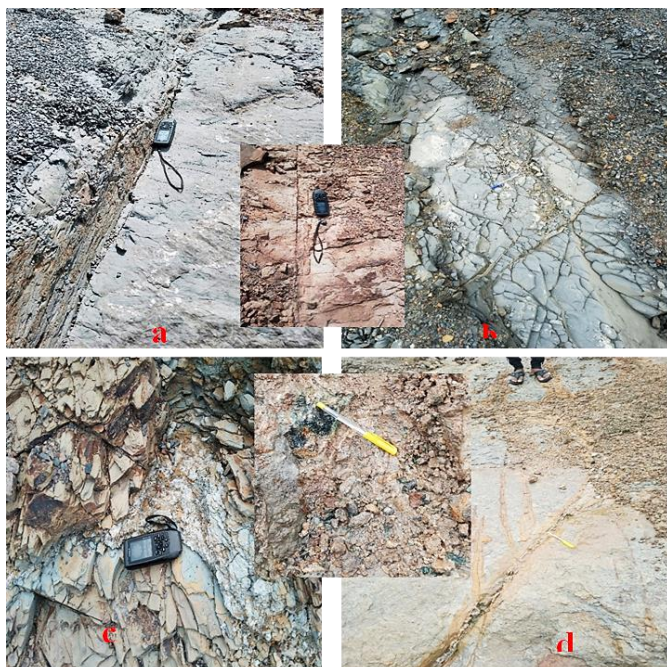


Figure 13: Field Photographs of Fractures resulting from a thermo-magmatic event associated with Pb-Zn deposit at different sites visited, the yellow pen shows Pb-Zn ore filling the fractures (a) mining field at Mukpuma-Akpatata, (b and c) Mining from Mkpuma-Ekwaoku, (d) Quartz veins at long the trend host Pb-Zn deposit at one of the Mining fields.



Figure 14: A Sulphide vein (Red arrow) within the Dolerite Sill Ore at Greenfield Mine 4 Ishiagu (Picture was taken by Isabella (Isabella, 2020)).

The occurrence of clay cake, and veinlets (Sulphide ore and Quartz veins) are structurally inclined relative to the existence of mineralized veins in the area with respect to the heat emanating from mineralized veins (figure. 13), or the proximity of igneous intrusions. This could be evidence of thermal-related events (magmatism) attributed to the origin of lead-zinc ore. At Mkpuma Ekaoku in IZZI the dolerite sill was found < 500 m from the Pb-Zn vein occurring as boulders in the direction cross-cutting the mineralized veins (figure. 12).

5. CONCLUSION

The NW-SE ($\geq 300^\circ$ N) are the structures to search for during lead-zinc exploration in the area, mostly when they have low magnetic

susceptibility value. The structure in some locations maybe cross-cut by either N-S or NE-SW structures. Since the lead-zinc deposit in Benue Trough is structurally controlled, the right subsurface structural definition will account for 50% success of the base metal exploration in the area. However, magnetic method as a single geophysical approach cannot be used to prove the presence or otherwise of a lead-zinc deposit in an area, but very instrumental in structural analysis and deposit inference. A reliable lead-zinc exploration in the Benue Trough requires the integration of electrical geophysical methods and ground magnetic methods. A doubt on the ore productive structures is a minus in target definition even when using the conductive characteristics of the subsurface to infer presence of mineralized zone may still equate to mine failure without proper structural tie. The observed relatively proximity in emplacement of the intrusive rocks and some crosscutting of the intrusive rocks by lead-zinc bearing veins suggest a possible geogenic relationship between the intrusive rocks and the ore veins in the area.

Conflict of interest: The authors have no competing interest.

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