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Exploration of Lead-Zinc (Pb-Zn) Mineralization Using Very Low Frequency Electromanetic (VLF-EM) in Ishiagu, Ebonyi State

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Abstract

Very low frequency Electromagnetic (VLF-EM) exploration over the Ishiagu area of Abakaliki Basin, Lower Benue Trough, Nigeria was carried out to determine the Pb-Zn mineralization in the sedimentary bedrock. The conductivity contrast between the conductive mineralized veins and the host rock as generated by induction mechanism was used to delineate the potential zones of Pb-Zn mineralization. Results of high in-phase and quadrature readings due to strong EM induction were detected in the survey area and on the average, the deeper sources response range from 4.7% to about 7.6%, while the shallower sources response range from 8.8% to about 17.1% and these probably indicate the presence of Pb-Zn deposits with thick overburden in the northern part. Current density maps show the Pb-Zn mineralized veins trends in NW-SE direction with their subordinates in N-S direction. The central part of the study area displays very sharp VLF tipper responses indicating shallow sources, while the northern part displays broad VLF tipper responses indicating deeper sources. These readings correlate to the depth values over the Pb-Zn mineralized veins which range from 10 to 13 m in the central part and 16 to 22 m in the northern part of the mapped area. The high VLF anomalies delineated from Ishiagu area, in the SW part of Abakaliki basin as a rule yielded a high conductivity contrast result well-suited with the Pb-Zn mineralization and geologic information of the area.

Keywords: VLF-EM; Pb-Zn mineralization; Tipper response; In-phase and quadrature anomalies; Current density maps; Ellipse polarization; Wave superposition; KHF filtering techniques

Introduction

The Pb-Zn mineralization in Ishiagu has instigated repeated studies of the area using different geological and geophysical techniques, though less has been done with electromagnetic techniques. This paper presents the remarkable results obtained with VLF-EM method to detect the conductive ore-bearing mineralized veins within the ultrabasic rocks in Ishiagu, Ebonyi State, Nigeria. The well-established very low frequency electromagnetic (VLF-EM) method is a rapid, wide coverage and cost effective technique for locating both hidden ores and the structures associated with the mineralization, in use for over 30 years [1-4]. The proficiency of VLF method for high-grading mineralized area in preparation for competent mine development is of significant contribution to an integrated geophysical investigation effort. The readings of VLF technique, just like every other EM geophysical prospecting is based on variations in subsurface electrical conductivity which is the inverse of resistivity. This method therefore, provides a quick and powerful tool for the study of 2-D geological structures to a maximum skin depth of about 100 m, though variation in the skin depth is based on changes in subsurface conductivity.

Careful study reveals the Pb-Zn mineralization in Ishiagu to be structurally controlled such that both ore and gangue minerals occur in successive and symmetrical layers along vertically and/or steeply dipping fractures which often have parallel or matched walls, thus indicating its fissure filling mode of occurrence which is so pinpointing to VLF-EM prospecting [1,5]. The ground VLF-EM method is a quick and powerful geophysical technique for the study of shallow 2-D geological structures most especially in respect of mineral exploration. In addition, it has been used to high echelon of success to map weathered basement layer and detection of water-filled fractures or shallow faults. This method is very useful and pertinent because of how quickly data can be collected, and large survey area can also be covered quickly with the portable instruments. The surveyed area was selected in view of the uncertainty in the extent of concealed Pb-Zn lodes, overburden thickness and the geological context of the Ishiagu areas.

Location of the Study Area

Ishiagu Field is located in Ivo LGA of Ebonyi State between latitude 5°54' – 5°59' N and longitudes 7°30' – 7°35' E. The area (about 25 sq.km), is situated in the SW tip of the Abakaliki Basin on the Lower-Benue Trough geologic complex, SE Nigeria and is composed of a low-lying sedimentary terrain with some intrusions of different episodes. The Ishiagu area of the Abakaliki Basin is delineated by geology of the Abakaliki Basin as shown in Figure 1. Evolution of this generally low-lying to gently undulating shaly terrain is correlated to basement fragmentation, block faulting, subsidence and rifting of the Lower Benue Trough during the early Cretaceous separation of Africa and America [6]. 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 to Zurak in the upper Benue Trough, likewise the extent of igneous intrusions in the Benue Trough. Majority of the geologic and topographic features of the area align in the NW-SE direction, and conform to orientation of the folds from the Santonian orogenic deformation.

Geologic model of Pb-Zn mineralization in ishiagu

The Ishiagu Pb-Zn deposits represent an integral part of Benue Trough sedimentary basin evolution and strategies for exploring them must take into account the pertinent geologic model. The Ishiagu Pb-Zn mineralization is attributed to a sedimentary geological model based on the geotectonic setting, the mode of occurrence and fluid-inclusion characteristics. This model is noted to connate brines set

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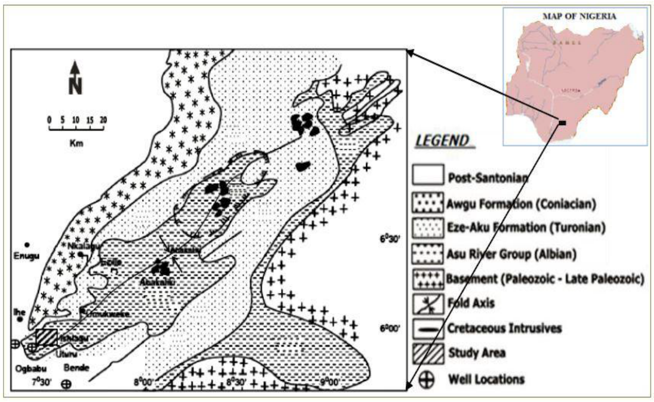

Figure 1: Geological setting of the Abakaliki basin showing the study area [12].

into motion by a high geothermal gradient accompanying continental rifting. The model (Figure 2) interprets the Pb-Zn deposits in Ishiagu area as distinct epigenetic ore bodies generated by convectional flow of hot brines that leached the metals from arkosic sediments and later precipitated them as metallic sulphides [7]. Fractures generated by the Cenomanian tectonic events in the Asu River Group (ARG) is marked 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-bound.

The Pb-Zn mineralized zone extends over a distance of 500 km in a narrow belt from Ishiagu in the Lower Benue Trough to Zurak in the Upper Benue Trough, likewise the extent of igneous intrusions in the Benue Trough.

Methodology

The field data for this research was acquired from ten measurement profiles, 300 m each in the survey area. The well pegged geophysical grid in Figure 3 was established from an east-west trending baseline 300 m long at a bearing of 90°, while the profiles, parallel to each other and to the baseline with 100 m spacing were approximately perpendicular to the transmitter and to the strike direction. The field data was then acquired by systematically traversing along these profiles at a 10 m 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 transmitters at remote distance. The ABEM WADI receiver requires no physical contact with the transmitter and the ground during VLF survey as it operates on induction mechanism. The optimal configuration of VLF survey as in Figure 4 is to have the geologic strike oriented parallel to the transmitter direction so that a vertical magnetic component is generated for any conductivity contrast by the propagating horizontal and concentric magnetic and orthogonal electrical fields due to induction [8]. Thus, the DMB transmitter located in Germany that is oriented to the north from the site and of 26.9 kHz VLF frequency was chosen for this survey in consideration to the two prevailing fracture sets in the Abakaliki Basin trending northwest and northeast respectively, with subordinates trending north directly. The survey area entirely covering Amata Village is in the vicinity of already existing mines in Ihietutu.

The VLF-EM prospecting is fundamentally based on the primary EM wave impedance over 2-D structures and this wave impedance depends upon the orientation of the EM field components with respect to the geologic strike of the 2-D geologic structures. The EM wave impedance is therefore, evaluated with the "E-parallel" polarization mode being the most apposite for detecting the associated anomalous secondary magnetic field. In VLF-EM prospecting, the superposition of the primary magnetic field (H_y) from the transmitter and the secondary magnetic field (H_z) from the subsurface gives an important diagnostic parameter, Tipper, (B) that feasibly reflects the conductivity contrast of every 2-D structures in the subsurface.

$$B = H_z / H_y \quad (1)$$

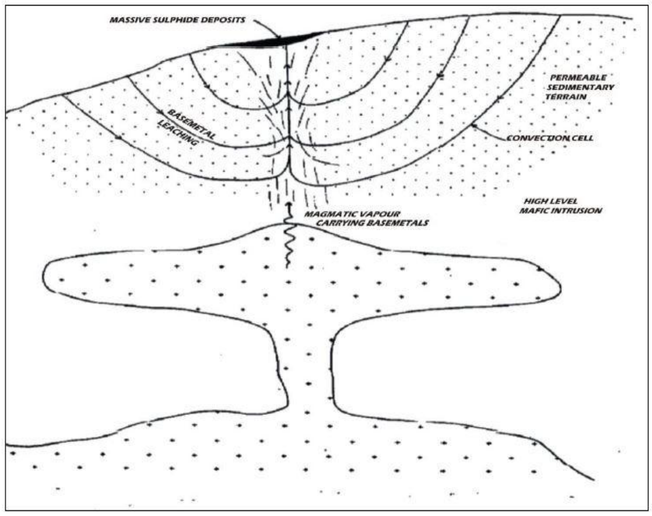

Figure 2: Genetic evolution for an active hydrothermal system precipitating massive sulfide deposits [7].

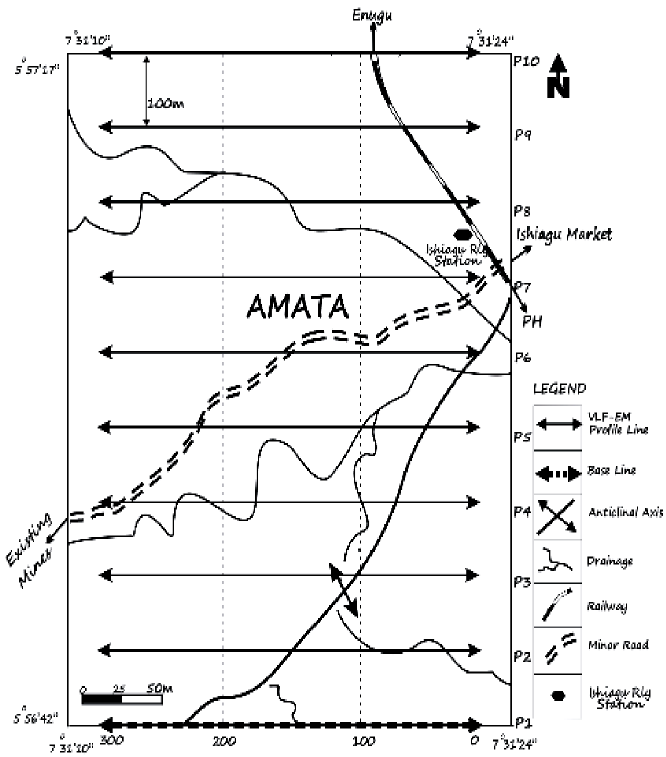

Figure 3: Layout of the measurements grid for the VLF survey area.

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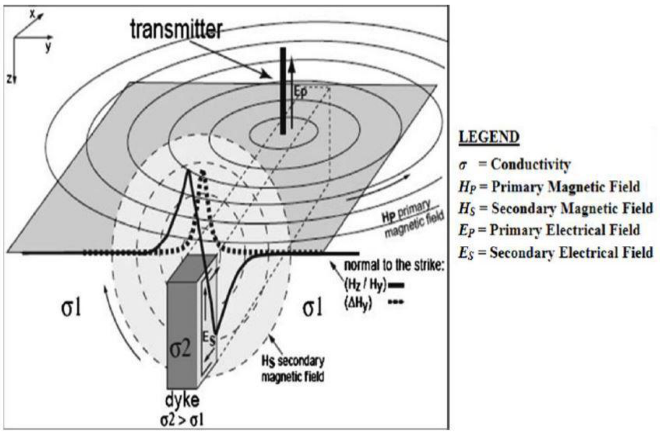

Figure 4: Field components of VLF Field from transmitter at remote distance [8].

Tipper is derived by the phase lag between (H_y) and (H_z) magnetic fields due to induction thus, allowing this method to become widely used for geophysical prospecting. Recorded in the field by the equipment are the in-phase and quadrature components of this complex quantity, Tipper, obtainable mathematically by evaluating the shape of the polarized ellipse. This measurement initiates the detection of structures and subsurface features of interest even in areas concealed with overburden containing relatively thin horizons of anomalously high conductivity. Figure 5a and 5b is the typical raw VLF-EM readings attained from Ishiagu field presented as nomograms.

Anomalies of the raw VLF-EM profiles are usually complicated and this calls for data processing so as to improve the resolution of local anomalies and limit the possible interpretational error. This was achieved in this work using the prominent KHF-filtering techniques as outlined by Fraser [9], Karous and Hjelt [10]. The Fraser filtering technique transforms the zero-crossing on a raw in-phase reading to maximum peak and the corresponding quadrature component transformed to minimum peak for anomalously conductive structures. The analogous apparent current density pseudo-section with depth as gotten by Karous-Hjelt filtering offer the possibility to generate a pictorial image of the profile indicating the geometry of the 2-D structure that instigated the anomaly. This pseudo-section is shown as colour codes with red colour indicating high conductivity (i.e. positive) and blue colour indicating low conductivity (i.e. negative). Figure 6a and 6b is a representation of various anomalies of varying degree of conductivity trending in different directions as delineated from the honed profile sections of Ishiagu field.

Generally, VLF analysis is on the bases that the higher the in-phase values of the anomaly, the greater the conductivity of the underlying structures in relation to the surrounding rock [11]. 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. Suspected mineralized veins, (F_1–F_{16}) were delineated on the gridded survey area using characteristic coincidence of positive inflections on filtered in-phase anomaly and were further interpreted on current density maps [12-14]. With good geologic information of the area, it is therefore logical to interpret the VLF-EM anomalies caused by the mineralized veins.

Results and Interpretation

Finally, the in-phase readings on stacked profiles (Figure 7) and the current density maps (Figures 8 and 9) were used for the interpretation of the geologic structures in terms of conductive mineralized veins and this provided more detailed information on the extension, thickness and depth distribution of the Pb-Zn mineralized veins in Ishiagu field [15-19]. Generally, good 2-D structures with less overburden were detected by induction, hence, the Pb-Zn mineralized veins lying in the area of survey with less overburden (in this case closer to the Abakaliki anticlinal axis) were utterly inducted; while those concealed by very thick overburden were not easily inducted, but accomplished through current gathering and are thus, of moderate responses [20-22].

The VLF readings of P_{Anom-1} in the southern part of the surveyed area is attributed to less mineralization as the conductive anomaly obtained directly from the shallow and outcropped Pb-Zn host rock (Asu River Group) is still of moderate intensity. But the strong P_{Anom-3} and P_{Anom-4} in the central part of the surveyed area are attributed to the shallow Pb-Zn mineralized veins, though deeper in their northern section as thick overburden (Eze-Aku Shale) in that zone reduces the skin depth of VLF signal, causing moderate VLF readings in the zone [23]. Evaluation of the positive and very close to zero quadrature components in this northern outskirt also substantiates the thick overburden over the attributed 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

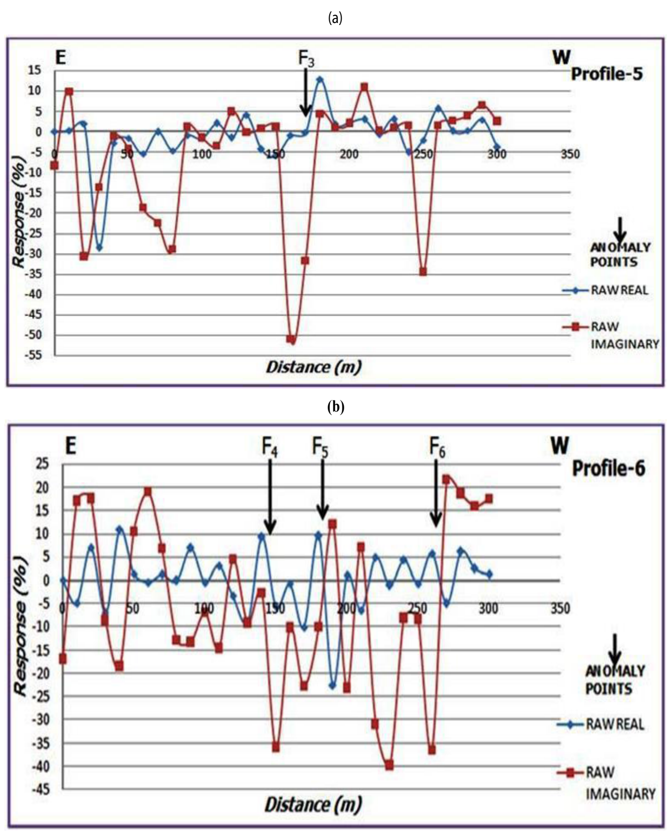

Figure 5: Typical Raw In-phase and quadrature components of tipper (%) Obtained from the Ishiagu Field *(Trend: E –W);* (a) Profile-5; (b) Profile-6.

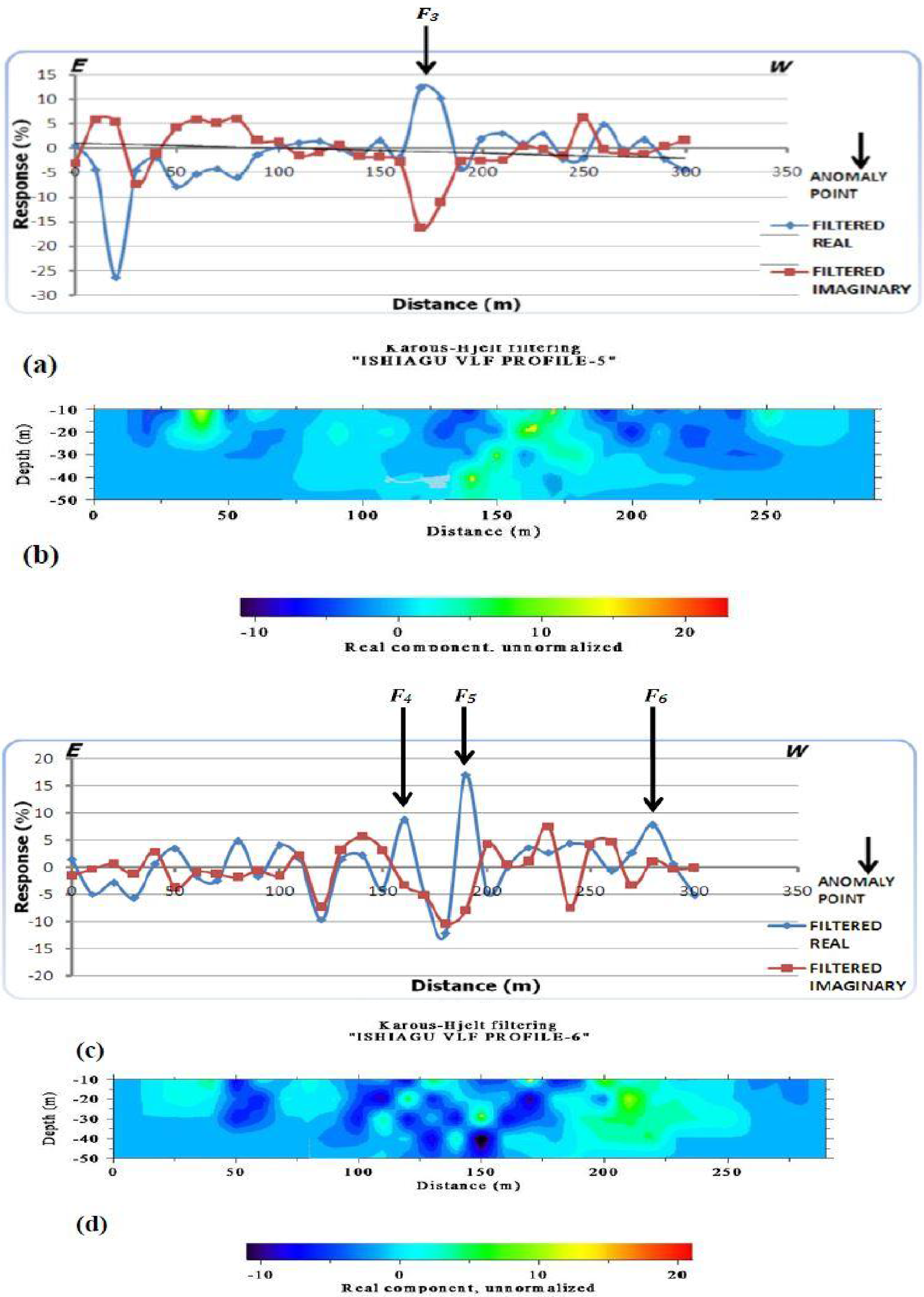

Figure 6: Filtered VLF-EM In-phase and quadrature components of tipper (%) and corresponding current density pseudo-sections of; (a-b) profile-5 (*Trend: E –W*) and (c-d) Profile-6 (*Trend: E –W*).

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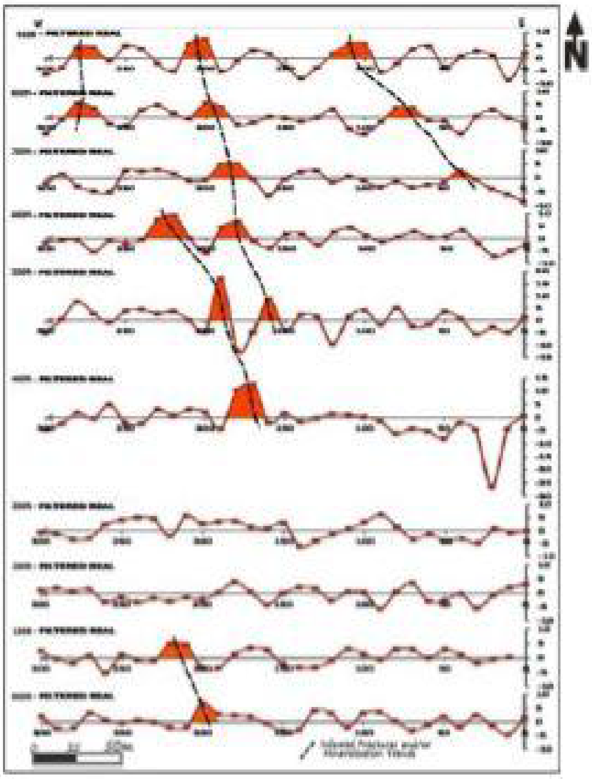

Figure 7: The Detected VLF-EM anomalies (Pb-Zn Veins) of the study area.

mineralized veins in Ishiagu field [24-26]. The sharpness of the in-phase anomalies of P_{Anom-3} and P_{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 [27]. The northern parts of these anomalies along with P_{Anom-5} outlying from the anticlinal axis (Figure 8) are of broad and moderate VLF responses indicating their occurrence at a profound depth with enormous 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 [28].

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 to be for the cretaceous intrusions in Ishiagu area. The N_{Anom-1} anomaly is on the same trend with the prospective mineralized veins. Its parallel and proximity to the P_{Anom-3} and P_{Anom-4} as emerged on profiles P-5, P-6 and P-7 (Figure 9) 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 N_{Anom-1} and N_{Anom-2} respectively also suggest these intrusions to be of Cenomanian and Santonian episodes respectively [29-32].

The depth to these anomalous bodies was also obtained in this work from the shape of the raw VLF-EM readings. The peak-to-peak horizontal distance on a raw in-phase anomaly is about the same as the depth of the conductive body known to be positioned at the crossover point of the anomaly [33]. This simple "rule of thumb" was applied in this work to evaluate the depth of these prospective mineralized veins as outlined in Table 1. The computed depth values obtained from the Ishiagu field was plotted and contoured using surfer-10 software (Figure 10). 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 [34].

Consequently, the overall trace of the VLF anomalies most proximate to the anticlinal axis likely indicates the near surface trace

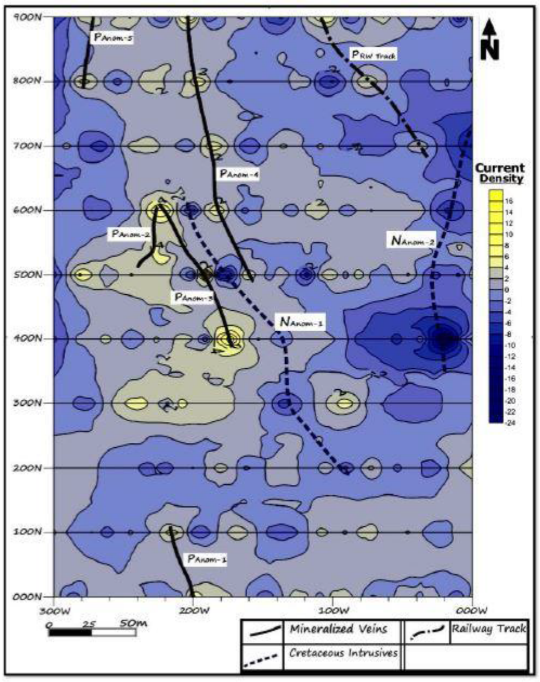

Figure 8: Current density map for the Pb-Zn mineralization in Ishiagu area.

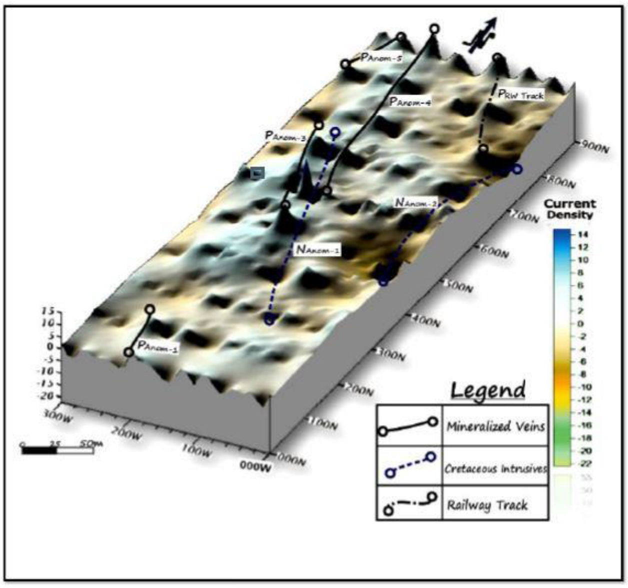

Figure 9: 3-D View of the current density map for the Pb-Zn mineralization in Ishiagu.

Profiles	Anomaly Points	Measured Horizontal Distance (m)	Vein Numbers	Vein Trend	Vein Length (m)	Depths (m)
P1	F1	200	Anom1	NNW-SSE	100	10
P2	F2	212	Anom1	NNW-SSE	100	16
P3		80	Intru1	NW-SE	400	10
P4		132	Intru1	NW-SE	400	12
P5		20	Intru2	N-S	350	22
		135	Intru1	NW-SE	400	10
	F3	171	Anom3	NW-SE	200	12
P6		30	Intru2	N-S	350	12
	F4	160	Anom4	NNW-SSE	400	10
		175	Intru1	NW-SE	400	7
	F5	190	Anom3	NW-SE	200	11
	F6	278	Anom2	N-S	80	12
P7		18	Intru2	N-S	350	9
	F7	182	Anom4	NNW-SSE	400	17
		180	Intru1	NW-SE	400	10
	F8	223	Anom2	N-S	80	19
			Anom3	NW-SE	200	
P8		3	Intru2	N-S	350	14
	F9	35	RW Track	NW-SE	-	-
	F10	175	Anom4	NNW-SSE	400	19
P9	F11	71	RW Track	NW-SE	-	-
	F12	194	Anom4	NNW-SSE	400	19
	F13	276	Anom5	NE-SW	100	13
P10	F14	100	RW Track	NE-SW	-	-
	F15	202	Anom4	NNW-SSE	400	22
	F16	244	Anom5	NE-SW	100	12

Table 1: Summary of the Obtained VLF-EM Parameters of Ishiagu Area.

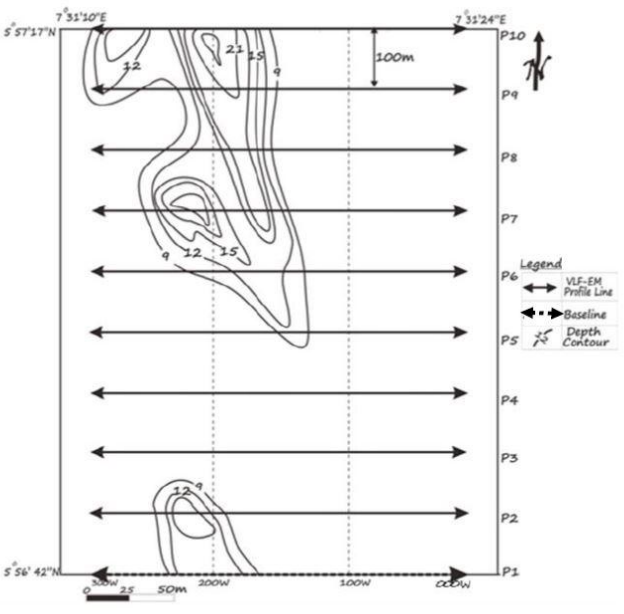

Figure 10: Depth map of the prospective Pb-Zn mineralized veins (*contour interval*~3 m).

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 to fracture extension as a clear clue to extension of Pb-Zn mineralization in Ishiagu area [35]. The NW trending of these outlying fractures 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 of Ishiagu. To this upshot, concerted efforts involving 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 in Ishiagu, thus calling for trenching across these prospective mineralized veins for further authentication.

Conclusion

The high VLF anomalies delineated from Ishiagu area, in the SW part of Abakaliki basin as a rule yielded a high conductivity contrast result well-suited for Pb-Zn mineralization and the geologic information of the area. KHF filtering techniques were integrated and applied in the VLF data interpretation of the Ishiagu area and results of strong EM induction were detected, probably indicating the presence of Pb-Zn deposits. 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 survey area indicate deeper sources while the sharp tipper responses observed in the central part indicate shallow sources in correspondence to the NE trending anticlinal axis.

All these deductions in queue to the geologic information of the area definitely confirm the efficacy of VLF technique to enhance geological mapping over well concealed mineralized areas. In all cases where there is VLF data available on a given profile, the VLF responses correlate with changes in the apparent resistivity. 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. 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 area.

Because of the economic efficiency of this method, speed of field survey and cost effectiveness of the operation, the VLF method is recommended for rapid geophysical exploration of Pb-Zn mineralized zones.

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