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TRANSFORMING THE GEOMAGNETIC TRANSFER FUNCTION OF VLF-EM TO CURRENT DENSITY FOR ISHIAGU Pb-Zn DEPOSITS, EBONYI STATE

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Abstract
The economic value of mineral deposits today calls for more interest in geophysical exploration over the Ishiagu area of Abakaliki Basin, Nigeria to delineate the Pb-Zn mineralization in the sedimentary bedrock. Recorded as VLF-EM anomalies are the in-phase and quadrature components of the geomagnetic transfer function, tipper due to induction and these reflect the conductivity contrast between the Pb-Zn mineralized veins and the host rock. Results of sharp tipper responses due to strong EM induction were detected in the surveyed area and on the average, the deeper sources responses range from 4.7% to 7.6%, while the shallower sources responses range from 8.8% to 17.1%. Interpretation with the recorded tipper responses was noted to be of much misfit to the dimensionality, trends and geometry of the Pb-Zn mineralization in view at the nearby existing mines. As a geoelectrical conductivity technique, the efficacy and high resolution of the work is revealed by the 2D current density transformation of the tipper responses. Dimensionality analysis of the current density maps bares these prospective Pb-Zn mineralized veins to trend in the NW–SE direction with their subordinates in N–S direction in correlation to the geologic information of the area that describes/indicates the various episodes of deformation with their characteristic structures. The shallow anomaly sources of Pb-Zn mineralized veins as shown by very sharp tipper responses were detected in the central part, while the deeper sources as shown by broad tipper responses were in the northern part of the study area. The dimensions, trends and shallow depth range of the prospective mineralized veins obtained from VLF readings immensely indicate the prominence of Ishiagu Pb-Zn mineralization.

Keywords*: VLF-EM, Tipper, Current Density Transformation, Mineralized Veins, Conductivity*.

Introduction

Nigeria is characterized with various economic mineral deposits. Assortments of economic mineral deposits usually consist of conducting sulfide to oxidized metallic minerals, which interact radically with electromagnetic (EM) signals. Therefore, EM methods are vital tools for metallic minerals exploration. Some other methods like Induced-polarization (IP) or controlled-source audiomagnetotelluric (CSAMT) methods also provide good images of mineral deposits [***22***]; however, data acquisition is cumbersome and expensive, marking these methods incongruous for reconnaissance surveys and exploration of small targets.

The Very Low Frequency electromagnetic (VLF-EM) method is a cost effective and widely used shallow depth geophysical technique that measures EM anomalies related to the conductivity of the subsurface, with application in mineral exploration and environmental geophysical studies. The VLF technique in its original forms was first applied for electrically conductive orebodies by Paal and his group in 1963, and has been used mainly in economic mineral and hydrogeophysical applications [***18, 9, 3, 8***]. The single frequency method operated on limited bandwidth algorithm is one of a class of EM geophysical techniques that conform to a plane-wave sounding of subsurface resistivity structure, though the zero crossing readings of the geomagnetic transfer function are so unsuitable to create clear geologic image of the subsurface for interpretation. The high resolution of the current density obtainable by transforming the complex geomagnetic transfer function of the method has been premiered since 1983, though its application in exploring for economic mineral deposits in Nigeria is of little account, [***20, 15***].

Ishiagu Field is located in Ivo LGA of Ebonyi State between latitude 5°54' – 5°59' N and longitude 7°30' – 7°35' E. The area (about 25 sq.km), is situated in the SW tip of the Abakaliki

Basin, Lower-Benue Trough (LBT) geologic complex, SE Nigeria and is composed of a low-lying sedimentary terrain with some intrusions of different episodes. Majority of the geologic and topographic features of the area align and conform to orientation of the folds from the Santonian orogenic deformation. The Pb-Zn deposits in Ishiagu area appear to be the southern limit of mineralization in the Benue Trough and the Pb-Zn mineralized zone extends over a distance of 500 km in a narrow belt from Ishiagu in the Lower Benue Trough (LBT) to Zurak in the Upper Benue Trough (UBT), likewise the extent of igneous intrusions in the Benue Trough. The orebodies in Ishiagu, the outskirt of the LBT are the focus of this study.

To extend mining activities in Ishiagu, a better understanding and reconsideration of the continuation of exposed ores is necessary. Having confirmed the local mining in the area to be based on outcropped orebodies and some other prior geophysical exploration methods applied, this VLF study was then chosen for a better resolution of the continuity and trends of exposed mineralized zones at depth.

The main objectives of this study are: (1) To collect VLF-EM data to examine its application as a tool for a detailed mineral exploration program; (2) To help delineate possible continuation of existing ore bodies laterally and vertically, and (3) To describe the magmatic centers in Ishiagu area using the VLF-EM signals. This research work on its accomplishment will validate how VLF-EM technique with surface geologic observations improves our understanding of the nature of the complex, shallow Pb-Zn mineralization in the Abakaliki sedimentary basin.

Local Geologic Setting

The Ishiagu area is characterized by many structural and depositional elements (Figure 1), and its evolution is related to Abakaliki basin basement fragmentation, block faulting, subsidence and rifting during the early Cretaceous separation of Africa and America [***13***]. The sedimentary infill in the basin records the first tectono-sedimentary cycle that inundated the southeastern Nigeria rift basins. The Cretaceous sedimentary succession in the basin is composed of Albian − Cenomanian and Turonian − Coniacian sedimentary cycles bounded by the Cenomanian and Santonian unconformities respectively. These repetitive transgressive – regressive sedimentary cycles of the basin, which however suffered two deformations in the Cenomanian and Santonian periods along NE–SW axis, dominate Ishiagu area.

The NW–SE compressional tectonic deformation of Santonian episode in the basin produced multiple NE–SW trending folds and fractures parallel to the fold axis, though the predated Cenomanian episode deformation also produced the NW–SE trending tensional tectonic fractures that controlled the Pb-Zn mineralization of the area. The various episodes of Abakaliki basin tectonics is evidenced in Ishiagu area by the open symmetrical anticline trending north-easterly and the two steeply dipping dominant fracture sets, striking N40^{O}W and N50^{O}E [***10***].

As Ishiagu Pb-Zn deposits represent an integral part of Benue Trough sedimentary basin evolution, strategies for exploring them must take into account the pertinent geologic model based on the geotectonic setting. This model is noted to connate brines set into motion by a high geothermal gradient accompanying continental rifting. Hence, fissure-filling is significantly the notable style of secondary mineralization in the area, indicating epigenetic emplacement [***1***] as the key model of Pb-Zn mineralization in the basin (Figure 2). The joints and fractures generated by the Cenomanian tectonic events in the Asu River Group (ARG) are the key control of the precipitated base metals. This model thus, suggests the primary ore target to be in the ARG sediments of the Abakaliki basin in which the metal ore bodies are strata-bounded.

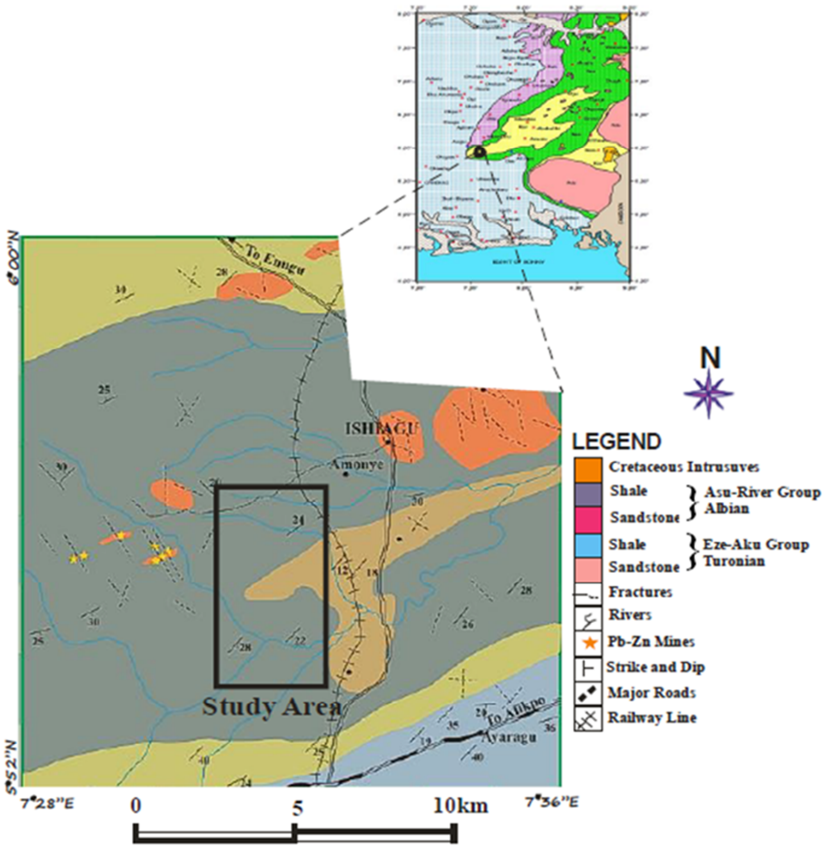


Figure 1: Geologic Setting of Ishiagu in the SouthEastern Nigeria. [17].

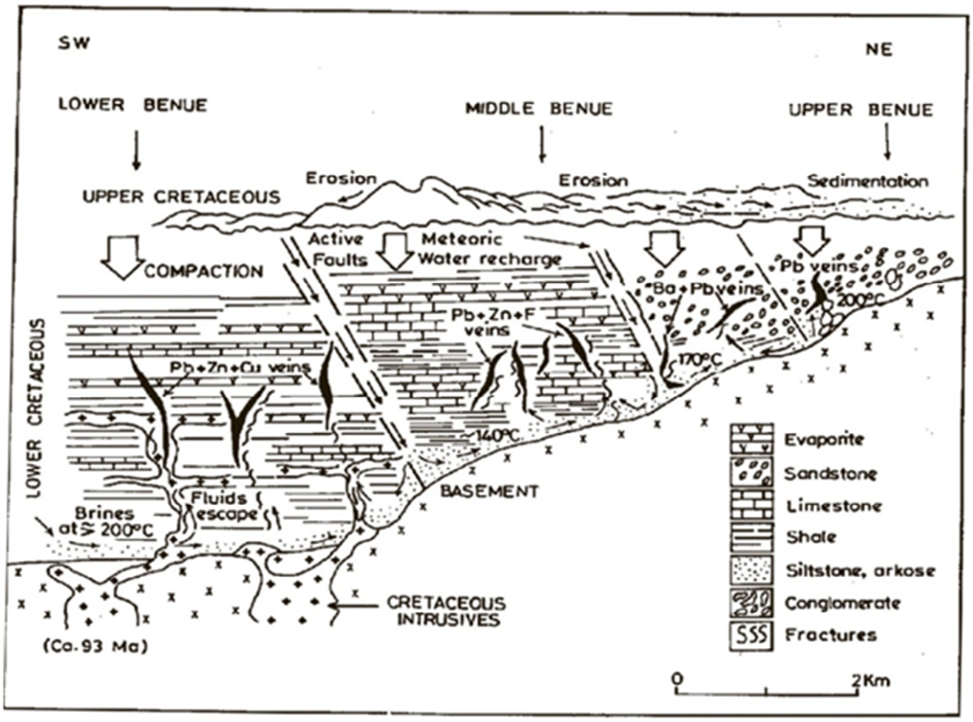


Figure 2: Genetic Model of Fracture-Type Pb/Zn Mineralization in the Nigerian Benue Trough. [1]

Materials and Methods

The principles of electromagnetic (EM) induction as described by Maxwell's equations have been well understood for over 150 years and now applied in VLF method. The great Maxwell's work brought about the extension and mathematical formulation of previous works on electricity and magnetism by Faraday, Ampère and others into a linked set of partial differential equations, collectively known as Maxwell's Equations, first presented in 1864 [***5***]. The application of Maxwell's equations were reviewed, simplified and adapted to VLF-EM method in geophysical prospecting by many authors, among the pioneers are Tikhonov, Cagniard, Cantwell and Grant [***21, 6, 7 and 12***].

- $\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$ (*Faraday's Induction Law*) (*1a*)
- $\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$ (*Ampere's Law*) (*1b*)
- $\vec{\nabla} \cdot \vec{B} = 0$ (*Gauss's Magnetic field Law*) (*1c*)
- $\vec{\nabla} \cdot \vec{D} = \rho$ (*Gauss's Electric field Law*) (*1d*)

Where

$\vec{E}$ = Electrical field intensity (*in volts per meter, V/m*)
$\vec{H}$= Magnetic field intensity (*in ampere-turns per meter, A/m*)
$\vec{B}$= μH is the magnetic induction (*in Tesla, T*),
$\vec{J}$= σE is the current density (*in amperes per square meter, A/m^2*)
$\vec{D}$= ϵE is Electric displacement or electric flux density (*in Coulomb per square meter, C/m^2*)
ρ = Electric charge density (*Coulomb per cube meter, C/m^3*)
t = Time (*in Seconds, s*)
σ = Electrical conductivity (*in Siemens per meter, S/m*)
μ = Magnetic permeability (*in Henrys per meter, V/A·m*)

The operation mechanism of the VLF-EM technique is to utilize the magnetic components of EM field of remote fixed transmitters designed for military and navigation communications operating at frequency range of 15 to 30 kHz, to identify electrically conductive subsurface features through current induction. These transmitters normally are vertical electric dipoles. The optimal configuration of VLF survey (Figure 3) is to have the geologic strike oriented parallel to transmitter so that a vertical magnetic component is inductively generated for any conductivity contrast by the horizontal and concentric magnetic field traversing the strike. As induction flow results from the primary magnetic component of the EM field, physical contact of the transmitter and receiver with the ground is trivial, thus, ground VLF survey can be conducted by only one operator. This method thus, provides a quick and powerful tool for the study of 2-D geological structures to a maximum skin depth of about 100m [***11***], though variation in the skin depth is based on overburden conductivity. Furthermore, airborne VLF surveys are possible.

At each measurement point, it is possible to define the geomagnetic transfer function, Tipper vector, (A,B) that expresses the linear relationship between the primary (H_x and H_y,) and secondary (H_z) magnetic field components, expressed as:

$$H_z = AH_x + BH_y. \quad (2)$$

Measured practically over any 2D geological structures, due to limits of the available VLF instruments is the so-called Tipper scalar (B_{sca}) estimated as:

$$H_z = B_{sca}H_y \quad (3)$$

This transfer function contains useful conductivity information of the structures below the measurement point. Thus, for a 2D geologic structure, Tipper (ie. the vertical secondary magnetic field, $\boldsymbol{H_z}$ normalized by

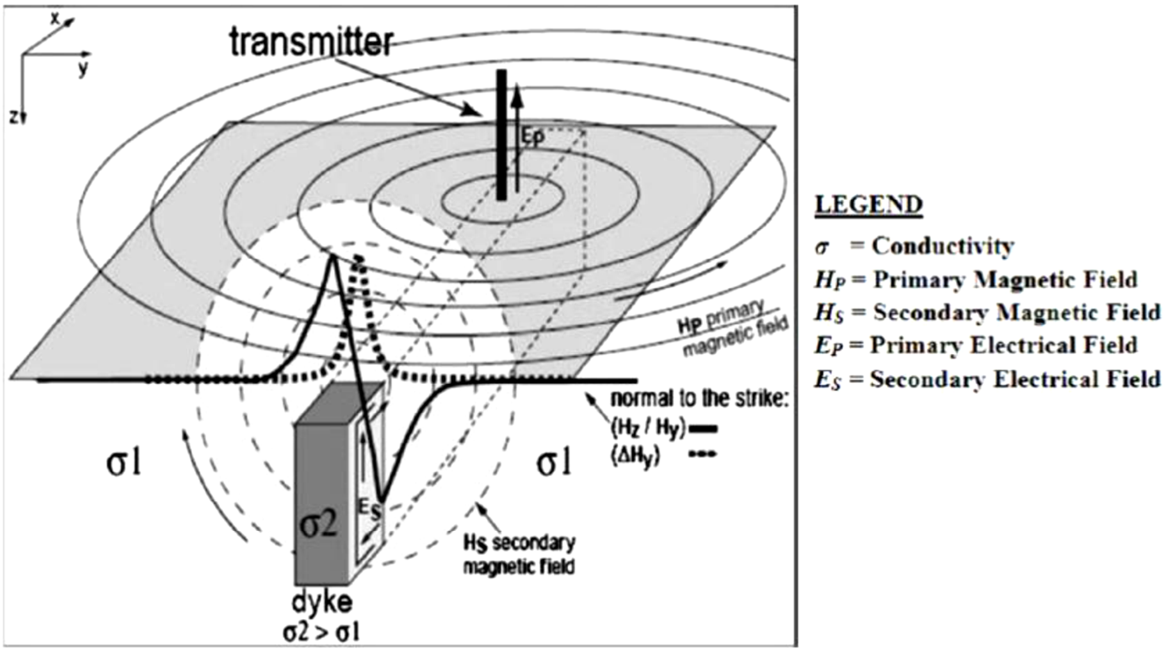


Figure 3: Field Components of VLF Field from Transmitter at Remote Distance [4] the total horizontal primary magnetic field, H_y) varies along the profile showing the strongest gradients at conductivity contrasts.

The superposition of the $\boldsymbol{H_z}$ and $\boldsymbol{H_y}$ at a given frequency which normally has a time lag due to the underlying EM induction process in the earth generates the resultant analyzed by the polarized ellipse (Figure 4) to produce the in-phase and quadrature parts of Tipper, as recorded by the equipment. The $\boldsymbol{H_y}$ and $\boldsymbol{H_z}$ fields of similar frequency vary in magnitude with each other as they propagate over time, and the superposition of the phase lagged magnetic fields yields a unit resultant value, Tipper (B) based on dot product of the phase-lagged vectors as revealed by the polarized ellipse. Mathematically, the unit resultant of the phase-lagged superposition is a complex number as it varies in both y- and z-axes, thus clarifying the real and imaginary components of Tipper as recorded in VLF-EM prospecting.

Inclination of the major axis of the polarized ellipse from the horizontal is called the tilt angle, ($\boldsymbol{\alpha}$) and this, coupled with the magnitude of the resultant field as recorded in VLF-EM method signifies the conductivity strength of the structures. On the other hand, the inclination of minor axis from the vertical called phase angle, ($\boldsymbol{\varphi}$) also signifies the conductivity strength of structures, though recorded by different EM methods. The inter relationship between $\boldsymbol{H_y}$, $\boldsymbol{H_z}$ and the resultant ($\boldsymbol{H_1}$) as divulged by the polarized ellipse generates the in-phase and quadrature parameters recorded in VLF survey. Resolution of the resultant field, $\boldsymbol{H_1}$ on Y-axis is $\boldsymbol{H_1 cos\ \alpha}$, and this is called **in-phase** or **real component**, while resolution on the Z-axis is $\boldsymbol{H_1 Sin\ \alpha}$, a vector turned 90° anticlockwise from $\boldsymbol{H_y}$, and is called **out-phase, imaginary** or **quadrature component**. The in-phase and quadrature parameters of VLF-EM according to Srigutomo *et al*, [***19***] can respectively be expressed as;

$$tan\alpha = \frac{2(H_z/H_y)cos\Delta\varphi}{1-(H_z/H_y)^2} \qquad (4)$$

and

$$\varepsilon = \frac{H_z H_y sin\Delta\varphi}{H_1^2} \qquad (5)$$

[19]

Where:

H_y = the horizontal axis and amplitude of the primary magnetic field;
H_z = the vertical axis of the secondary magnetic field
H_2 = the amplitude of the inductively generated secondary field
H_1 = the resultant magnetic field, ($H_1 = |H_z e^{i\Delta\varphi} sin\alpha + H_y cos\alpha|$)
α = the tilt angle of the polarized elliptical field
ε = the ellipticity of the polarized elliptical field; and
$\Delta\varphi$ = the phase lag of the secondary field relative to the primary field and is defined as $\varphi_z - \varphi_y$).

The tilt angle, α, as obtained from eqn. (4) approximates the real part of tipper which is in-phase with H_y as it makes an angle of zero degree with it, while the ellipticity, ε, (eqn. 5), in contrast, approximates the imaginary part of tipper referred to as the quadrature measurement. The readings are often expressed in percentage, with ($Tan\alpha$ **x 100%**) for in-phase and (ε **x 100%**) for quadrature anomalies. It is common practice to plot the in-phase and quadrature parts of the normalized vertical field as nomograms on profiles for qualitative interpretations. Typical responses read as crossovers for conductors of limited lateral extent such as massive sulfide veins or shear zones.

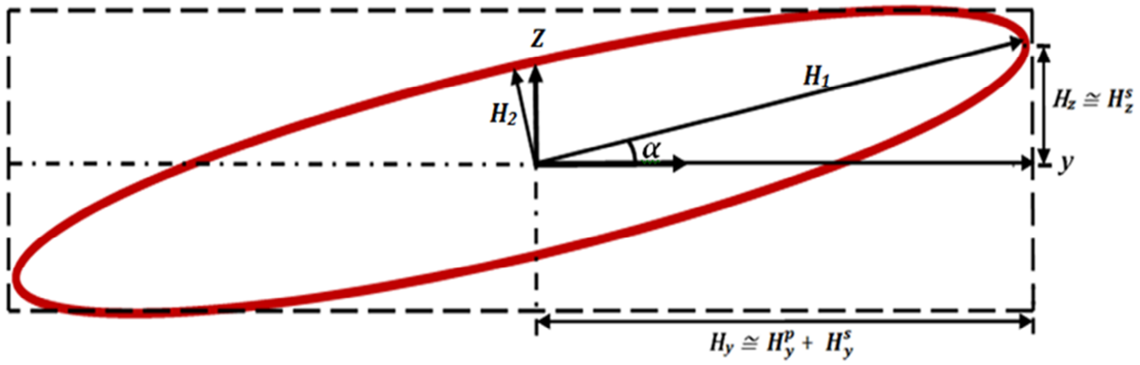


Figure 4: The Ellipse Polarization of VLF-EM over Earth's Inhomogeneity

The field data for this research was acquired from ten measurement profiles, 300m each in the surveyed area. The well pegged geophysical grid (Figure 5) established from a E-W trending baseline 300m long at a bearing of 90°, with 9 profiles parallel to it at 100m spacing is approximately perpendicular to the transmitter and to the strike direction. The field data was then acquired by systematically traversing along these profiles at a 10m interval with an ABEM Wadi VLF receiver, Model-9133001869, operating on the VLF principle of recording tipper responses at every measurement station using radio waves from the DMB transmitter located in Germany that is oriented to the north from the site and of 26.9kHz frequency. This transmitter was chosen for this survey in consideration to the two prevailing fracture sets in the Abakaliki Basin trending NW and NE respectively. The surveyed area is in the vicinity of already existing Ihietutu mines.

VLF Data Filtering

The detection of limited conductors is the major interest in mining prospecting and several techniques based on linear filtering have been developed to delineate them. The VLF-EM zero crossing readings are so unsuitable to be contoured for interpretation and the speciousness have been noted to be the structurally encompassed nonlinear and harmonic noise arising from different sources like complex geologic setting of conductive bodies, power line, global lightening, temporal variations in primary field strength, etc [***16***]. The 2D VLF-EM data interpretation thus, calls for filtering techniques that will consecutively remove partially biased noise of artificial and geological sources, to enhance the signal-to-noise ratio.

Various VLF data processing techniques like Fraser filtering to improve the resolution of local anomalies of somewhat ambiguous in-phase and quadrature readings have been in use. The Fraser filtered in-phase profiles show positive peaks of different intensities and sharpness, suggesting the presence of shallow and deep conductors. Similarly, the 2D transformation of the magnetic function to apparent current density with depth using KHF technique [**14**] is increasingly accepted as a valuable tool for economic mineral exploration, and global expansion in its activity has been seen. This technique is applied in this work.

The 2D current density transformation by Karous and Hjelt filter (KHF) is simply based on a discrete integral equation applied to the observed in-phase component of the magnetic transfer function of VLF-EM. Description of the magnetic field arising from a 2D subsurface current distribution based on Biot-Savart law is applied to solve for the current distribution of induced magnetic field, assumed to be located in a thin horizontal sheet of varying current density at a depth equal to the measurement station interval.

Escalating the data points at greater station intervals apart, the behavior of the current distribution in the assumed horizontal sheets, now at progressively greater depths, can be inferred with the KHF filter described as:

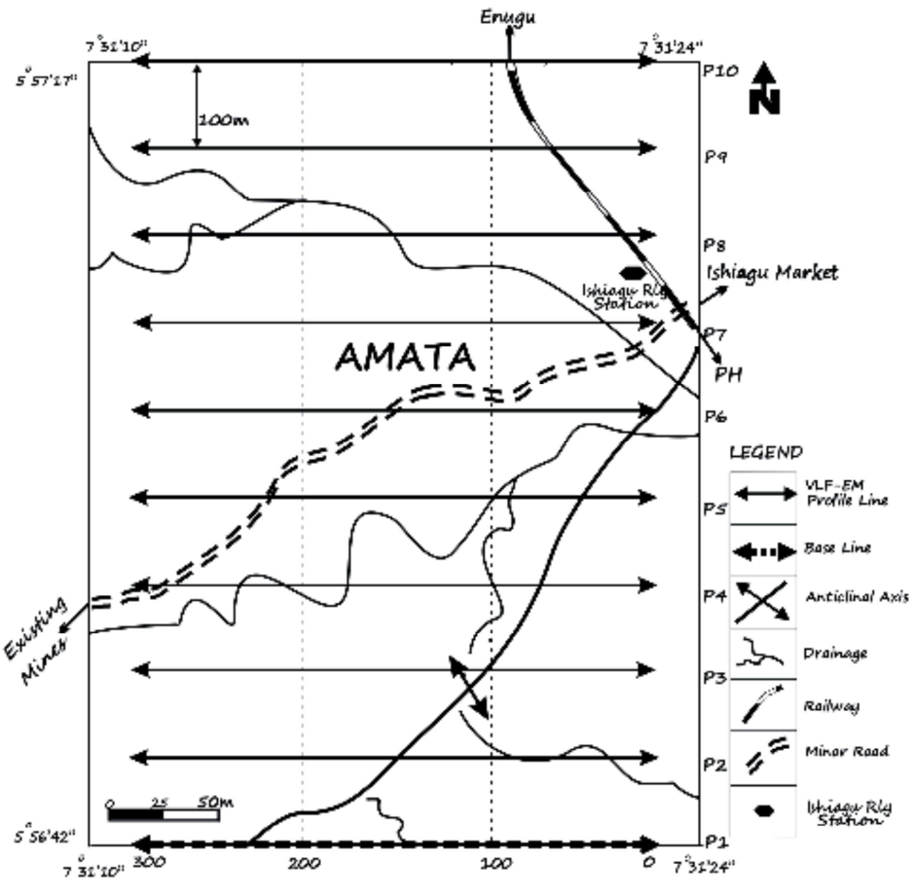


Figure 5: Layout of the measurements grid for the VLF survey area.

$$\left(\frac{\Delta Z}{2\pi}\right) I_a (\Delta x/2) = -0.102H_{-3} + 0.059H_{-2} - 0.561H_{-1} + 0.561H_{+1} - 0{:}059H_{+2} + 0.102H_{+3}$$

Where
ΔZ is the assumed thickness of the current sheet; Δx is the distance between the data points (equivalent to depth to the current sheet); H stands for in-phase values at each of the six data points.

The evaluated current density is located beneath the center point of the six data points. The applications of transformed current density in mineral exploration aids in creating geologic image of the surveyed area, identifying the overburden thickness of the mineralized veins, resolving conductivity anomalies with depth, and optimizing apposite mine development techniques and mine placement. The KHF technique is thus marked a vital tool for semi-quantitative interpretation of VLF data to few ten meters depth based on the EM skin depth. Figures 6 and 7 are respective representations of various anomalies of varying degree of conductivity trending in different directions as delineated by Fraser filtering technique and high resolution 2D current density transformation through the VLF-EM readings obtained from Ishiagu field.

Succinctly, the extent of the Tipper responses in Ishiagu field is highly controlled by the conductivity contrast of some geologic features and these anomalies vary greatly; some of the anomaly peaks are sharp and of high intensity while others are broad and of lower intensity (Figure 8). Suspected mineralized veins, ($F_1 - F_{16}$) were delineated on the gridded survey area using characteristic coincidence of positive inflections on Fraser filtered in-phase anomaly and were further interpreted on current density maps. With good geologic information of the area, it is therefore logical to interpret the VLF-EM anomalies caused by the mineralized veins and also outline those invented by fissure filled intrusives in Ishiagu area.

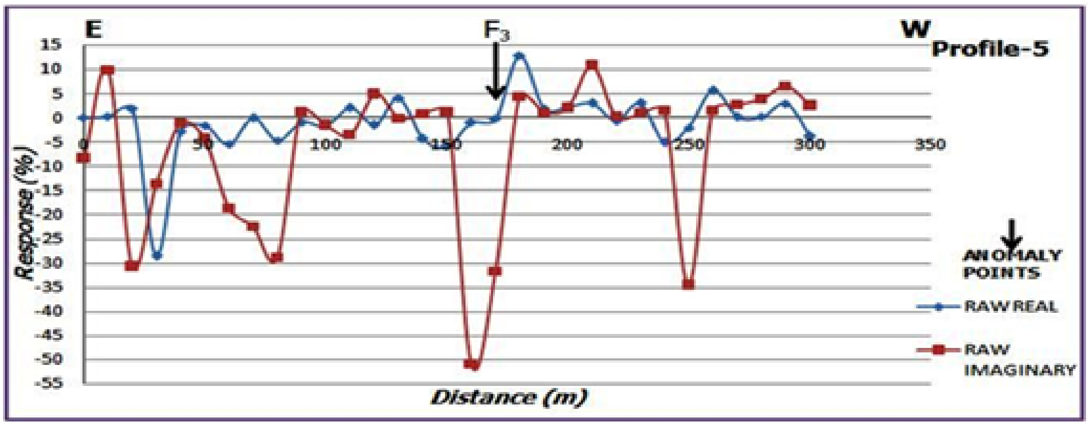
Stacking the current density profiles as gridded maps or pseudo-sections for tracing the anomaly laterally and vertically offers the possibility to generate a pictorial image of the field indicating the geometry, trends and dimensions of the 2-D structures instigating the anomalies.

Results and Discussion
Dimensionality analysis revealing the trends of 2D conductivity structures as displayed on the stacked profiles of filtered in-phase readings (Figure 8) has been one of the basic properties of VLF transfer function, but provided on the transformed current density maps (Figure 9 and 10) are more detailed information on the geometry, extension, thickness and depth distribution of the Pb-Zn mineralized veins in Ishiagu field. Therefore, interpretation with the 2D current density map is preferable as the 2D geologic model based on current density transformation data show better resolution than those derived from the Fraser filtered data. Generally, good 2-D structures with less overburden were detected by induction.

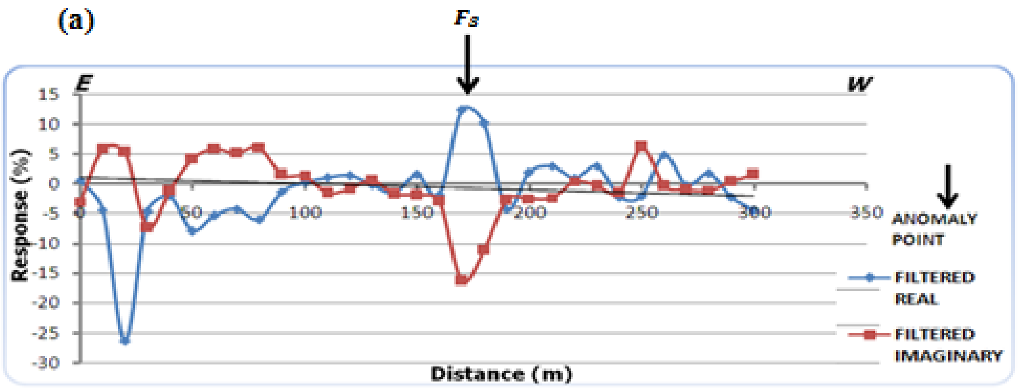
Hence, the Pb-Zn mineralized veins in the area of survey with less overburden, in this case closer to the Abakaliki anticlinal axis (Figure 1) were utterly inducted; while those concealed by thick overburden were not easily inducted, but accomplished through current gathering and are thus, of moderate responses.

The VLF readings of $\mathbf{P_{Anom\text{-}1}}$ in the southern part of the surveyed area is attributed to water saturation as the conductive anomaly obtained directly from the outcropped Pb- Zn host rock (ARG) is still of moderate intensity. But the strong $\mathbf{P_{Anom\text{-}3}}$ and $\mathbf{P_{Anom\text{-}4}}$ in the central part bares the shallow Pb-Zn mineralized veins, though deeper in the northern section with characteristic moderate VLF readings due to thick overburden (Eze-Aku Shale) that reduces the skin depth of VLF signal. Evaluation of the positive and very close to zero quadrature components in this northern outskirt also substantiates the thick overburden over the ascertained mineralized veins in the zone.

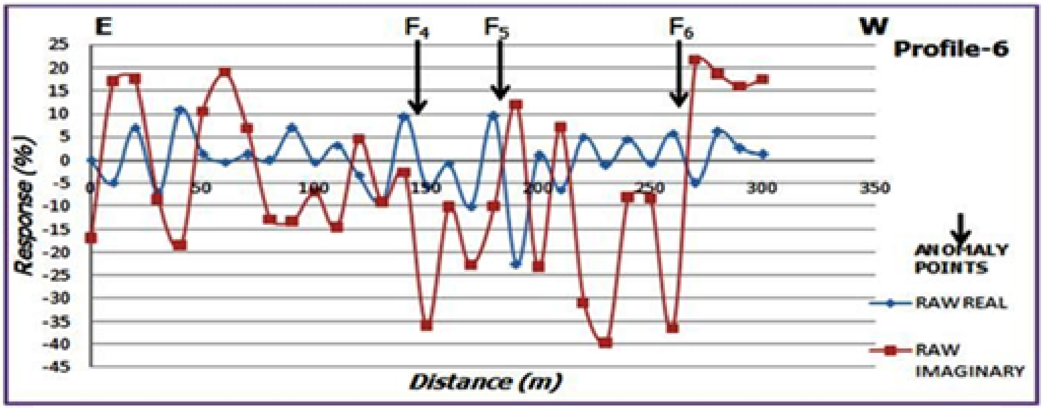
The collocation of the shallow part of the core positive in-phase anomalies to the anticlinal axis and to the corresponding negative in-phase anomalies create a prominent criterion of using VLF readings to analyze the composition and structural control of the characterized mineralized veins in Ishiagu field. The sharpness of the in-phase anomalies of $\mathbf{P}_{\mathbf{Anom-3}}$ and $\mathbf{P}_{\mathbf{Anom-4}}$ in the central zone due to their shallow depths and their proximity to the anticlinal axis elucidates the characterized mineralized veins in Ishiagu field to be structurally controlled by the NW–SE trending fractures produced by the tensional tectonic deformation of Cenomanian episode. The northern parts of these anomalies along with $\mathbf{P}_{\mathbf{Anom-5}}$ outlying from the anticlinal axis (Figure 9) are of broad and moderate VLF responses indicating their occurrence at profound depths with overburden of Eze-Aku Shale. The broad and very close to zero values of the quadrature components of the anomalies at this outlying distance from the anticlinal axis also anticipate the northern parts of the detected mineralized veins in Ishiagu to be concealed by thick overburden.



(a)



(b)



(c)

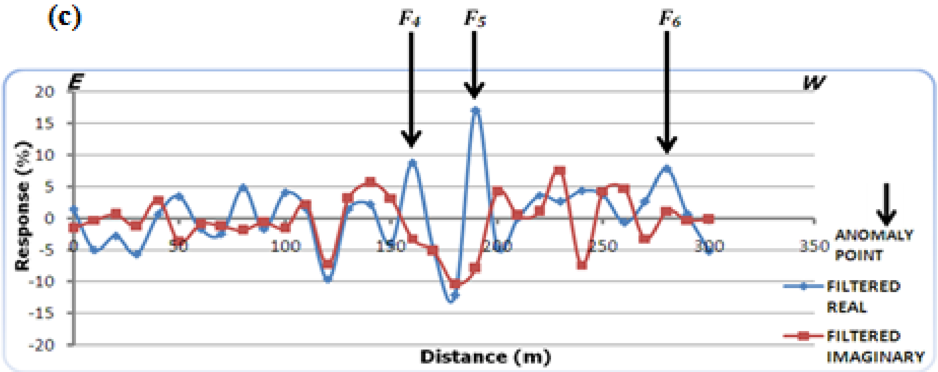


Figure 6: Outlook of Ishiagu Field Data (profiles 5 and 6): (a) and (c) Raw VLF-EM readings along profiles, and (b) and (d) the corresponding Fraser filtered data of the same profiles, (Trends: E – W).

As the igneous intrusions of the Abakaliki Basin are structurally controlled due to their occurrence in steeply dipping fractures, the negative in-phase anomalies are thus, interpreted for the cretaceous intrusions in Ishiagu area. The $\mathbf{N_{Anom\text{-}1}}$ anomaly is on the same trend with the prospective mineralized veins. Its parallel trend and proximity to the $\mathbf{P_{Anom\text{-}3}}$ and $\mathbf{P_{Anom\text{-}4}}$ as shown on profiles **P-5**, **P-6** and **P-7**

(Figure 10) is thus, a lucid indication of the occurrence of both ore and gangue minerals in successive layers along mineralized fractures, thus signifying their fissure filling mode of occurrence. The NW and NE trends of $\mathbf{N_{Anom\text{-}1}}$ and $\mathbf{N_{Anom\text{-}2}}$ respectively also suggest these intrusions to be of Cenomanian and Santonian episodes respectively.

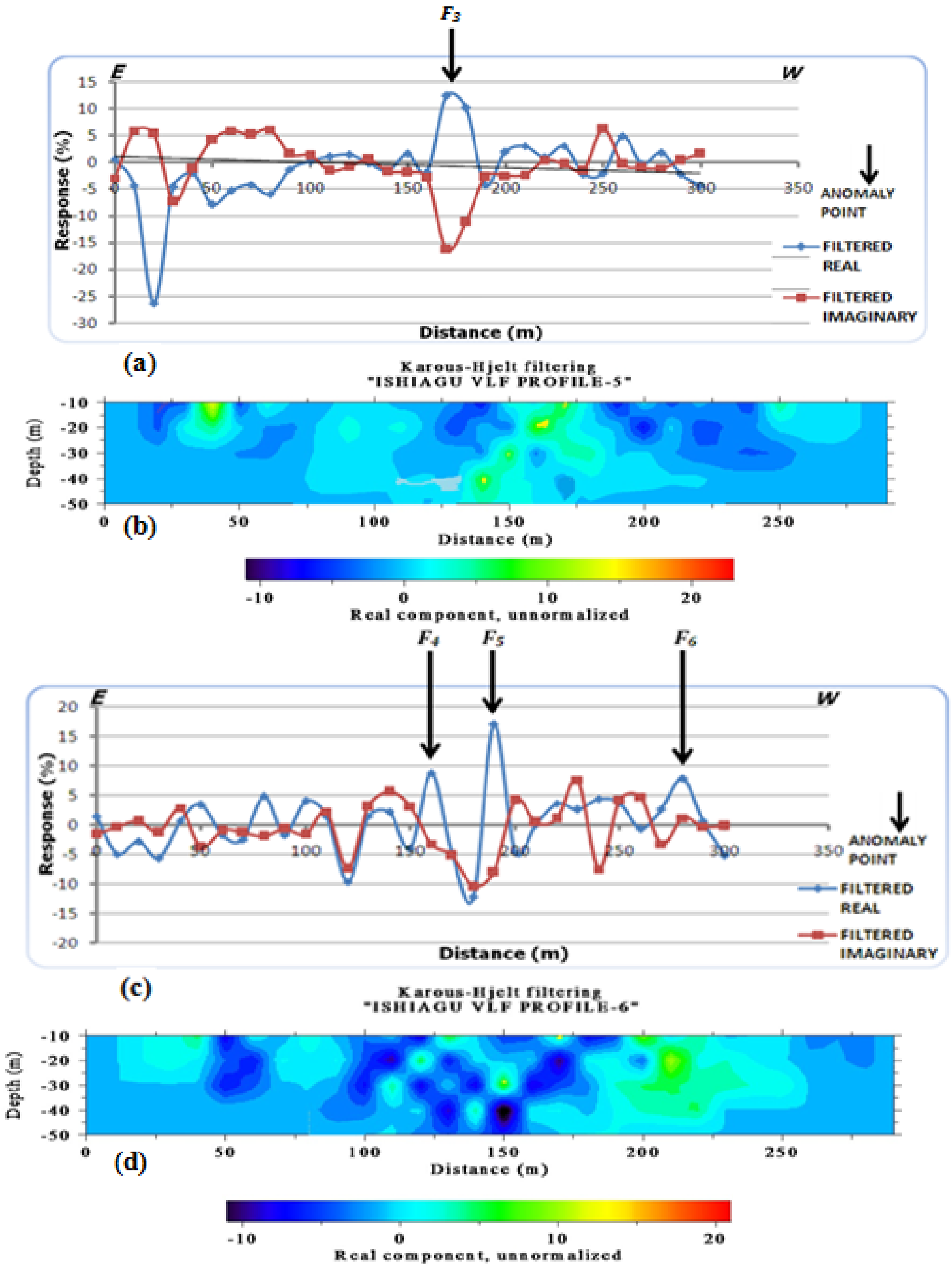


Figure 7: Fraser filtered VLF-EM readings along profiles 5 (a) and 6 (c), and 2D Current density sections from KHF Transformation of In-phase data of the same profiles (b) and (d), (Trends: E –W). Colour codes: red colour indicates high conductivity and blue colour indicates low conductivity.

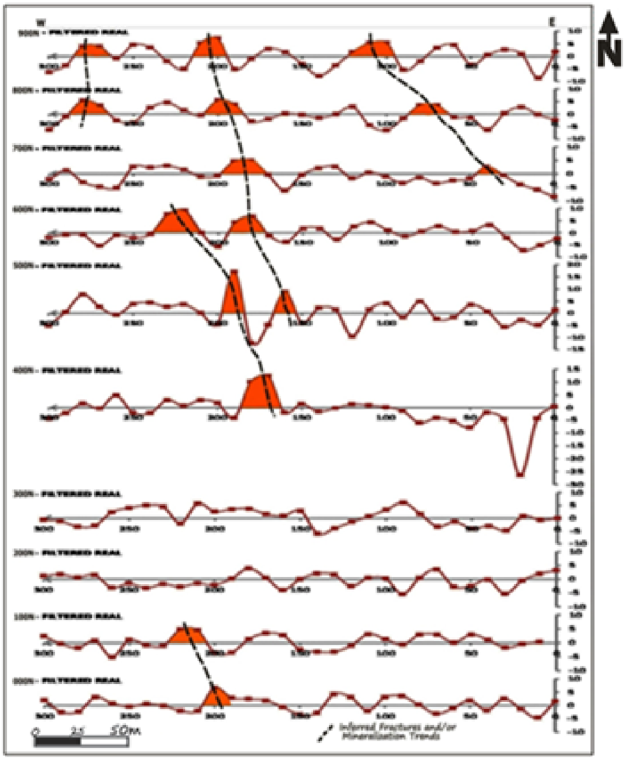


Figure 8: The Detected VLF-EM Anomalies (Pb-Zn Veins) of the Study Area.

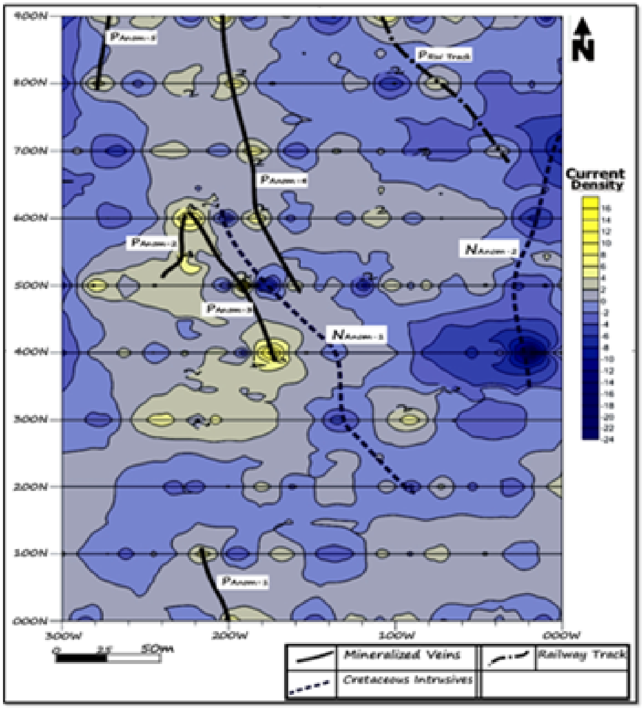


Figure 9: 2D Current Density Map for the Pb-Zn Mineralization in Ishiagu Area.

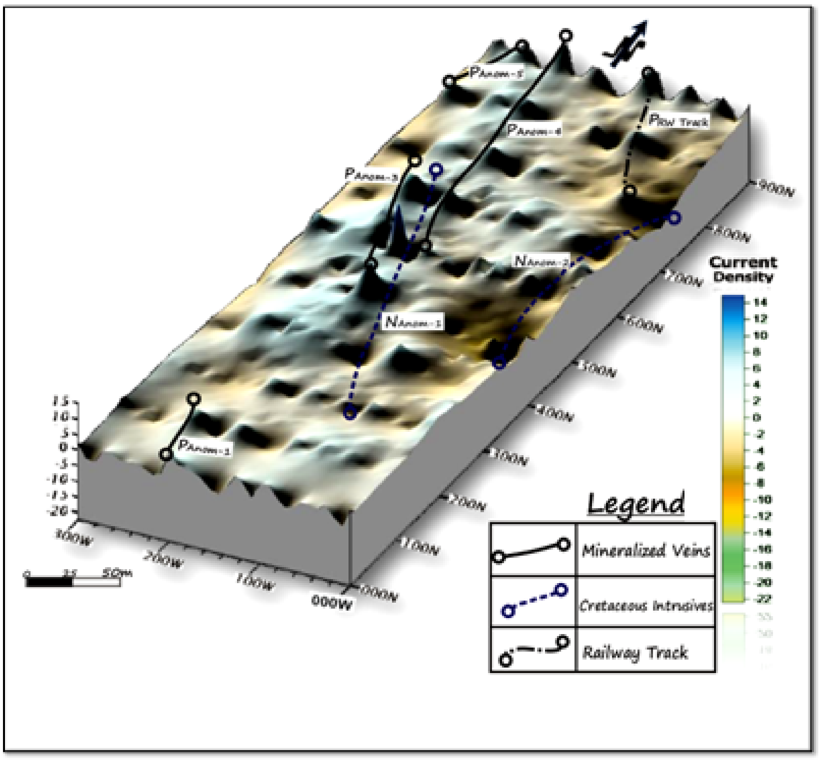


Figure 10: 3-D View of the current density map for the Pb-Zn mineralization in Ishiagu.

The depth to these anomalous bodies was also assessed in this work based on the sharp and/or broad shapes of the in-phase readings. This depth to the prospective mineralized veins is shallow in the entire southern and central parts of the study area contiguous to the NE trending anticlinal axis, but deeper in the northern part. Consequently, the overall trace of the VLF anomalies most proximate to the anticlinal axis likely indicates the near surface trace of significant Pb-Zn mineralized veins while the parts outlying from the anticlinal axis, though with moderate VLF anomalies due to thick overburden still indicates significant mineralized veins. Previous studies indicate that the Ishiagu mineralized fractures normally fade out farther away from the Pb-Zn lodes, thereby alluding fracture extension as a clue to extension of Pb-Zn mineralization in Ishiagu area. The NW trend of these outlying mineralized veins in correlation to the NE trending Abakaliki anticlinal axis is also an apparent evidence of Pb-Zn mineralization potentials of the ascertained VLF anomalies in the surveyed area in Ishiagu. To this upshot, concerted efforts involving 2D and 3D current density of VLF-EM geophysical method and detailed geologic investigation has given a better definition of the parameters of these interesting structures that revealed several Pb-Zn mineralized veins and fissure filled intrusives in Ishiagu, thus calling for trenching across these prospective mineralized veins for further authentication.

Conclusion

Presented in this study is the result of VLF-EM method in delineating the conductivity contrasts for Pb-Zn mineralization and the geologic image of Ishiagu field, in the SW part of Abakaliki basin. The KHF filter, along with the Fraser filtering technique of the VLF reading as applied in this study reveal the high resolution of 2D current density transformation readings for economic mineral exploration. The limited knowledge about the conductivity variations of the structurally controlled Pb-Zn mineralization and igneous intrusions in Ishiagu field was circuitously inferred from this study. Current density maps also revealed the inferred mineralized veins' trends in NW–SE direction with their subordinates in N–S direction and this conforms to the tensional tectonic deformations of Cenomanian episode in the Abakaliki Basin. The broad Tipper responses in the northern part of the surveyed area indicate deeper sources while the sharp tipper responses observed in the central part indicate shallow sources in correspondence to the NE-SW trending anticlinal axis. The outcome of this scrutinized VLF technique in terms of its intrinsic characteristics, rather than through the obtained results obviously revealed the mineralization potential of the concealed fractures in the Ishiagu area, though at greater depth in the northern outskirt. The utmost resolution of the study: conductivity contrasts with depth, and optimizing suitable mine development techniques and mine placement by the transformed Current density map analysis, thus marks KHF technique a vital tool for semi-quantitative interpretation of VLF-EM data. Recommended for full exploitation of Pb-Zn deposits in this surveyed area of Ishiagu is the trenching across the southern parts of the inferred Pb-Zn mineralized veins so as to establish the suitable ground plans for effective mine development. Some highly negative in-phase anomalies attributed to some intrusive bodies as detected in this work, also calls for the wariness of the locations and trends of these bodies in the course of efficient and cost effective mine development in Ishiagu. It is thus, clarified that any VLF responses on a given profile correlates with changes in the apparent resistivity so long as there exist VLF data.

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