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Research Article

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Special Issue

A Themed Issue in Honour of Professor Clement Uche Atuanya on His retirement.

This themed issue pays tribute to Professor Clement Uche Atuanya in recognition of his illustrious career in Metallurgical and Materials Engineering as he retires from Nnamdi Azikiwe University, Awka. We celebrate his enduring legacy of dedication to advancing knowledge and his impact on academia and beyond through this collection of writings.

Edited by
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Identification of tantalite mineralization zones in Igbonla area, North-Central Nigeria using Very Low Frequency Electromagnetic (VLF-EM) techniques

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Abstract
The identification of potential tantalite mineralization zone became very crucial due to its technological uses to improve economic growth of Nigeria. The study aims to give researchers and government agencies a comprehensive perspective of the subsurface using Very-Low Frequency Electromagnetic (VLF-EM) survey to identify possible tantalite mineralization zones within Igbonla, Kwara state. The methodology involved conducting a VLF-EM survey using ABEM WADI VLF receiver. The data collected was processed and analyzed to delineate the presence of tantalite using KHFFLIT software. The results of the study indicate the presence of three different fracture zones generally identified based on generated 2-D map of current density and are prominently oriented in the NW-SE direction. The first zone is the conductive zone which is characterized by a high current density values ranging from 15 to 40 %. This could be potential tantalite mineralization zone. The second zone is the Non-conductive zone which is characterized by a very low current density, with negative values ranging from -5 to -40. This zone could be attributed to sulphide or aquifer. The third zone is the intermediate zone with a current density ranging 14 to -4 %. The areas with high VLF responses indicate probable mineral veins over the study area. These zones could as well be studied further for potential mineralization. The results indicate that VLF-EM survey has successfully identified anomalies potentially associated with tantalite mineralization.

Keywords: Tantalite, Mineralization, VLF-EM, Igbonla, Conductive Zone, Intermediate Zone, Non-Conductive Zone

1. Introduction

The geophysical surveys remain the best tool available for discovering what's beneath the surface of the planet earth without wasting time, being intrusive, being costly, and in a less arduous way (Abdelrady et al., 2023; Okada, 2022). In Nigeria's mining industry, various geophysical techniques have been crucial to the finding and extraction of minerals (Azubuike et al., 2023). These surveys map and quantify the physical characteristics such as density, magnetic susceptibility and electrical conductivity of the earth's subsurface using a variety of tools, equipment and methods, providing important details about the composition, arrangement, and resources. It is important to state that reconnaissance geophysical surveys are one of the most affordable options for preliminary mapping and exploration among the various geophysical survey kinds.

In general, geophysical surveys look for anomalously high or low concentrations of mineral signatures that are either explicitly or implicitly connected to differences in one or more physical properties between the object to be studied and the subsurface rock(s) (Ojo et al., 2014; Shirazy et al., 2021). The results of geophysical surveys are then utilized to locate interesting targets or to contrast variances in property value determined by geological changes. It is implied that the main goal of geophysical survey is to gather further data about the local geology, specifically for target delineation.

A single geophysical approach rarely produces highly dependable or desirable findings because each one is only better suited for a specific kind or form of mineral deposit with a restricted depth of exploration. The Very low frequency electromagnetic method is one of the geophysical methods that make use of the principles of electromagnetic induction. Specifically, it uses the military radio transmitter to receive and transmit signals (Gross et al., 2018). It has been used before to identify conductors that may host cracks and economic mineralization (Adamu et al., 2022). It also finds its importance in linear conductive and resistive layers, geoenvironmental problems, groundwater exploration and locating the position of anomalous source bodies beneath the earth surface. The three primary benefits of the VLF approach are its high speed, wide coverage, and affordability.

The main aim of this study is to give researchers a comprehensive perspective of subsurface in order to delineate tantalite mineralization zones in the southern region of Kwara state at Igbona Irepodun local government area. The specific goal is to collect information and data to ascertain whether tantalite is present and concentrated in the target location. This survey is crucial because tantalite, a transition metal element has significant economic values, and it has become well-known due to its remarkable qualities, such as its high dielectric constant (Melcher et al., 2015; Zhang et al., 2024), consistency of its oxides, and resistance to corrosion (Pickering et al., 2019). Additionally, Tantalite metal has also recently gained a lot of attention from the aerospace, military, automotive, and medical fields (Habinshuti et al., 2021; Rajak et al., 2022).

Very Low Frequency Electromagnetic (VLF-EM) has been successfully used for mineral exploration in different part of Nigeria. The VLF-EM survey is a reliable technique for identifying network of fractures usually hidden by overburden materials that overlie the crystalline basement as reported by Faruk (2019). This project was aimed at confirming the occurrence of sulphide mineralization within the study area, using both the geological information and VLF techniques. This result indicated that there is high conductivity inferring that the suspected deposit is expected to be economically viable.

A detailed Very Low Frequency Electromagnetic (VLF-EM) hydrogeophysical survey has also been undertaken by (Mahmud, I. et al., 2023) to identify conductive zones and recommend potential areas for possible groundwater development in the Bichi area of Kano state northwestern Nigeria. Also, Chinyem et al (2014) conducted a combination of electromagnetic and geoelectric sounding to locate fissured zones and associated groundwater at Igbonla and environs. The integration of both electromagnetic profiling and electrical resistivity sounding has provided valuable information on the hydrogeological framework and subsurface disposition of major aquifer units of Igbonla.

Exploration for the tantalite mineral has yet received many literatures. However, the earliest study on tantalite mineralization in Nigeria identified tantalite-bearing pegmatites in Nasarawa area of Nigeria and reported high grade tantalite occurrences. More recently, Amuda et al (2018) studied geochemical characteristics of tantalite mineralization in Nigeria. The researchers found that the tantalite deposits in Nigeria are enriched in tantalum, nobium and other trace elements, indicating a potential for commercial exploitation.
The research for identification of tantalite mineralization zones in Igbonla area using VLF-EM techniques lies in the fact that it provides a non-invasive method for locating and mapping tantalite deposits. Traditionally, exploration for the mineral in Igbonla area involves labour-intensive and expensive method of random drilling by the miners. This method is most time consuming and not resourceful. The method described here utilizes electromagnetic signals in the very low frequency range to detect conductivity contrasts in the subsurface. Previous studies within the area relied solely on geological mapping of the tantalite deposit and this new technique allows for a systematic assessment of the area, identifying potential zones that may have been overlooked in previous studies.

2.0 Material and methods

2.1 Location of study area

Location of Study Area

The study area is in Igbonla, a village in Irepodun local government area of Kwara state, approximately located about 5.6 km away from Ajase-Ipo and about 50 km to the capital town of Ilorin. The village is in the heart of rainforest in the southern part of Kwara State. It is accessible through a series of roads from Ajase-Ipo, Offa and Omu-Aran. The Igbonla community has a large population in the farming profession because of its arable expense of land. It lies between Latitude 8.3110 N – 8.3130 N and longitude 4.9670 E – 4.9690 E. Figure 1 shows the inset of map of Kwara state showing Igbonla in the map of Nigeria and the survey profile lines.

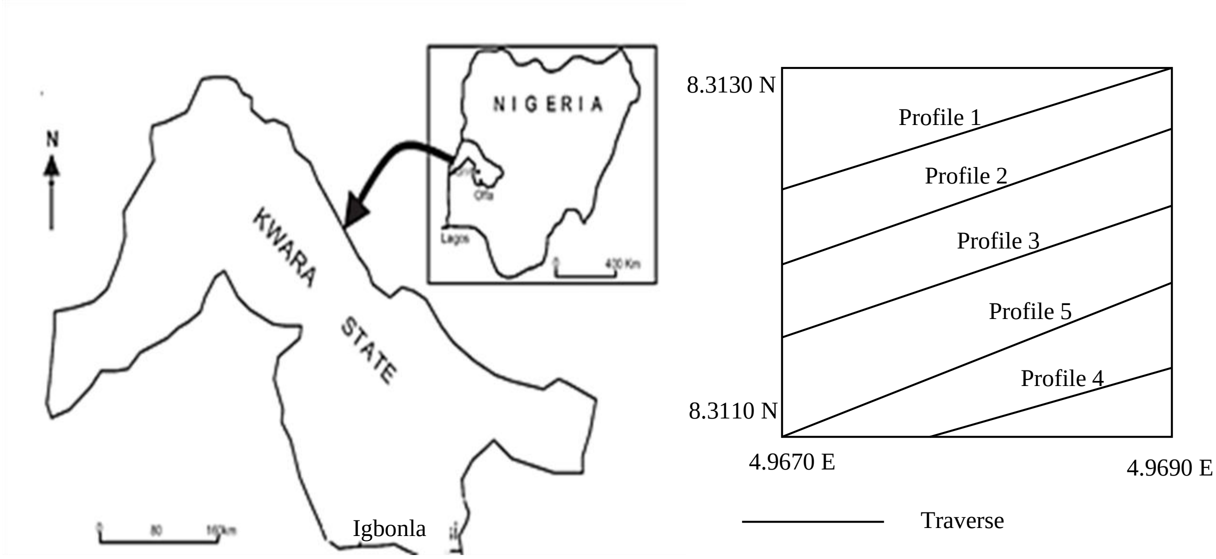

Figure 1: Inset of Map of Study Area Showing Profile Lines

2.2 Geological Setting of Study Area

Tantalite is a rare metal related to the mineral columbite. It is highly sought after mineral due to its high content of tantalum, a critical element for modern technologies. In Nigeria, tantalite mineralization is mainly found in the central part of the country, particularly in states like Plateau, Nasarawa, Kogi and some parts of Kwara. The mineral is associated with pegmatite dikes and alluvial deposits. Accurate identification and characterization of tantalite mineralization zone is essential for effective resource exploration and extraction.

Igbonla area is located in Irepodun Local government area of kwara state. Precambrian and Cambrian basement complex rock underlies much of Kwara state, with cretaceous and newer sediments covering the remaining area (Tijani, 2023). Igbonla therefore is located in the basement complex and is covered with a heterogeneous assemblage of Precambrian migmatite-gneiss complex, metasediments and granites that have undergone metamorphism. During geological research in the area, (Kayode et al (2015) identified three primary lithologic units: porphyritic granite, granite-gneiss, and migmatite-gneiss which can be host to some minerals. Other lithologic units present include quartzite with biotite gneiss, fine grained biotite and hornblende granite (Fig. 2). The main rock type in Igbonla include intruded granite, migmatites, pegmatite and quartzite which corresponds to the host of the main mineral of economic interest in Igbonla, Tantalite, and the Tantalite mineralization style is primarily hosted within lithium-cesium-tantalum (LCT) pegmatites, placer deposits made from carbonatites, granitic pegmatites rich in rare-earth elements, and alkaline granite-syenite complexes.

According to Shikika et al. (2020), tantalite and niobium are inextricably related and originate primarily from the columbite-tantalite group of minerals, which are found in trace amounts in primordial granites, granitic pegmatites, and greisen rocks. Tantalite can also be found in a variety of oxide mineral forms, such as wodginite, tapiolite, tantalite, and microlite. Igneous rocks, such as carbonatites, granites, pegmatites, and syenites, have mineral deposits that contain tantalum. The mineralization in the area is trending in the approximate N-S direction and the fault system is related to the Pan African Orogeny which occurred about 600 Ma.

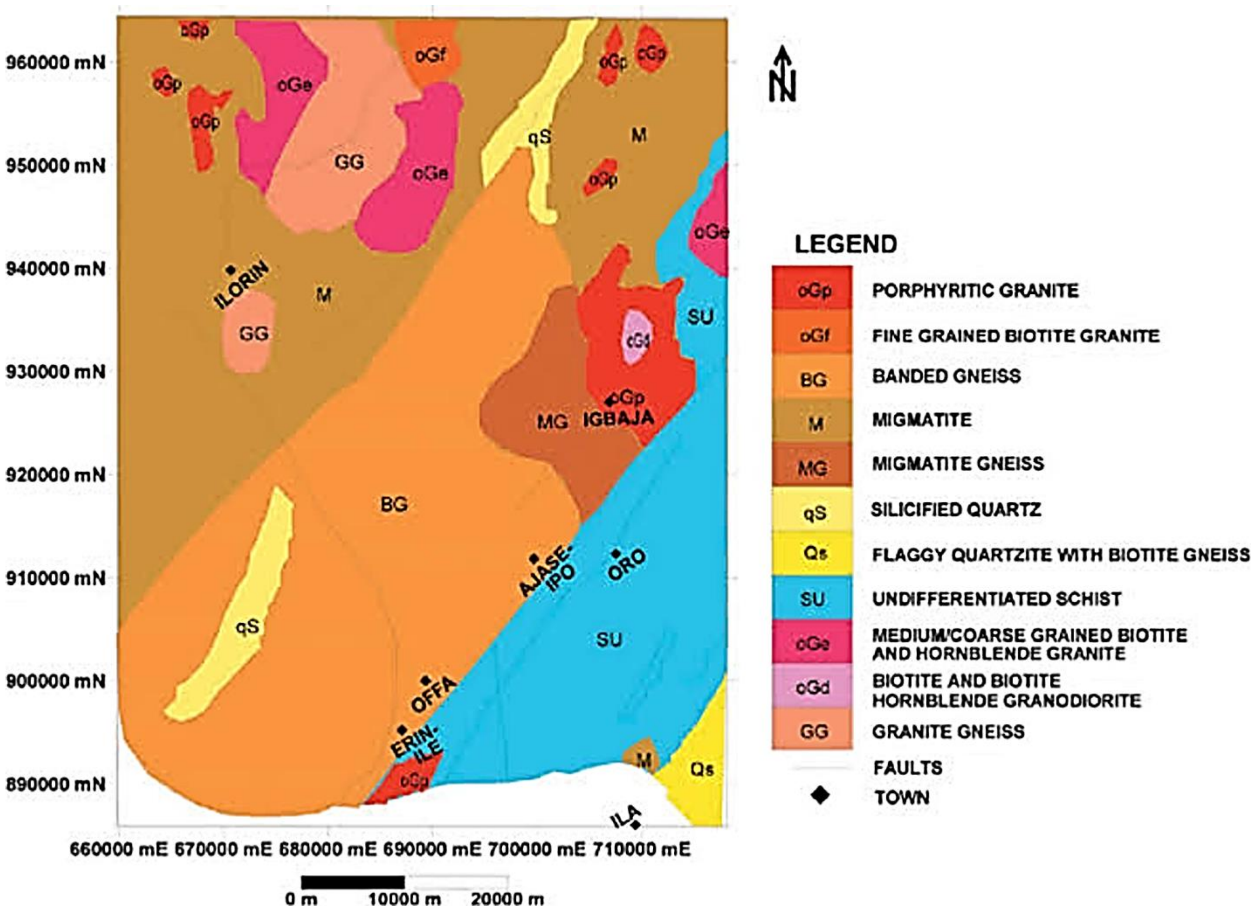

Figure 2: Geological map of Irepodun

2.3 Very Low Frequency Electromagnetic Method

The Very Low Frequency electromagnetic (VLF-EM) geophysical prospecting method is an inductive exploration approach and a passive geophysical method mostly utilized for mapping shallow subsurface structural features where current flow is induced by primary electromagnetic (EM) waves (Alao et al., 2024; Fasihi et al., 2023). The VLF method depends on transmitters dispersed over the globe. The frequency range of electromagnetic waves is 3–30 kHz. The interaction between the electromagnetic waves and the earth is then measured once the waves are transmitted globally. A secondary field is created when buried conductors interact with VLF electromagnetic radiation. Above the surface of the earth, the primary and secondary fields can be measured concurrently.

In this survey, a signal from a far-off radio station that broadcasts between 15 and 25 kHz—a very low frequency—was used. Throughout the whole research region, five NE electromagnetic profiles were taken at 5 m point intervals using the station UMS (Moscow, Russia), which operates at roughly 17 KHz. The electromagnetic field (EM field) emitted from a vertical LF transmitter station onto a uniform or horizontally layered earth model is comprised of two components: the horizontal magnetic field (H_x) and the vertical electrical field (E_y), both of which are perpendicular to the propagation direction. The term "in-phase" refers to the portion of the vertical field that is in phase with the horizontal magnetic field in this instance; "out-of-phase" refers to the portion that is out of phase with the horizontal magnetic field (quadrature Component).

A ground-based VLF survey was conducted in November 2022 in Igbonla, Kwara state. The survey was conducted utilizing a VLF receiver, to measure the natural electromagnetic signal in the target area. An ABEM WADI VLF receiver model was specifically used in this study following the manufacturer's instruction strictly. There were five VLF traverse lines totaling about 1900 m length in the VLF-EM survey. The VLF receiver was turned on and the initial amplitude and frequency readings were recorded. Approximately, 400 measurements were made at intervals of roughly 5 m on two grids that ran parallel to the two principal azimuths. The strengths of the vertical and horizontal fields at the ground surface were recorded by the ABEM WADI instrument in a ratio, which is reported as a percentage.

The relationship between the filtered real, or in-phase, and filtered imaginary, or out-of-phase, curves in comparison to standard model curves forms the basis for the interpretation. There has been no phase diagram interpretation or curve matching, the interpretation is therefore primarily qualitative. Fraser Filtering is a simple filtering technique that transforms crossovers into peaks, and removes regional gradients and intensifies anomalies from near surface (Fraser, 1969). In this study, the Fraser filter has been applied to both in-phase (real) and quadrature components of the VLF measurements. The Fraser filter shifts the data by 90 degrees and transforms the anomaly such that those parts with the maximum slope appear with the maximum positive/negative amplitude.

The analysis of VLF responses in terms of buried conductors was assisted by applying the Karous-Hjelt (K-H) linear filter to the observed in-phase or quadrature component of VLF data (Karous & Hjelt, 1983). An anomalous zone, then, is defined, areas with high positive peaks in the real component and a low negative anomaly in the imaginary phase. Furthermore, a zone of shallow overburden is indicated by a maximum negative anomaly in both the real and imaginary components, which is expected to disclose significant fractures in the form of a dyke (Jamal & Singh, 2018). The EM graphs exhibit a pretty thick overburden when real and imaginary data points are distributed evenly over them. Anomalies zones are also shown by the inflexion points connecting real and imaginary curves.

The VLF data processing were carried out using the KHFFILT software and the Surfer 11 version. In most cases, the out-phase components overlaps the in-phase components. This may be due to the geologic noise that is in the VLF data which did not allow the easy recognition of the conductive zones. Therefore, the noise was first filtered using a suggested simple numerical technique according to equation 1 as proposed by Fraser (1969).

$$F_{2,3} = (M_3 + M_4) - (M_2 + M_1) \qquad (1)$$

where M_1, M_2, M_3 and M_4 are four consecutive data points of the VLF profile. The equation above was repeated for the remaining consecutive data points on the traverse line such as M_4, M_5, M_6 and M_8 to obtain $M_{5,6}$ as in equation 2 i.e

$$F_{5,6} = (M_6 + M_7) - (M_5 + M_4) \qquad (2)$$

The filtered graph indicates crossover points which connote anomalous conductive bodies and positive in-phase which signifies fractures. The positive quadrature value may indicate possible faults. It should be noted that not all crossover points indicates genuine fractures. Some cross over points may imply clay, void or sand.

3.0 Results and Discussions

After the acquisition of the VLF-EM data using a ground based electromagnetic survey instrument, data preprocessing contain noise removal and signal drift to improve the quality. After preprocessing, the data is interpreted to identify potential tantalite mineralization zone. Tantalite mineralization zones are attributed to fracture zones in hard rock. This was done using in-phase readings and current density maps generated to delineate geologic structures in terms of conductive mineralized veins, providing information on the thickness, placement, and depth of the suspected (tantalite) mineralized veins. Qualitatively, it is possible to discriminate between conductive and resistive structures using apparent current density cross-section. The VLF-EM results of the Fraser model filtered data plots as well as Karous-Hjelt filter 2-D inversion current density plots for profiles 1 - 5 are presented. The data analysis revealed the presence of positive and negative amplitude of filtered real and filtered imaginary for possible identification of fractures or conductive body.

In generally, good 2-D structures with shallow overburden were detected, while those with thick overburden were not pronounced but were still detected due to current gathering. The VLF-EM sections were plotted in the Karous-Hjelt filtered (KHFFILT) program which show both positive and negative Fraser and Karous-Hjelt anomalies along the profiles. This process yields pseudosection of relative current density variation with depth. The Fraser and Karous–Hjelt filtering results aided in the identification of the conductive structures in the study area. Well defined highly conductive zones related to ferromagnetic minerals had been detected. The inversion results of the filtered data sets for these profiles show a good correlation between pseudo-sections.

Profile 1

Figure 3 shows high positive VLF anomaly which may point out the presence of fracture (conductive body) around the distances 25 m, 50 m, 125 m, 150 m, 250 m, 275 m, 350 m, and 375 m respectively. The conductive zones are indicative of either faults/fractures, lithologic contacts, sheared zones of tantalite. These zones are zones of interest in tantalite deposits. Within 50, 95, 150, 275 and 380 meters, there are also noticeable, relatively highly negative VLF-EM responses which can be an indication of the presence of other conductive minerals such as sulphides and aquifers. The profile line is generally attributed to strong mineralization with varying degree of conductivity at approximate depth extending from 0 - 30 m oriented at NW – SE direction.

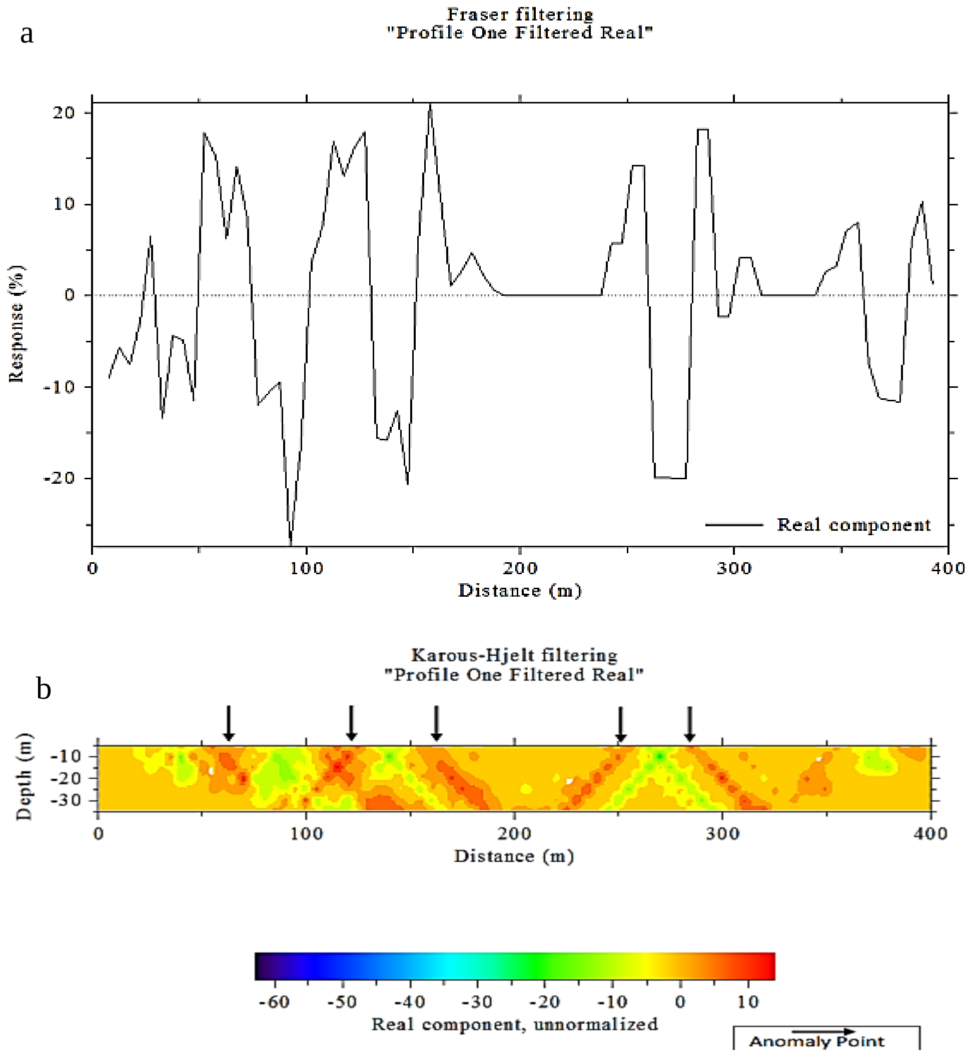

Figure 3: (a) Fraser filter response along profile 1 (b) 2D pseudo-section along profile 1

Profile 2

The interpretation of the VLF-EM profile and pseudo-section produced along profile 2 is displayed in Figure 4 below. High conductivity zones whose response are important and significant occurs at horizontal distances of 10 m, 65 m, 100 m, 125 m, 175 m, and 210 m. These points indicate the presence of conductive bodies suspected to be tantalite mineralization. Within 50, 90, and 200 meters, there are also noticeable, relatively highly negative VLF-EM responses which can be an indication of the presence of other conductive minerals such as sulphides. It can also be an indicative of groundwater or aquifers. Furthermore, the profile 2 inversion shows the existence of a high conductive and a low resistive body that descends to a approximate depth extending from 0 - 30 m oriented at NW – SE direction.

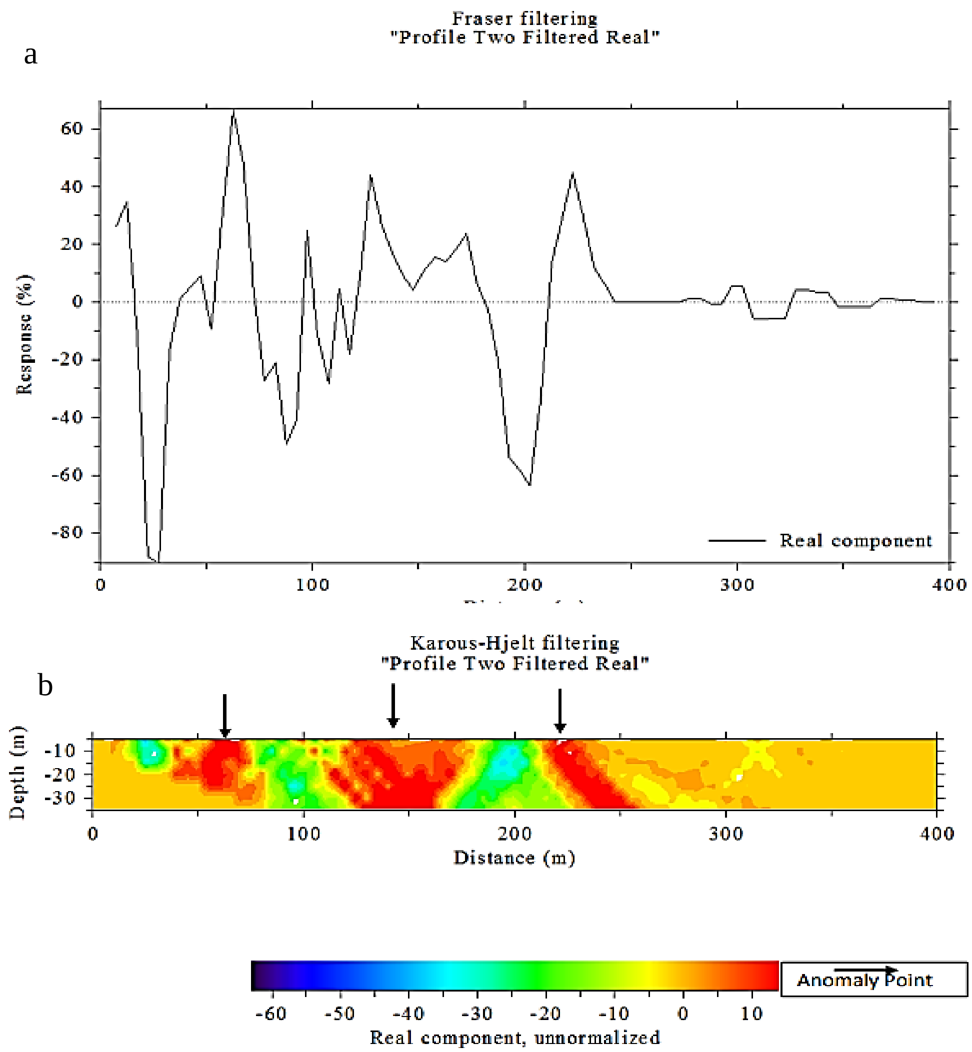

Figure 4: (a) Fraser filter response along profile 2 (b) 2D pseudo-section along profile 2

Profile 3

Figure 5 conductive bodies were observed at 80, 100, 130, 230, and 230 meters away, with extremely low VLF anomalies being recorded in locations between 125 and 230 meters. Furthermore, the profile 3 inversion shows the existence of a low resistive body that extends to a depth of 30 m oriented majorly at NW-SE direction. Additionally, certain low and high current density values were confirmed by the 2-D sections. High values were associated with relatively high conductivity, which could be explained as fractured zones, tantalum-bearing pegmatite dykes, and/or slant sills. On the other hand, low current density values might be indicative of resistive zones, which could be fresh basement.

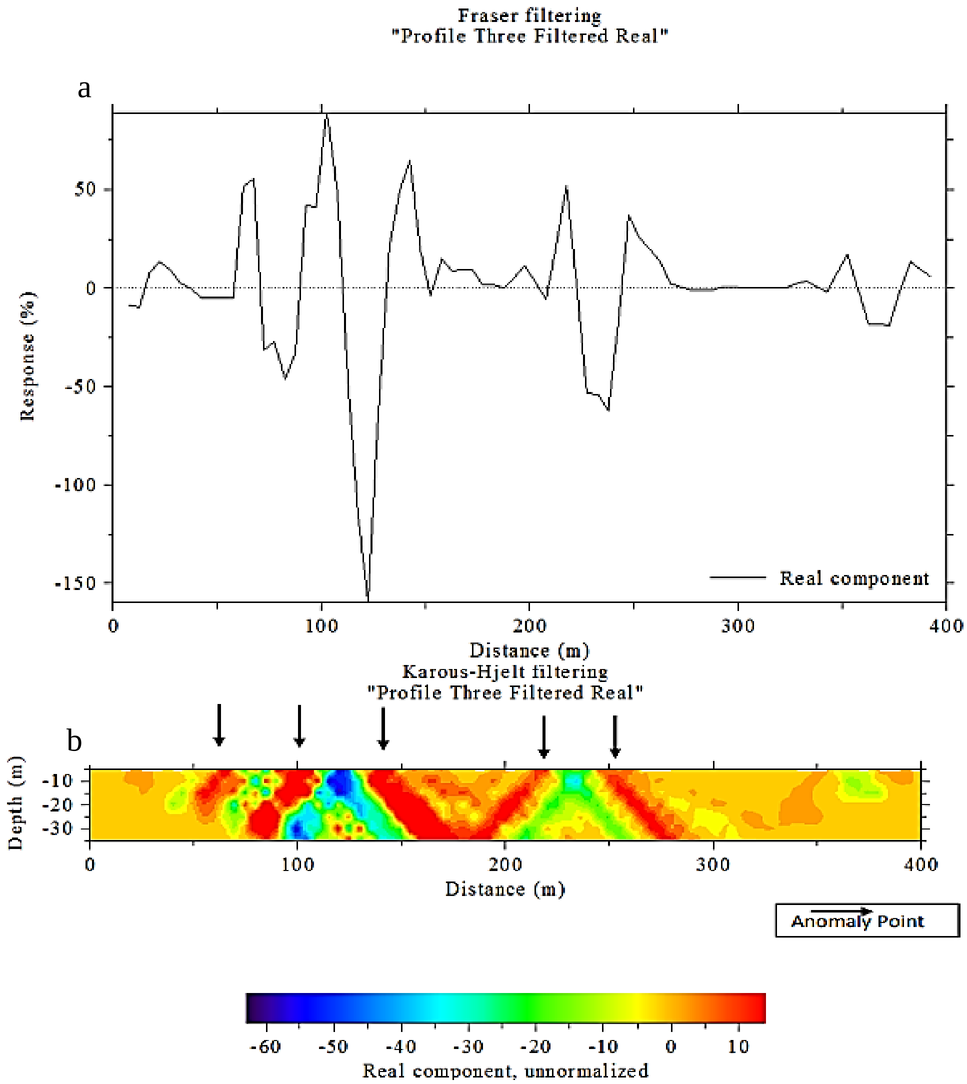

Fig. V: (a) Fraser filter response along profile 3 (b) 2D pseudo-section along profile 3

Profile 4

Figure 6 also indicated the presence of conductive body seen around the distances 20 m, 50 m, 125 m, 160 m, 190 m, and 250 m. Other peak areas indicated low VLF anomalies. Here, low conductivity peaks are at 35 m, 150 m, 230 m 260 m and 340 m which could corresponds to fresh basement. Also, the inversion of the profile 4 demonstrates the existence of low resistive body which extends to 30 m depth and further confirms the presence of the fresh basement rock at distances of the basement terrain. The anomalous zones are indicated with arrows.

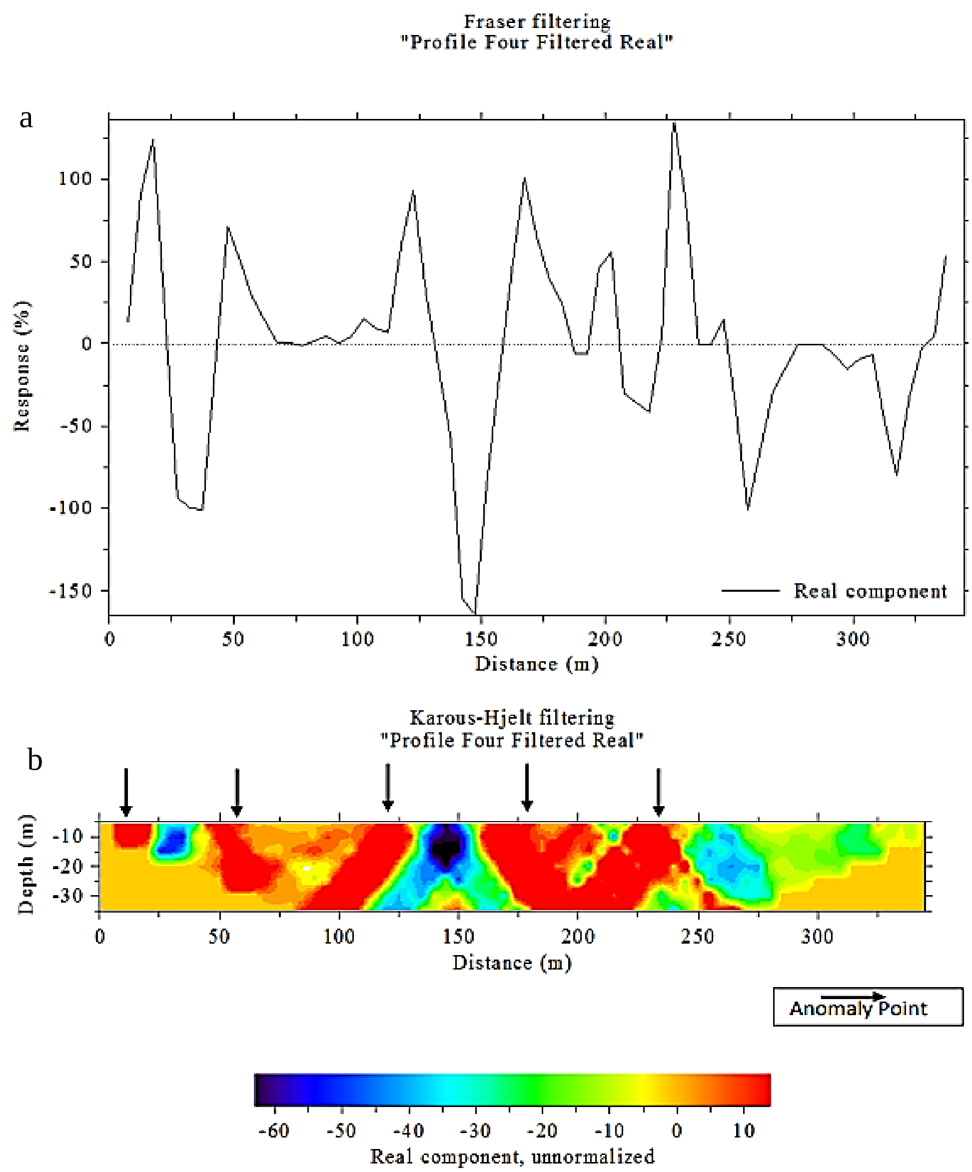

Figure 6: (a) Fraser filter response along profile 4 (b) 2D pseudo-section along profile 4

Profile 5

Figure 7 shows the presence of conductive body seen around the distances 25m, 30m, 60 m, 75 m, 120 m, 150 m, 175 m, 250 m, and 325m on profile line 5, while other area indicated low VLF anomalies. Also, the inversion of the profile 5 demonstrates the presence of low resistive body which also extends to 30 m depth; this coincides with the landfill structure boundaries between 50 m to 125 m to 150 m, 220 m to 275 m and 325 m to 360 m along the profile. The anomalous zones are indicated by arrow.

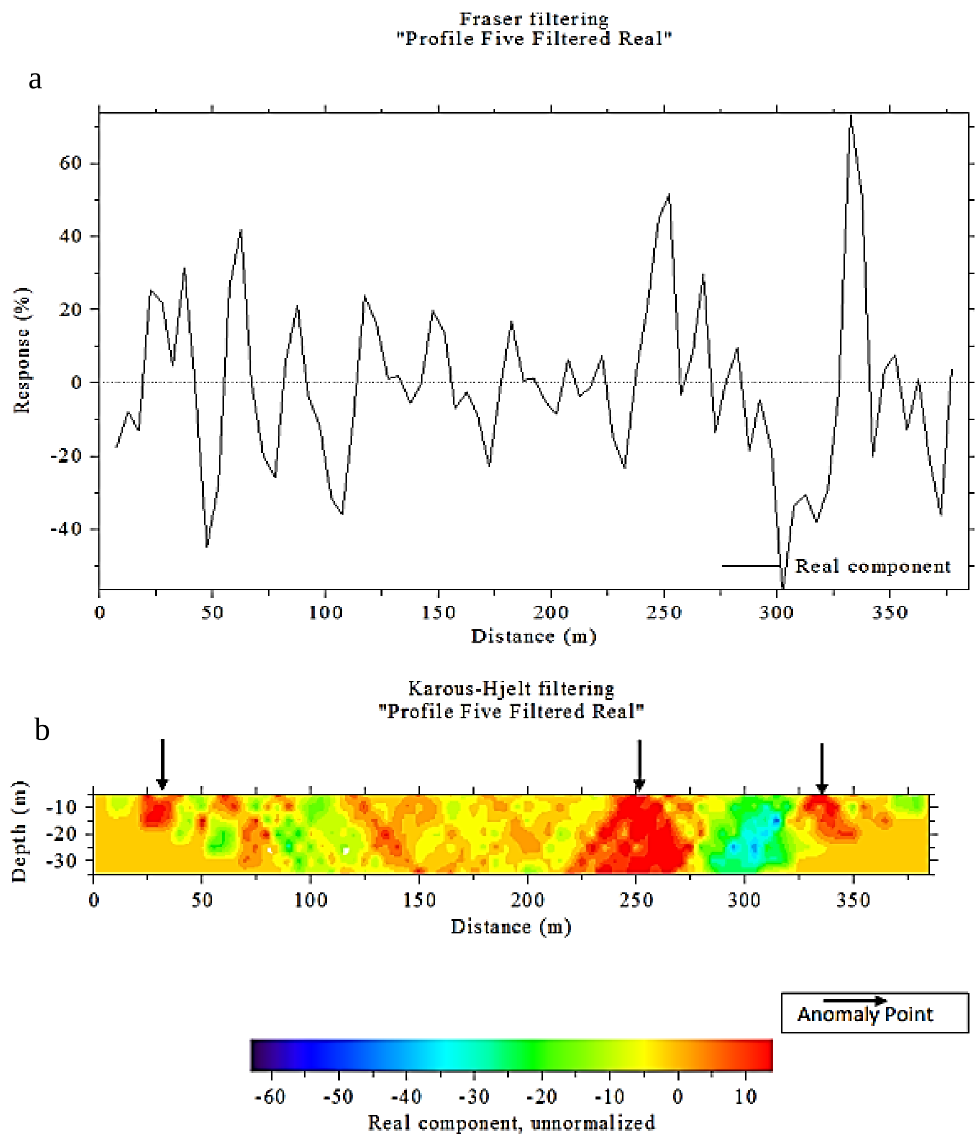

Figure 7: (a) Fraser filter response along profile 5 (b) 2D pseudo-section along profile 5

2-Dimenstional Contour Map of Current Density

The 2-D current density contour map shown in Figure 8 shows places with strong VLF current density response as areas colored pink in the color legend bar, and areas with low VLF current density as areas colored deep black. Based on the existing density pattern, three different zones were generally identified. The first zone is the Conductive Zone which is characterized by a high current density values ranged from 15 to 40 %. These areas could be an anomalous zone in which conductive minerals such as ferromagnetics minerals can be easily and economically founded. This could also be potential tantalite mineralization zone. The second zone is the Non-Conductive Zone which is characterized by a very low current density, with value ranged from -5 to -40%. This zone could be the fresh basement rock in the area. The third zone is the Intermediate Zone with a current density ranged from 14 to -4 %. Typical rocks of these zones are slightly resistive to slightly conductive, such as fairly saturated weathered crystalline rocks and partly saturated sandy units. These zones could as well be studied further for potential mineralization.

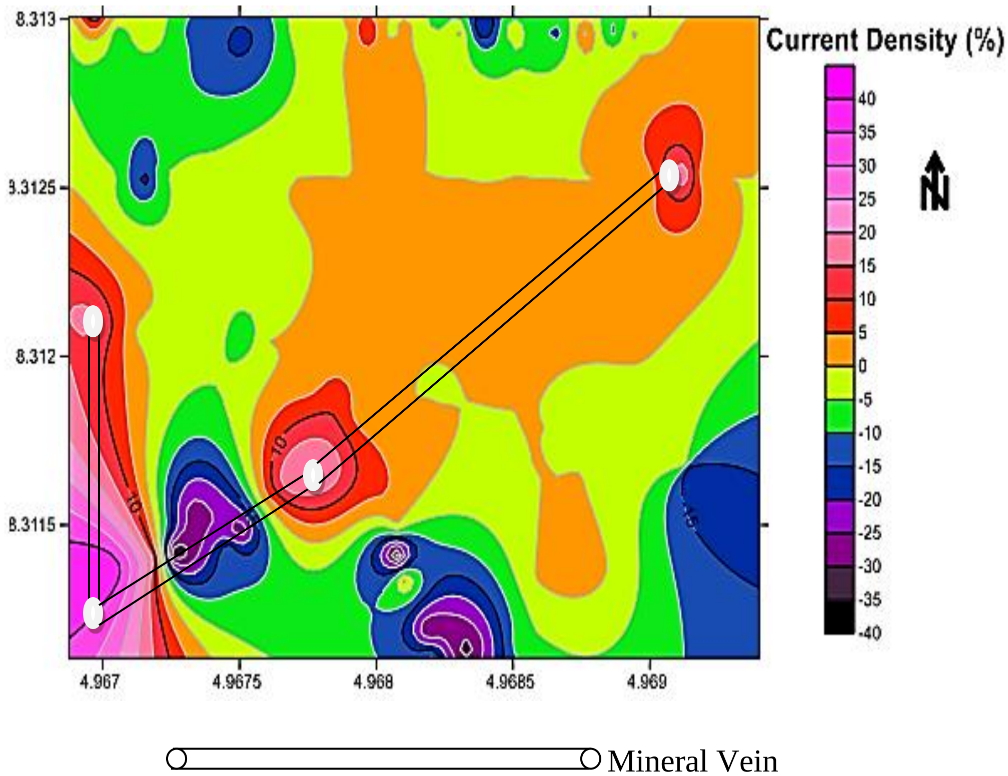

Figure: VLF-EM filtered real 2-D current density contour map

4.0. Conclusion

The VLF-EM method can serve as a reconnaissance tool for the assessment of subsurface conductive zones and has been successfully been used to map Tantalite mineralization veins in Igbonla area, Kwara state, Nigeria. This study highlights a carefully planned VLF-EM survey for the purpose of identifying tantalite mineralized veins (pegmatite). Qualitative interpretations of VLF-EM profiles using different linear filtering such as observed and computed in-phase and out-phase components and Karous–Hjelt filters shows that the site has a developed subsurface low resistivity zone within and outside the landfill boundaries which are suspected to be due to the presence of fractures and conductors corresponding to tantalite. The results of the survey also show a trend of mineralization in the south western part of the survey area with even more concealed conductors in the northern region. All these deductions are in line to the geologic information of the area definitely confirm the efficacy of VLF technique to enhance geological mapping over well concealed mineralized areas. The high VLF anomalies delineated from Igbonla area, in the southern part of Kwara state yielded a high conductivity contrast result which extend to 30 m depth and well-suited for Tantalite mineralization and the geologic information of the area. KHF filtering techniques were integrated and applied in the VLF data interpretation of the area and results of strong EM induction were detected, probably indicating the presence of Tantalite. Current density maps also revealed the inferred mineralized veins trends in the area. Three zones were further delineated including conductive, non-conductive and intermediate zones.

5.0 Recommendation

On a final note, the VLF-EM method is a highly recommended technique in the geophysical exploration of tantalite, as it is economical, fast and effective in its operation. Since the area of study has very scanty qualitative/quantitative geological information, there should be a conforming extensive geological mapping/survey for there to be a comprehensive geophysical survey within the area. An initial and more progressive geophysical survey using at least two methods and more sophisticated instrument is therefore recommended. Electrical and magnetic method with Very Low Frequency (VLF) methods should be conceded out within these areas for a better and wide reaching result Also, follow-up activities to include detailed geological mapping, targeted geochemical sampling and drilling to ascertain the grade and extent of the mineralization are also recommended.

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