PHYSICSAccess Research Paper
ISSN Online: 2756-3898, ISSN Print: 2714-500X https://doi.org/10.47514/phyaccess.2023.3.1.006

In-Phase/Quadrature Signatures of a Very Low-Frequency Electromagnetic Survey for the Delineation of Cassiterite at Rafin Bareda, Dutsen-Wai, Kaduna State, Nigeria

Micah Adamu[1], **Nasir K Abdullahi**[2] **and Matoh D Dogara**[2]

[1] Government Secondary School, Kagadama, Ministry of Education, Kaduna State, Nigeria
[2] Department of Physics, Kaduna State University, Kaduna, Kaduna State, Nigeria

Corresponding E-mail: micahadamu39@gmail.com

Received 01-03-2023
Accepted for publication 18-04-2023
Published 19-04-2023

Abstract

The VLF-EM geophysical technique was used to delineate the zones of cassiterite at Rafin Bareda, Dutsen-Wai, Kubau Local Government area of Kaduna State, Nigeria which is located at Latitudes 10°51'46"N and Longitudes18°12'50"E. The research covered eleven profiles taken uniformly in the West-East direction each of length 1000 m with a total of 1100 stations. Scentrix VLF equipment was used to obtain the VLF-EM data (In-phase and Quadrature in percentages) with a detected field of 19.1 kHz transmitter in Rosnay, France. The plots of in-phase and Quadrature revealed various cross-overs (fractures/mineralized zones). However, the Fraser filter of the in-phase components was employed to reduce noise and enhance signal strength. Consequently, the Fraser-filtered of in-phase plots peaks around the crossover which confirmed the probable fractured/mineralized cassiterite zones. The Fraser filtered of the in-phase components revealed the continuous and extending nature of probable mineralized cassiterite zones which are dominant on profiles G and H.

Keywords: Cassiterite; Rafin Bareda; VLF-EM method; In-phase; Quadrature; Fraser-filtered.

I. INTRODUCTION

The major issues in our contemporary times ranged from economic and environmental problems emanating due to the activities of human beings to explore nature such as artisanal mining, quarrying, etc. Nigeria is lucky to have an enormous number of unexploited solid minerals such as gold, cassiterite, columbite, Tantalite etc. [1]. These mineral resources which include cassiterite find a variety of industrial applications. Cassiterite (SnO_2) is the sole source of Tin, often used in the production of corrosion-resistance alloys including circuit boards, for televisions, computers, microwaves and foil paper, in that, it contained a minimal liquefying value that is considered most appropriate in this regard. More so, electronic products for medical reasons commenced the production of solder with a higher percentage of Tin with 2.5% of lead rather than 40% of lead [2]. As the technological application of Tin is growing high from the long history of Tin production, hence, the Tin demand in the future will probably grow high. About 80% of Cassiterite in Nigeria is found as sediments (tin placer deposit) resulting from veins and granitic rocks [10]. Other sources of ore-bearing cassiterite (Tin ore) in Nigeria are the alluvial and elluvial deposits from the biotites granite within the Jurassic alkaline ring complex of the Jos plateau

[2]. Cassiterite is found together with other minerals such as columbite, monazite and accessories like zircon and topaz [2]. The younger granite provinces in Nigeria include Dutsen-Wai, Nok, Kudaru, Jema'a, Richi, Pankshin, Amo, Keffi, Jos, etc., [3].

The study area is surrounded by an identical amphibiotic grade basement composed of migmatite and granite gneisses (Fig.1); Volcanic, biotite granite and albite riebeckite granite are the three basic igneous units common to the younger granite group arranged in succeeding order.

Several mining practices (formal and informal) have taken place over the years at Rafin Bareda [5]. Most active mining sites around Rafin Bareda, Dutsen-Wai have been carried out by novices using trial and error means, to meet their individual financial needs not minding the safety, environmental degradation and the host community. Most mining in the basement complex occurs either on the surface or underground [6]. These forms of mining are very expensive and can lead to the death of human beings, as in the reported death cases of more than hundreds of children in Zamfara state, in 2005, due to contamination and most cases tunnel collapse. Although, the scenario is yet to be reported in the study area but observed to be rampant where there is extreme mining, especially in Jos, Plateau state and environs.

The geophysical method such as Very-low Frequency Electromagnetic (VLF-EM) method is used simultaneously for environmental and minerals exploration purposes with greater advantages because of the minimal or complete restriction to inversion and disturbance of the sub-surface, aside from quick coverage of a wide area, no demand for installation of transmitter and a few crew requirement for the research.

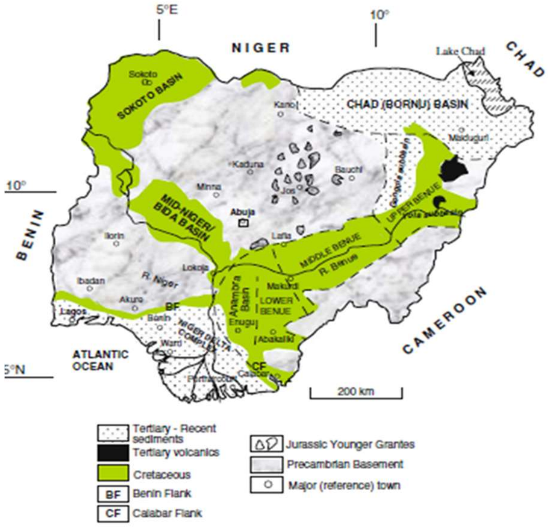

Fig. 1 Dutsen-Wai Younger Granites Rocks [4]

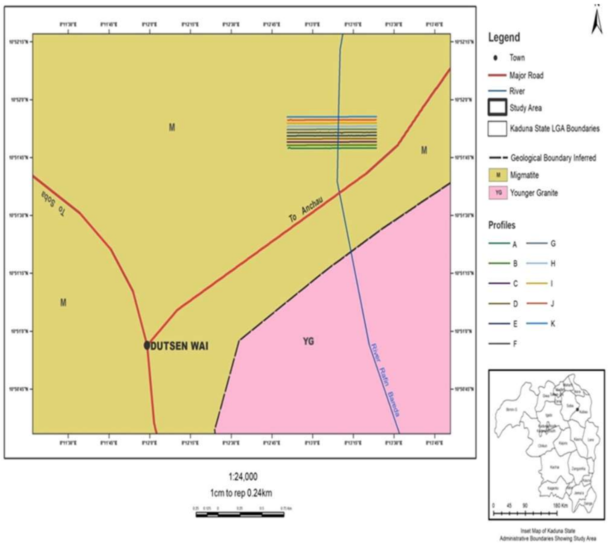

Fig. 2 The geology of the study area

II. THEORY OF VLF EM METHOD

VLF survey method is similar to the electromagnetic survey except that the transmitter of the VLF-EM method is located from a very far distance away from the receiver which allows prospecting over shallow subsurface; while the transmitter of the electromagnetic method is purposely installed closer to the receiver which allows survey over deeper depth. The transmitter generates a displacement current at the ground surface inducing a magnetic field component, the induced magnetic fields generate an electric field around the conductive zone. The incident fields are known as primary fields in the VLF-EM method, while, the induced fields are known as the secondary fields; with a frequency of 15 to 30 kHz transmitting between the surface of the earth and the ionosphere. In the presence of conductive bodies, the primary field which encompasses the electric and the magnetic fields induces a secondary current inside called Eddy current and becomes polarized (changes in phase, amplitude and direction) as in Fig. 2.

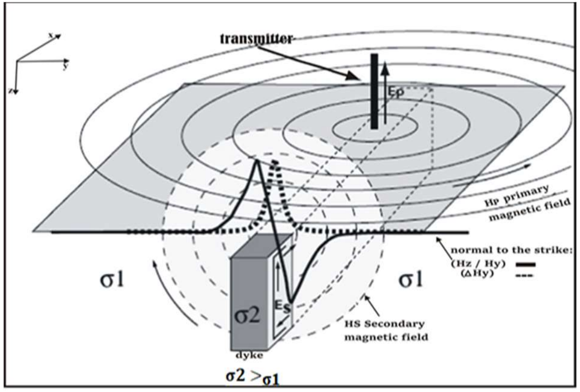

Fig. 3 VLF-EM fields in E-polarization with hypothetical signals over a perpendicular conductive dike [7]

Where H_z is the vertical magnetic field component, H_y is the horizontal magnetic field component, σ_1 and σ_2 are the uniform conductive and anomalous conductive sub-surfaces respectively; E_p is the primary electric field component and E_s is the secondary electric field component.

By measuring the total fields, the primary and the secondary fields, the geological properties of the subsurface of the earth can be detected [8]. The response of the sub-surface to the incoming field called the tilt angle (θ) is given by (1).

$$\theta = tan^{-1}\left(\frac{\mathrm{Hz}}{\mathrm{Hy}} Sin\alpha cos\phi\right) \approx \frac{\mathrm{Hz}}{\mathrm{Hy}} Sin\alpha cos\phi \qquad (1)$$

The eccentricity, ε is the change of the minor axis to the major axis of the polarized ellipse that is,

$$\varepsilon = \frac{b}{a} \approx \frac{\mathrm{Hz} sin\alpha sin\phi}{\mathrm{Hy}} \qquad (2)$$

Where b is the minor axis signal and a, is the major axis signal. The term $\frac{\mathrm{Hz}}{\mathrm{Hy}} Sin\alpha$ is approximated as the in-phase (real) component of the magnetic field. The eccentricity represents the imaginary or quadrature dimension in the VLF-EM survey.

A. Skin-depth

This is the measure of penetration of electromagnetic waves through a conductor and is a function of frequency. The skin depth is given by (3).

$$(\delta) = \left(\frac{2}{\mu\sigma\omega}\right)^{1/2} \approx 503.8\left(\frac{\rho}{f}\right)^{1/2} \qquad (3)$$

Where μ the permeability of the free space, ω is the angular frequency and f is the frequency of the transmitting station.

B. Depth of Penetration

The maximum depth Z_e [9] at which a conductor may still produce a recognizable EM anomaly is given by (4):

$$Z_e = \frac{100}{\sqrt{\sigma f}} \qquad (4)$$

III. VLF EM DATA PROCESSING

Preceding data acquisition, reduction and analysis of data was carried out as a means for interpretation. These techniques required the smoothing of the field data to envisage the sub-surface geological structures. The in-phase and Quadrature components were confined to pass-through filters to reduce noise and enhance signal [10, 11]. Though, this results in a loss of 20% to 30% of data [9]. The Fraser filter derivative is given as;

$$(g_4 + g_3) - (g_2 + g_1) \qquad (5)$$

According to [10, 12], the Fraser filter

1) removes direct current and entirely mitigates long wavelength signals,
2) removes Nyquist frequency noise which may result in the distortion of the signal,
3) adjust both positive and negative frequencies to 90° and
4) its selective ability concentrates on the wavelength of five times the station spacing.

This filter function changes all re-occurring crossover or reflection points over the anomaly. The in-phase and distance of the filtered data were plotted to show the genuine conductive zones.

IV. MATERIALS AND METHOD

The instruments used for data acquisition include Scintrex VLF equipment compass and GPS. The Scintrex VLF equipment was used for collecting VLF data (i.e. in-phase and out-phase) magnetic components; GPS (Global Positioning Satellite) was used for collecting coordinates; the compass was also used for locating the direction of the geological strike. Other accessory equipments used include field-note and machetes for writing observations on the topography of the survey area and clearing of bushes where necessary respectively.

This method employed involves the use of the VLF-EM technique to investigate the minerals potentials (cassiterite) of the study area. For environmental purposes, eleven (11) profiles tagged A to K were investigated with each profile having 100 stations at a spacing of 10 m and profile separation of 25 m. A transmitter located in Rosnay, France with a passive Field of 19.1 kHz was used [12]. The compass was used to ascertain the northern direction which happened to be the direction of the suspected geological strike of the anomaly; it was in this direction that the suitable frequency used in this survey was captured. The primary field response is effective when the EM signals are at an angle of 90 degrees (vertical) to the structure. The coordinate system used here is the UTM (Universal Transverse Mercator) system by the use of the GPS [12]; the advantage of this system is that it measures in metric system using metres (or kilometres) for distance units and simplifies the mathematical computation in terms of scale and distance measuring.

V. RESULTS AND DISCUSSIONS

The results of the raw data (In-phase and Quadrature components) as depicted in Fig. 4, indicates that the raw result recorded from the fieldwork has been affected by intricacies such as interference, noise and near resistivity.

These plots (refer to Fig. 4) of raw data aid in predicting the location of geological anomaly (conductor) along the profiles. The in-phase is sensitive conductive bodies whereas, the quadrature response is sensitive to the changes in the subsurface conductivity changes. The in-phase also aid in locating fractures whenever it crosses the horizontal axis along the profile. The quadrature component at these cross-overs shows negative inflection (black arrow) and positive inflection (red arrow) with an amplitude which may indicate a good conductor in a weakly conductive ground and a relatively weak conductor in a non-conductive ground respectively [12]. The in-phase and quadrature components within the study area revealed several cross-overs varying from one Profile to another, which may be target locations for further investigations.

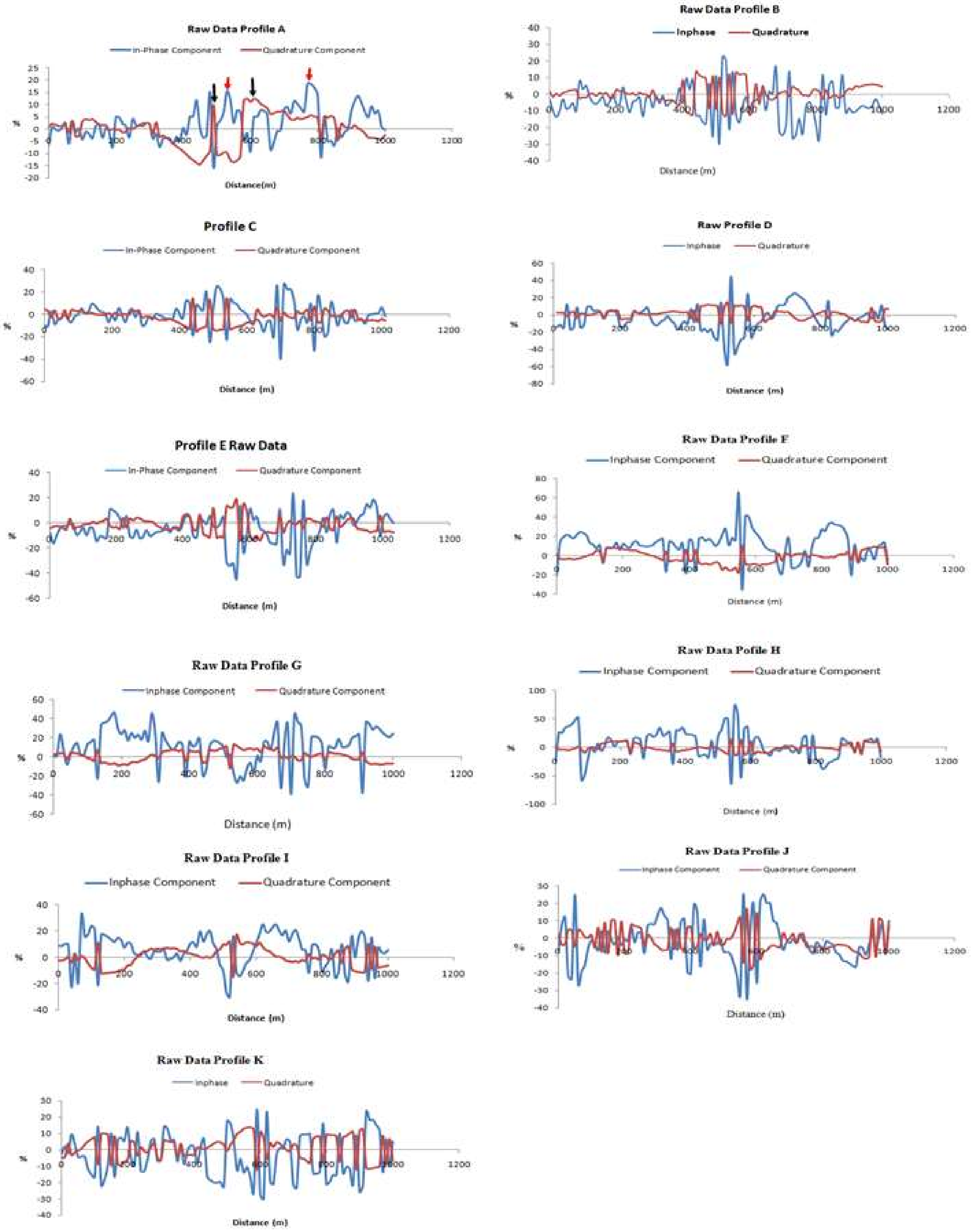

Fig. 4 Plots of raw data (in-phase and Quadrature) components

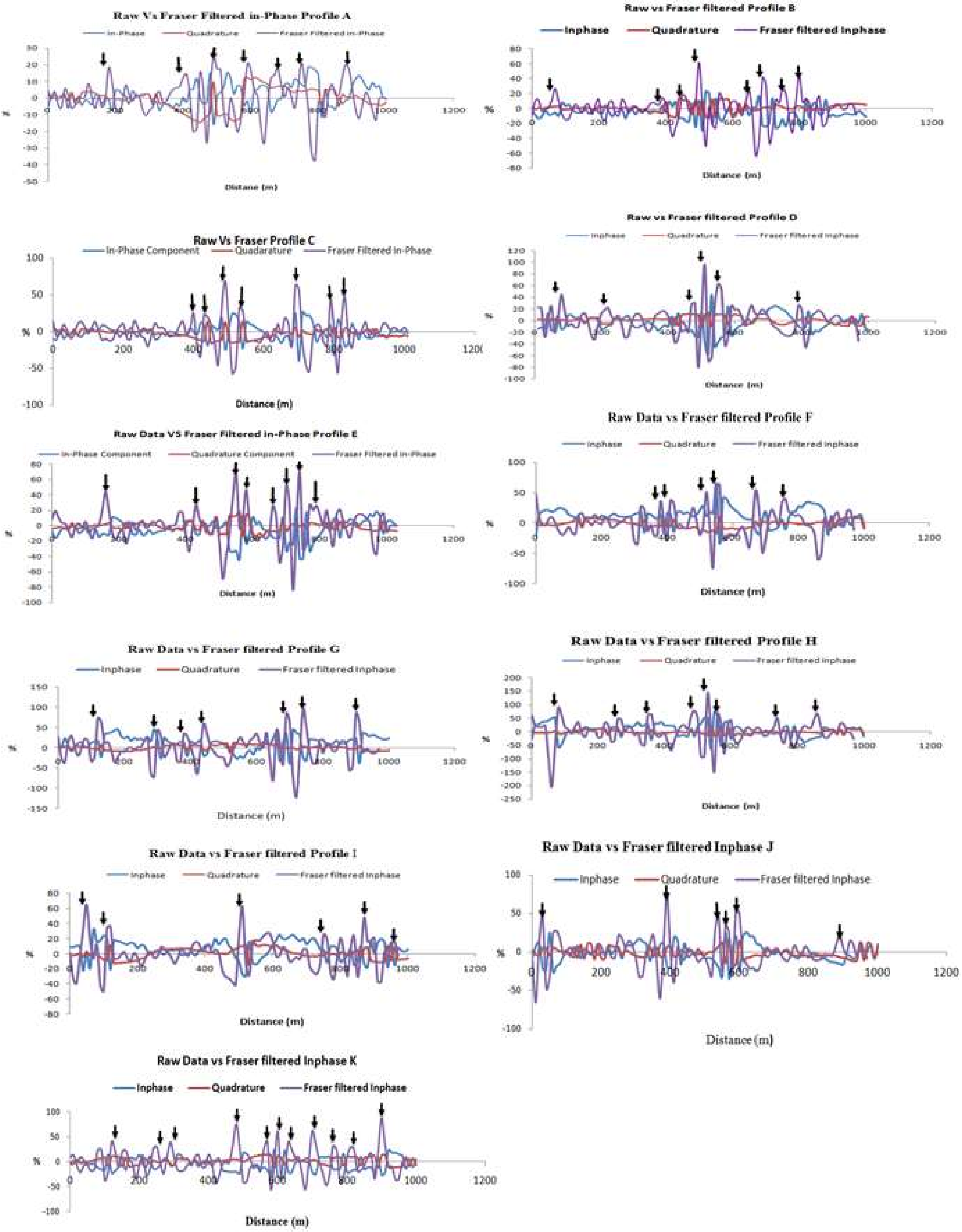

Fig. 5 Plots of in-phase/Quadrature/Fraser filtered in-phase against distance.

Fig. 5 indicates that the anomalies that affected the raw in-phase components have been filtered [13]. Fig. 5 comprises of raw VLF-EM data and the Fraser-filtered of the in-phase components of all the profiles. Profile A, have several cross-overs and the Fraser filter was applied to the in-phase components to modify these cross-overs. The Fraser-filtered in-phase revealed sharp peaks at $400\ m - 500\ m, 600\ m - 700\ m$ and $900\ m$ along the profile. These discrete locations may be prospective fracture/mineralized zones (indicated by the arrows). Fraser filtered of the in-phase have amplitude ranging from -37.3% to 24.7%, and at 800 m, the highest negative peak was recorded which suggests fresh intrusive subsurface structures [13].

In Profile B, the Fraser-filtered in-phase components yield strong amplitude over the top of the conductor [10], that is, it turns cross-overs into peaks [5]. The peaks along this profile were observed between 400 m to 800 m with a negative trough of -63.8%.

The Fraser-filtered in-phase (Profile C) modified the negative inflection into sharp positive peaks of 69.1%, 32.5%, 63.3%, 43.2% and 47.6% at distances of 490 m, 530 m, 690 m, 790 m and 830 m respectively. These peaks varied from -56.4% to 69.1% depicting a non-homogeneous sub-surface. In-phase is responsive to conductive anomaly; on the other hand, quadrature response is sensitive to the changes in the subsurface conductivity changes [14].

Profile D shown in Fig. 5 is aimed at locating the causative bodies (conductors) along the profile surveyed. The in-phase component varied from -56.1% to 44.5% with several cross-overs. The Fraser filter turned the crossover of the in-phase into positive peaks on top of conductors. These pointed peaks were located at 80 m, 210 m, 510 m and 550 m with the corresponding amplitude of 44.9%, 18.2 %, 94.9% and 63.8% respectively. The broader peak at 210 m suggests low frequency with a deeper source [5].

The raw VLF data and the Fraser filtered of the in-phase component of Profile E, varies from -83.2% to 70.2%. Similarly, positive peaks were located $at\ 160\ m, 550 m, 580\ m, 710\ m$ and 740 m, suggestive of the existence of fracture or conductor on the profile, while a negative trough possible for an un-fractured geological structure is depicted at 500 m [13].

The major positive peaks of Fraser filtered of Profile F, occurred at the profile distances of 320 m, 380 m, 520 m, 560 m, 670 m and 760 m with amplitudes of 27.2%, 36.1%, 51.2%, 64%, 54% and 40.3% respectively; which were locations for possible cassiterite mineralization on the profile.

Profile G displayed excessive sharp amplitudes at discrete distances of 120 m, 300 m, 380 m, 440 m, 690 m, 740 m and 900 m. The broad amplitude along the profile at 600 m has an amplitude of 34.6%; the low frequency suggests deeper sources.

Fraser-filtered in-phase of Profile H was applied on the in-phase component to change these cross-overs into peaks (Fig. 6) which aided in differentiating geological materials. The positive peaks confirmed fractures characterized by conductors. These peaks of Fraser-filtered constituted the largest range of the amplitudes from -205.3% to 143.5% in the study area with probable fractures located at 80 m, 350 m, $490\ m$, 560 m and 860 m. However, broader amplitudes of high frequencies were found at $80\ m, 490\ m$ and $860\ m$, in that order, indicating shallow massive fractures [8].

The discrete location along Profile I showed pointed amplitudes at $70\ m, 220\ m, 500\ m$ and $900\ m$. This variation could be characterized by fractures, fresh rocks, and other geological structures that host and preserved cassiterite mineralization.

The Fraser filtered of the in-phase component (Profile J), varies from -29.8% and 38.3%. The possible highest peaks of 44.2%, 21.7%, 74.3%, 44.5% and 51.9% amplitudes suggest the existence of fractures or conductors in the profile. The quadrature component varied from -17.6% to 17% with positive inflections at 200 m, 750 m and 960 m. These points implied a relatively weak conductor in a non-conductive ground.

The Fraser-filtered of the in-phase component (Profile K) shows sharp amplitude at profile distances of 120 m, 480 m, 700 m and 900 m, all consisting of broad amplitudes of 40.6%, 76.2%, 61.3%, 62.2% and 88.6% respectively. The negative peaks of the Fraser-filtered may be an intrusive causative body of mineralized cassiterite. However, broader amplitudes of high frequencies indicate shallow massive fractures [5].

These graphs (refer to Fig. 5) showed numerous cross-overs of the in-phase component to the horizontal axis along all the profiles which indicate the presence of sub-surface anomalies (conductors) [5]. These cross-overs were subsequently turned into peaks by the application of the Fraser.

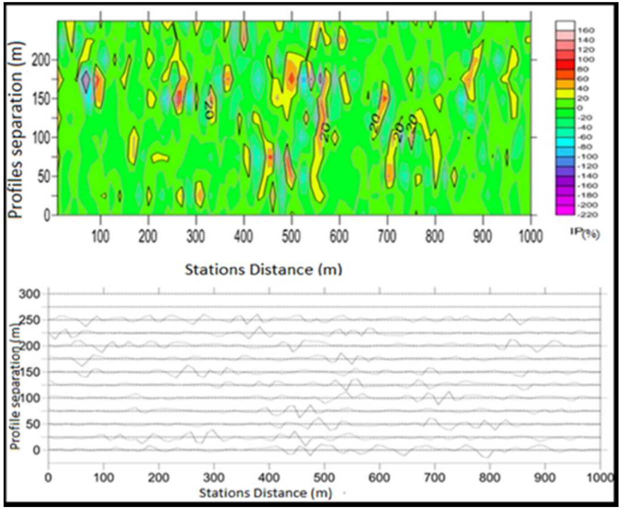

Fig. 6 2-D map of in-phase (%) component with its stacked profiles showing the tendency of the sub-surface fracture of the study area.

Fig. 6 represents 2D of the in-phase component with the stacked profiles; the map exposes the entire area investigated, showing the spatial distribution of possible fractures that can be mined for cassiterite within the study area. These possible minable targets are found precisely at the spot of purple to red colouration in the vicinity. On the other hand, the stacked plot of the in-phase component revealed a trend of fracture along the collected profile. Consequently, the positive and negative peaks in Fig. 6 show fractures and fresh sub-surfaces respectively.

Fig. 7 is a 2D map showing the level of elevation in relation to mineralization within the study area. It is pertinent to know that lines 2-3 at a distance of 450 m, lines 4-8 at a distance of 100 m and lines 9-11 at a distance of 450 m all to the East-west direction and lines1-4 at a distance of 300 m, line 9-10 at the distance of 250 m all to the West-East direction, showed high elevation; while, regions with yellow, green, light blue and blue colouration represent decreasing level of elevation in that order. Areas with very low elevations were recorded at the eastern part of the research site. It is also imperative to note that, zones with low elevation provide more fractures/conductors/cassiterites mineralization zones with high elevation as established in Fig. 7.

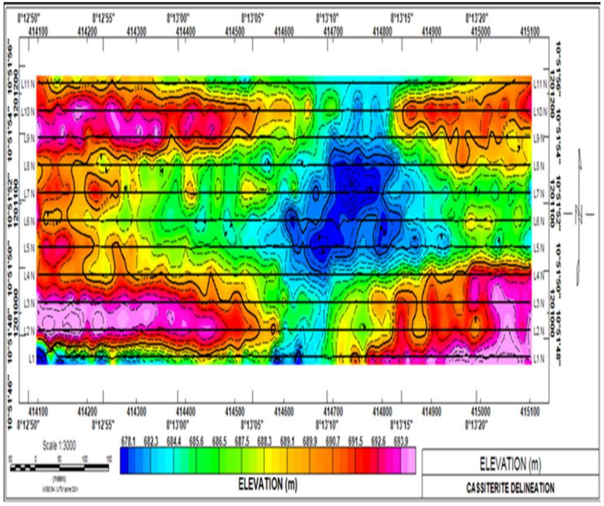

Fig. 7 Elevation trends in the study area.

VI. CONCLUSION

The present research used the VLF-EM technique and its filtering process such as Fraser filtering of the in-phase aimed at delineating potential mineralized Cassiterite zones. Results revealed anomalies located on all profiles at the crossover of the plotted raw VLF data (In-phase and Quadrature components). Similarly, the in-phase, Quadrature and Fraser-filtered in-phase components plots show the peak of Fraser-filtered components around the cross-over of the in-phase and Quadrature components. These in-phase and peaks indicate the probable fracture/mineralized cassiterite zones which were concentrated at profiles G and H and toward the eastern part of the study area. However, the mining activity of the artisan miners in most cases is not consistent with the inferred result of the present research revealed in the study area. Furthermore, the outcome of this research work has also shown that, despite years of extraction of cassiterite, there may be cassiterite deposits in Dutsen-Wai area and if active efficient mining activities are applied it can result in positive development and reduced negative impact caused by artisanal mining.

ACKNOWLEDGEMENT

The authors appreciate the leadership of the Department of Geology, Nigerian Geological Survey Agency (NGSA), Kaduna, for the use of the VLF equipment for this research.

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