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RESEARCH ARTICLE

GEOPHYSICAL CHARACTERIZATION OF BASEMENT ROCK FOR GROUNDWATER AND MINERALIZATION POTENTIAL USING VERY LOW FREQUENCY – ELECTROMAGNETIC (VLF-EM) TECHNIQUES AT SITE "G" AROUND IBADAN METROPOLIS, SOUTHWESTERN BASEMENT COMPLEX, NIGERIA.

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ABSTRACT

The research area, site "G" is located in the city of Ibadan and is surrounded by the basement complex rock mainly migmatite-gneiss and been a hard rock, it is not alienated from the problem of water scarcity. In this region, water is usually encountered either in weathered zone or fractured basement which serve as a conduit for groundwater passage. It is also along this fracture that materials such as quartzo-feldsparthic minerals occur and tend to heal the fracture, hence the need for intensive geological and geophysical exploration to locate this important basement fracture. Very low frequency Electromagnetic (VLF-EM) alongside with geological survey was adopted and conductivity data were acquired along fifteen VLF traverses utilizing very low frequency of about 15 KHz using ABEM WADI survey equipment. 13 profiles were in the east-west (E-W) direction which is the dip direction of the structural elements, while the 2 profiles were in north-south (N-S) direction to serve as a control. The acquired data were analyzed, filtered and displayed inform of profiles and Karous-Hjelt (K-H) filtered pseudo-section to show conductivity and resistivity in 2-D. The results reveal pocket of conductive zones which have been considered as fractures with different dimension and orientation. Most are single fractures, while some are closely spaced double fractures, some of which are connected to each other in depth. Also, some of these fractures contain water while some are dry, some are even suspected to be healed with quartzo-feldsparthic minerals and all of these depend on the conductivity / resistivity signature exhibited by the fractures. Therefore, it can be concluded that VLF has effectively characterise the basement into fractures that contain water, barren fracture and even fracture that contain quartzo-feldsparthic vein.

KEYWORDS

VLF-Electromagnetic, Karous-Hjelt pseudo-section, Basement fracture, Groundwater, Quartzo-feldsparthic.

1. INTRODUCTION

The basement complex of Nigeria occupies approximately half of the study area where large number of people reside. These are areas which are underlain by rocks which have low porosity and are relatively impermeable. A typical Basement Complex terrain is characterized by the abundance of mountain and rocks resulting in challegning to access to potable water. Groundwater exploration has been a critical problem in the basement complex terrain underlain by hard rocks which have low porosity and permeability (Cm-Tryck and Bromma, 1989). This low yielding terrain has created problem of water scarcity (Abdulbariu et al.,2023a). To emphasized that because of the complexities associated with basement complex terrains, proper knowledge of the hydrogeological properties of the auriferous strata is important for sustainable exploitation and development of groundwater reserves (Changde et al., 2022; Andarawus et al., 2022; Babale et al., 2022; Abdulbariu et al., 2023b). This difficult low water yield terrain has a been a major problem thereby creating water scarcity within the region and hence lead to the development of shallow hand dug well which cannot support the great demand of the entire community. The study area falls within this area which has been seriously affected by problem of water scarcity.

The occurrence of groundwater in the basement terrain is localized and concentrated within weathered zone and network of fractures in the underlying basement unit. Therefore, the search for water in this area require careful selection of sites using detailed geological knowledge and geophysical techniques in other to avoid drilling a non-productive borehole and also to provide the populace with good quality and sufficient quantity of water.

There has been tremendous use of geophysical techniques in locating aquifers and mineral deposits particularly in the basement terrain. In this regard, a geophysical method was used at the 'G' site in Ibadan, Southwestern Nigeria, where Very Low Frequency Electromagnetic (VLF-

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EM) was applied to characterize the hydrogeological setting of the area and its mineralization potential.

The VLF-EM serves for the quick detection of high-conductivity anomalous zones believed to be caused by orebody, heavy weathering, and fracture zones. Its great advantage is in its ability to identify a steeply to vertically dipping fracture surface with conductive minerals and/or water.

1.1 Previous Work

The very low-frequency electromagnetic method (VLF-EM) is effective for accelerated geological mapping and searching for buried conductive targets. The method uses signal radiation from military navigation radio transmitters. There are approximately 42 global ground military communication transmitters operating in the VLF range of 15–30 kHz (ABEM, 2007). These stations, sighted around the globe, generate effective signals used for a diverse range of applications which includes navigation and communication, groundwater detection or contamination, soil engineering, ionospheric, meteorological, archaeological and VLF band transmission studies, other applications include mineral exploration, mapping of fault zones, etc. (Wright 1988; Ramesh-Babu et al., 2007; Sundararajan et al., 2007).

It has been state that electrical resistivity and electromagnetic techniques are the most popular and widely used geophysical methods used in groundwater exploration (Molua and Emagbetere, 2005; Iseshien-Emekeme et al., 2004; Ezeh and Ugwu, 2010; Anomohanran, 2011a, b; Atakpo and Ofomola, 2012). This is because the data analysis is cost-effective and the field instrument operation are user friendly.

The VLF method has proven to be an effective exploration tool for massive sulphides, graphite, carbonaceous shales, sheared contacts and fracture zones. Therefore, over the last few decades, it has been employed globally to identify conductive features in mineral exploration, geological, engineering and environmental problems (Phillips and Richards 1975; Parker, 1980; Saydam 1981; Hayles and Sinha 1986; Ogilvy and Lee 1991; Ramesh Babu et al 2007; Sundararajan et al., 2007).

Also, very low frequency electromagnetic (VLF-EM) prospecting method is suitable for studying structural details and shallow subsurface conductors according to Fisher *et al*., 1983 because it is not only rapid but also cost effective.

The literature provides a thorough description and explanation of the theory, methodology, and additional information of VLF-EM (Paterson and Ronka, 1971; Philips and Richards, 1975; Wright, 1988; McNeill and Labson, 1991; Hutchinson and Barhta, 2002).

The recorded VLF-EM anomalies are mostly interpreted using anomaly curves and monograms, although the VLF-EM has been frequently employed over the previous few decades to map shallow subsurface structural features of diverse interests (Kaikkonen 1979; Saydam 1981). According to the most popular method for obtaining qualitative information about the subsurface is to employ Fraser and Hjelt filtering followed by contouring the observed responses (Fraser, 1969; Karous and Hjelt, 1983).

Other researchers who successfully employed the methods includes: utilized electromagnetic profiling/traversing for groundwater exploration in the Nigerian basement complex and ascertained positive results (Nurudeen and Amadi, 1990; Olayinka, 1990, Payne, 1988; Tijani et al., 2009).

The current studies therefore intend to utilize VLF-EM data to characterize the Groundwater and Mineralization Potential of area "G" around Ibadan Metropolis, Southwestern Basement Complex of Nigeria.

2. Study Location and Geology

The study area is the 'G' site, which falls within Ibadan Metropolis, Southwestern Nigeria. It is located between longitudes 03°55′49″ E and 03°56′04″ latitudes 07°29′28″ and 07°729′58″ (Fig. 1). Villages such as Alaka, Olugboji, Fajo, Gbanda, Idiroko, etc, exist close to the site. The site is approximately 500 by 1000 metres with long axis oriented along the north- south direction. The area can be accessed through the Ibadan- Oyo express way and the Ojoo – Arulogun road.

The area is underlain mainly by migmatite gneiss and it trends at an angle ranging from 002° to 012° and dips at an angle ranging from 34° to 58°W. The rock is medium to coarse grain. The other rock types are few outcrops of schist belt and few quartzite. It is also characterized by few joints and fractures with minor intrusions such as quartzo-feldspathic vein of various dimensions (Plates 1 and 2). The surface occurrence of these joints and fractures give an idea on the possible direction of groundwater flow.

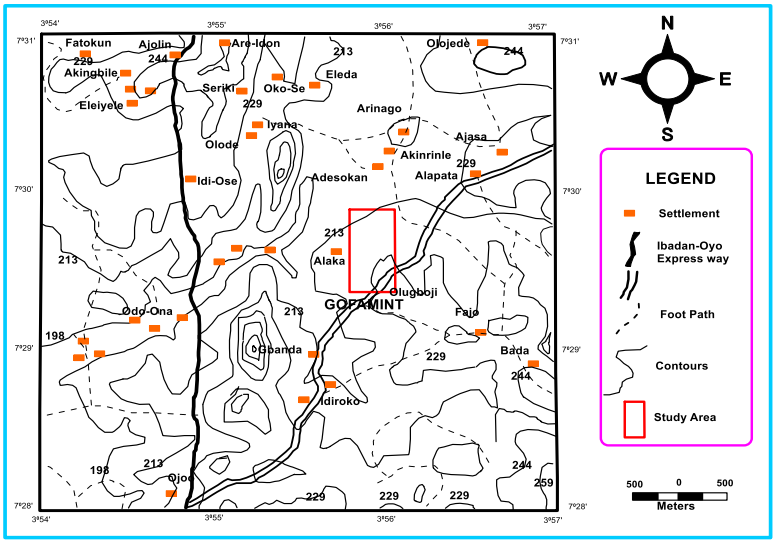

Figure 1: Map of the area showing settlement and topography

Plate 1: Outcrop of Migmatitic Gneiss characterised by joints.

Plate 2: Quartzo-feldsparthic vein in Migmatitic Gneiss

3. Materials and Methods

3.1 General Background

Good drinking water can be obtained from fracture zones in hard rock. Also some mineral deposits such as quartzo-feldsparthic deposits occur in fracture which are filled to form quartzo-feldsparthic veins. Therefore, drilling for these two important deposits without previous site investigation rarely yields positive results and hence effective investigation must include carefully conducted geological and geophysical works.

Very Low Frequency Electromagnetic (VLF – EM) was employed to investigate the study area. The VLF – EM method detect subsurface conductive anomalous zones. It does not require contact since it is the magnetizing force of the EM fields that induces current into the ground. The VLF – EM was used on profiling mode.

3.2 Principle of Electromagnetic (EM) Method

The VLF method was first used for mineral prospecting around 1960. Like most other electromagnetic methods, the VLF method can be used to find steeply dipping structures that differ from their surroundings with regard to electrical resistance. This method is thus very well suited for water prospecting in fracture zones. The VLF method is a geophysical exploration method that make use of magnetic component of electromagnetic fields to reveal objects located far beneath the surface. The technique relies on the induction of subsurface currents and magnetic fields that are used to estimate the electrical conductivity of the subsurface and the depth depends on the frequency of the wave.

The extent to which the field is affected is called depth of penetration. This is often designated by means of the Greek letter ∂ (delta).

$\partial = 503\sqrt{(\rho/f)}$ Where r is resistivity in Ωm, and f is frequency in Hz.

Therefore, the depth of penetration is determined by the resistivity (inverse of conductivity) of the overlying material and the target.

4. Results and Discussions

4.1 Geological Investigation

The study area is underlain by migmatitic-gneisses which are hard basement rock with fractures and veins and some minor faults. The rock outcrop is also characterised by structural elements such as joints, quartz and quartzo-feldspathic veins, banding and gneissic layering. Some of the outcrop show slight alteration.

4.2 Geophysical Investigation

The only use of the filtered imaginary is when it is plotted alongside with filtered real on the same scale in order to provide information about the electrical property of the conductor (steeply dipping fracture). The filtered real is presented as Fraser filtering curves or profiles and Karous – Hjelt (K-H) pseudo-section in figures 2 – 5, 6 – 10 and 11 – 15. The interpretation was based on these profiles and K – H pseudo-sections and they were basically qualitative or semi quantitative (Karous and Hjelt 1983). The positive peaks mapped as fractures on the filtered real. These points are zones of interest in groundwater abstraction in basement complex terrain and possibly areas of quartzo-feldsparthic vein. The pseudosection is a measure of conductivity of the subsurface as a function of depth (Tijani et al 2009). The conductivity is shown as colour codes with conductivity increasing from left to right (that is, from negative to positive). The high conductivity zones with red signatures could be due to the presence of fracture or build-up of clayey materials (McNeil and Labson, 1992). Different features of varying degree of conductivity trending in different directions were delineated on the section.

Gofamint Em Traverse 01**:** It is 200 metres in length and measurement was taken in an E-W direction. There are three regions of conductive anomalies (Fig. 2) but with one prominent peak at distance of 140 metres. The one that occur at 110 metres surface distance is relatively weak. At surface distance of 140 metres and 160 metres are double fractures (double zones) as shown in Fig 2 (Karous-Hjelt filtering) and this seems to be a small and weak anomaly probably represententing dry fracture filled by quartzo-feldsparthic minerals as depicted from Karous-Hjelt filtering and the plot of filtered real and imaginary. They occur at various depth as shown in figure 2 (Karous-Hjelt filtering).

Gofamint Em Traverse 02: It is 170 metres in length and profile direction was in an E-W direction. An anomaly at a surface distance of 150 metres is not prominent and from figure 3 it might result from a shallow conductor. Also there are two prominent conductive anomalies at surface distance of 55 and 100 meters (Fig. 3). They are interpreted as poor conductor (fractures containing fresh water). The one at 55 meters which occurs at depth range between 10 to 30 meters and beyond seems to be relatively prominent as shown in K-H pseudo-sections (fig. 3) and as seen in the field (the hand dug well at this location contains large volume of water. This well serves as a control). Therefore, borehole, can be sited here to tap a large volume of water at greater depth. This is because the strength of the anomaly is a little bit weak at the surface and get stronger at depth beyond 30m. But anomaly at 100m surface distance only occur from depth between 10 to 12m. They are both vertical fractures.

Gofamint Em Traverse 03: Profile length is 180 meters and direction is E-W. It shows one prominent conductive anomalous zone at a surface distance of 55 meters (Fig: 4) which shows that the causative body is a good conductor (fracture) likely to contain fresh water as well as polarizable conductive-rich mineral as shown in K-H pseudo-sections (fig. 4). An existing borehole contains usable quantity of water and therefore serves as control. The fracture extends from depth of approximately 10m to 30m and even beyond and it has slightly conductive units (depicted by yellow colouration) surrounding the very high conductive zone (red colouration) at the centre indicating gradation in conductivity.

Gofamint Em Traverse 05: The entire length of the profile is 180 meters and measurement direction is E-W. Profile reveals numerous distinct conductive zones with the most prominent positive peak at surface distance of 125 meters (Fig. 5). This peak might have resulted from a shallow good conductor at a depth range of between 10 to 14 meters (Fig. 5) because both filtered real and imaginary have similar amplitude (Fig. 5). The least peak anomaly occurs at surface distance of about 23 meters and it is a poor conductor which extends from depth of 10 meters to a depth of about 20 meters (Fig. 5), this maybe the quarzo-feldsparthic zone. Also, the anomaly at nearly 80 meters surface distance can be developed into borehole because of its moderate depth of between 19 to 25 meters even beyond. But the most promising one is at surface distance of 110 meters which seems to be strong and it occurs at subsurface depth between 20 to 26 meters and this is the best point along this profile that can be developed into borehole. They are all revealed in Karous-Hjelt pseudo-section.

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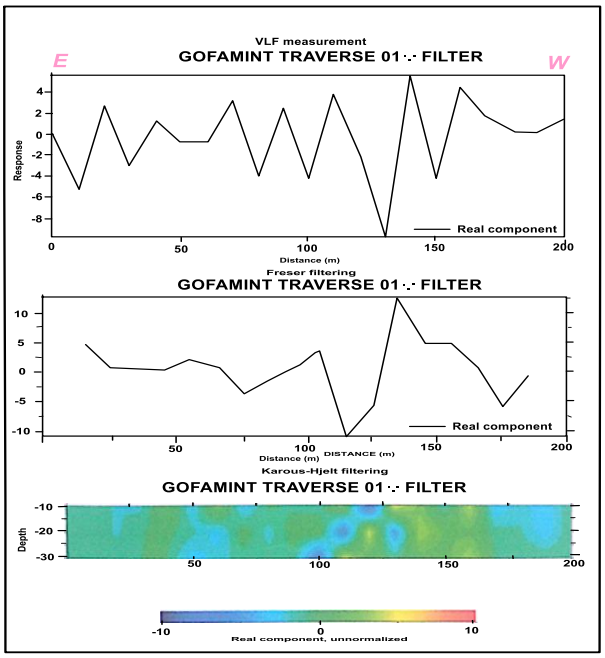

Figure 2: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

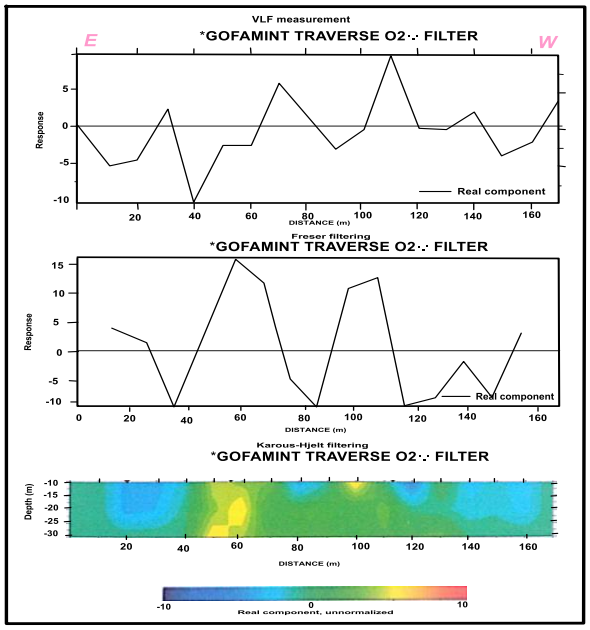

Figure 3: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

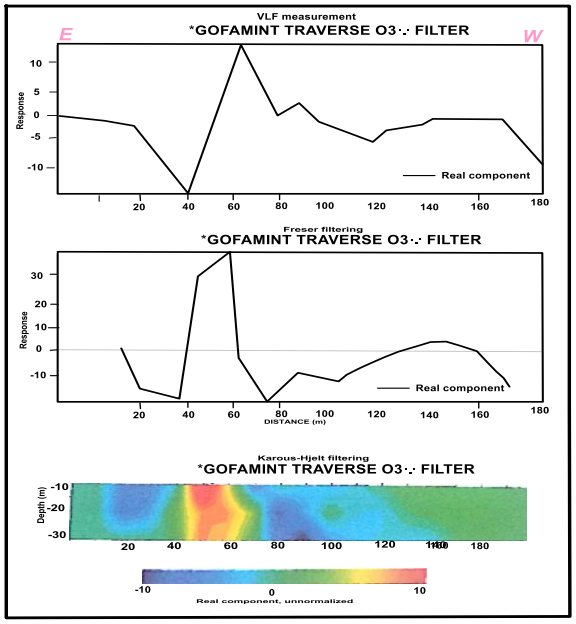

Figure 4: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

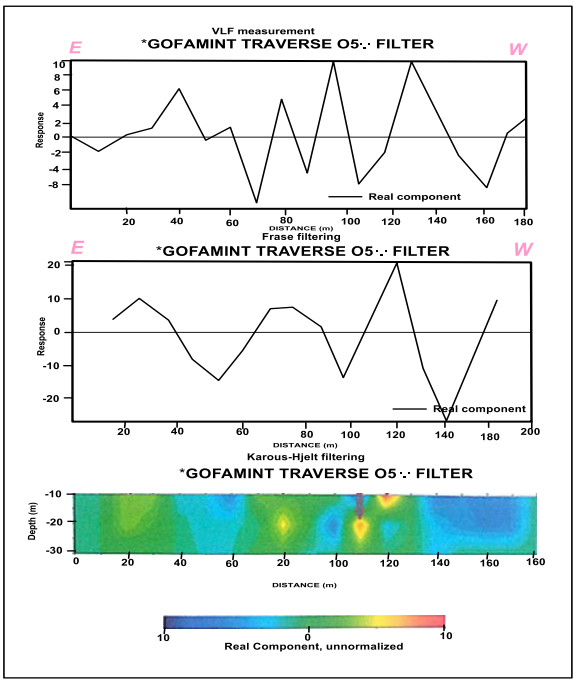

Figure 5: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

Gofaminit Em Traverse 06: The traverse length is 180 meters oriented in E-W direction. There are two prominent anomaly peaks (Fig. 6). They occur at surface distance between 50-100m and between 100-150 meters (Fig. 6). They seem to be weak anomaly. The conductive anomaly at first range which is at the depth between 10-30m can be developed into borehole while the one at second range can be developed into hand dug well.

Gofamint Em Traverse 07: It is 180 meters in length and taken in an E-W direction. Again, two positive anomaly peaks are revealed. The first one is at a surface distance of 20m, depth of 10-22m and while the second one is at a surface distance between 60-80 meters (Fig. 7). This second one is a closely spaced double fracture, one shallow conductor at 60 meters surface distance (shallow fracture) at the depth of 10-12m and one deep conductor at a surface distance between 70-80 meters (deep fracture) at the depth between 19-30m. They appear very conspicuous in figures 16. The anomaly at 70-80m meters may be prolific point for borehole development for groundwater abstraction because of its moderate conductivity.

Gofamint Em Traverse 08: The profile has a length of 290 meters and also in an E-W direction, there are series of high and low positive peaks (Fig 8) the anomalies at the two extreme ends seems to result from fractures containing freshwater. The first is one centred at a surface distance of 50m and occur at depth between 20-35m while the second one is centred at a surface distance of 240m and occurs at depth between 10-40m beneath the surface (Fig. 8). Borehole can be suggested at this second position of conductivity anomaly.

Gofamint Em Traverse 09: The traverse length is 210 meters in an E-W direction. The most prominent conductivity anomalous zone occurs at surface distance between 110-130m and it is a closely-spaced double fracture which join together at greater depth as can be seen in figure 20 and this occur as pocket of high in Karous-Hjelt pseudo-section (Fig. 9). The shallow fracture occurs at depth between 10-20m while the deeper one occurs at 20-30m and even deeper. No borehole can be suggested because of the possibility of drilling dry well but it can be investigated further for possibility of quartzo-feldsparthic infillings.

Gofamint Em Traverse 10: It is 300 meters in length and orient in E-W direction. The profile is characterized by numerous low to high anomaly positive peak (Fig. 10). The most prominent anomalies occur at surface distance 25m, 75m, 125m, and 150m and they occur as pocket of conductive zones in K-H pseudosection (fig. 10). The anomaly 25m distance is strongly peaked and occur at depth between 10-27m and this can be developed while others occur as pocket of localized anomalies at various depth as shown in fig. 10.

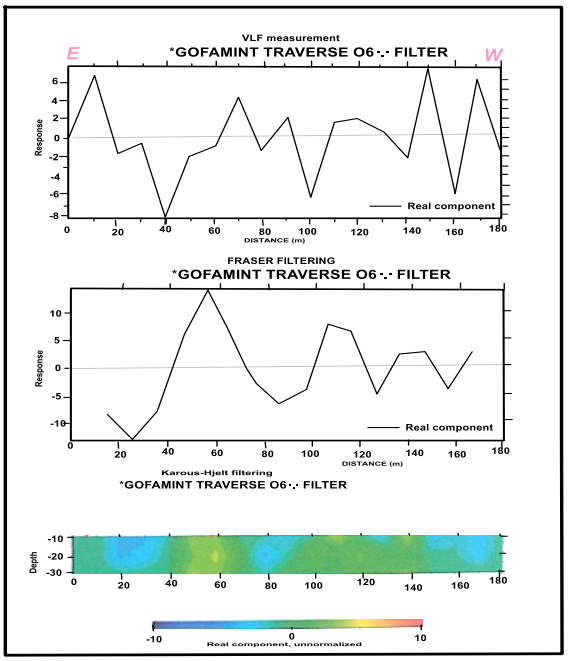

Figure 6: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

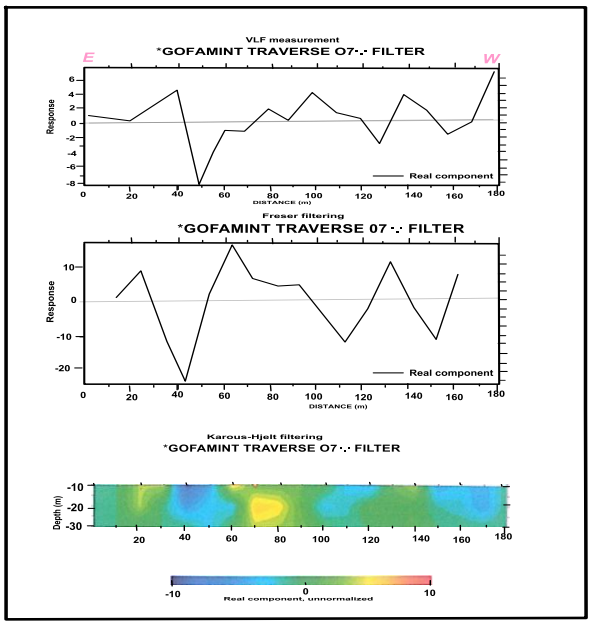

Figure 7: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

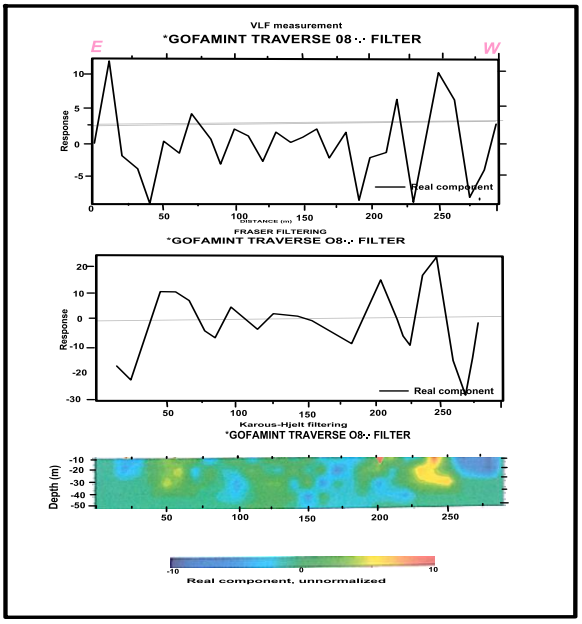

Figure 8: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering

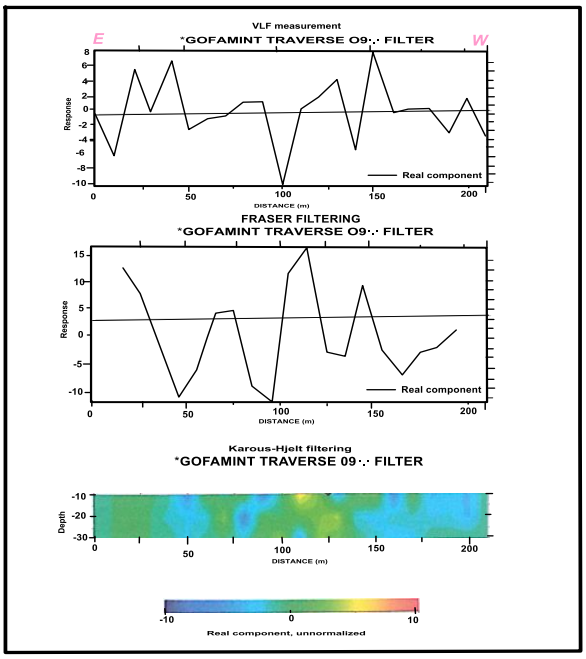

Figure 9: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

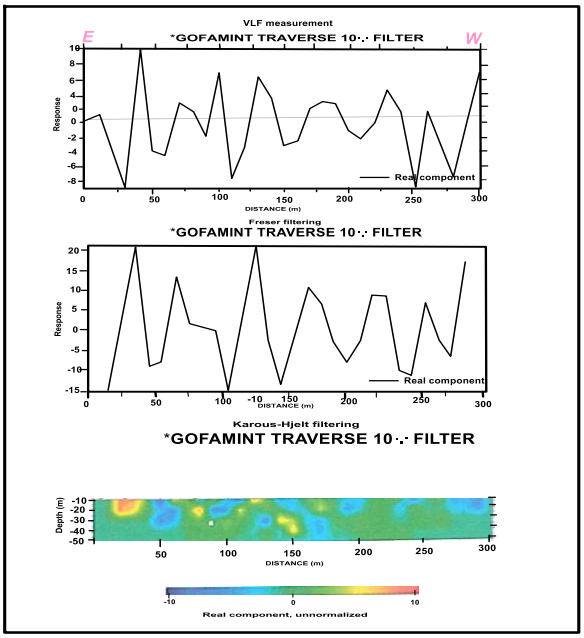

Figure 10: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

Gofamint Em Traverse 11: This has a traverse length of 280 meters with measurement taken in an E-W direction. One prominent anomaly peak was observed at station point 200-230 meters which are double fractures closely-spaced and joined together at depth. They occur within the depth of 10-30m. They all tend to be poor conductors having tendency to contain water (Fig. 11). At other surface locations the anomalies are not pronounced (Fig. 11). They occur as pocket of conductive zones in the K-H pseudo-section.

Gofamint Em Traverse 12**:** It is 270 meters in length and profile orientation is E-W. There are series of low positive peak at several surface distance. They represent fractures which are most probably dry and may be filled with quartzo-feldsparthic minerals (Fig. 12).

Gofamint Em Traverse 13: It is 310 meters in length and also oriented in E-W direction. There are series of conductive zones (Fig. 13). Between station points 65 and 85 meters are double zone (two close fractures) which are approximately 20 meters apart (Fig. 13). Also another double fractures occur at surface distance between 220-245m. The anomaly at 80 meters surface distance which occur at depth of 20m and the one at 245 meters which occurs at depth of 40m (this one may have low yield) can be developed into source of water. This interpretation is in line with the existing hand dug well (control point at 80m surface distance) which contains good quantity of water. Other pockets of conductive zones are also delineated.

Gofamint Em Traverse 14: This is the longest traverse length and parallel to the geological strike. It is 510 meters in length and measurement was taken in N-S direction. It was aimed at serving as control for the other traverse taking perpendicular to the geological strike. Numerous conductive zones earlier picked in the E-W traverse were also depicted. Five prominent conductivity anomaly indications are observed at distance of 55, 200, 240, 290, 335, 360 and 370 meters but the main anomaly with considerable depth occur at surface distance between 135-400m (Fig. 14). The profile is generally characterized by network of interconnected fractures with different orientation occurring at various depth from the surface indicating good water potential in the study site.

They appear as pockets of conductive zones in the Karous-Hjelt pseudo-section. Other conductive zones are also delineated. Some of those anomalies at southern part of the site seems to result from good conductors (Fig. 14).

Gofamint Em Traverse 15: This is second to largest traverse and also run in N-S direction, that is parallel to traverse 14. It is 460 meters in length. Also, several positively peaked anomaly indications are present and the most important and prominent among them are double closely spaced fractured at station points between 55m and 130 meters. They occur at relatively appreciable depth within the range of 20-50m below the surface (Fig. 15). They fuse or join together at greater depth (Fig. 15). They may be able to host good quantity of water (aquifer). Also, at station points between distance of 340 and 400 meters is another double fracture join together at depth (Fig. 15). Though, not as strong as the first one in terms of anomaly indication, it can still provide reasonable quantity of water. Other conductive zones between these two intervals are also delineated.

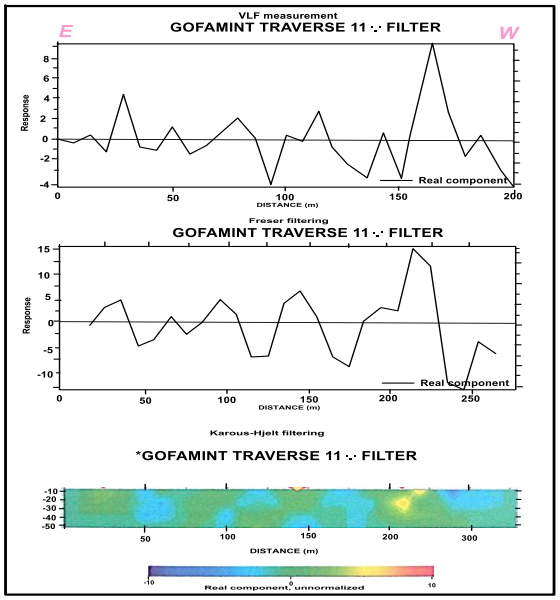

Figure 11: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

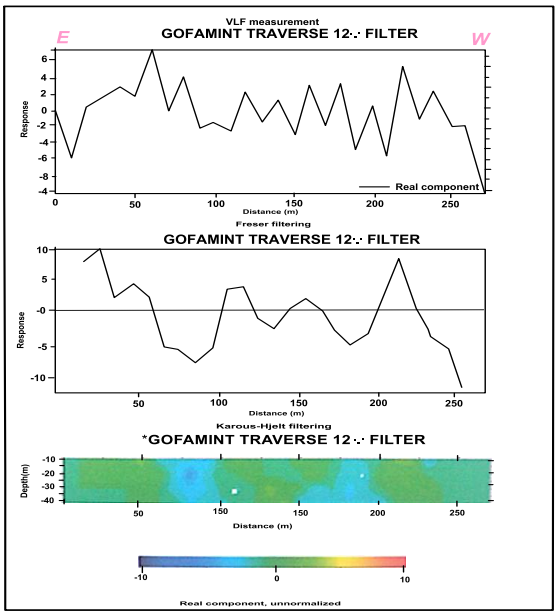

Figure12: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

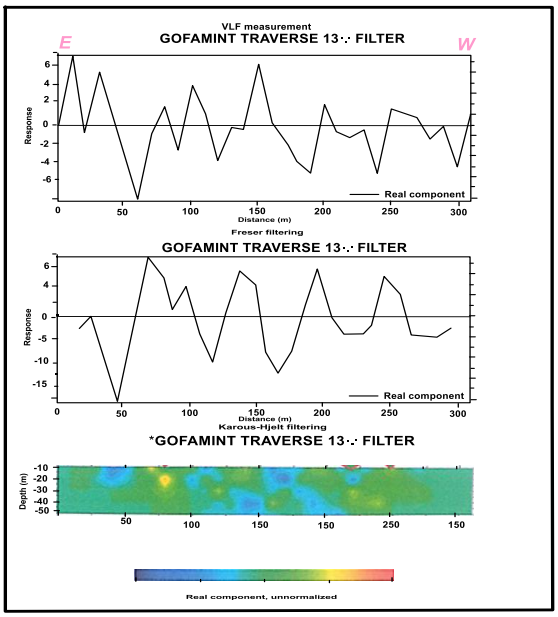

Figure 13: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

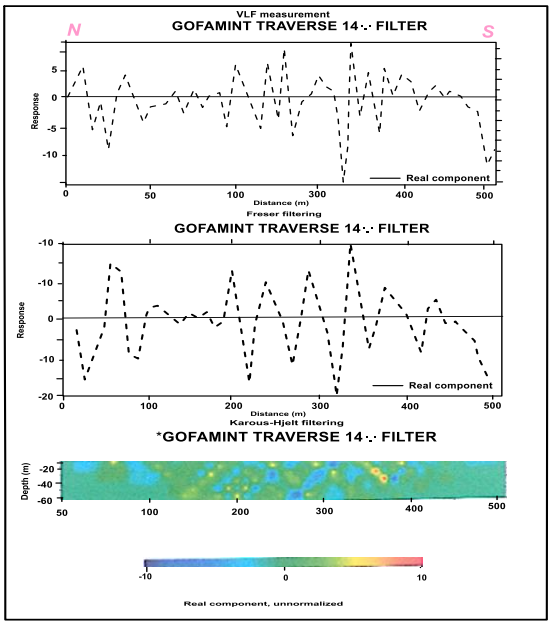

Figure 14: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

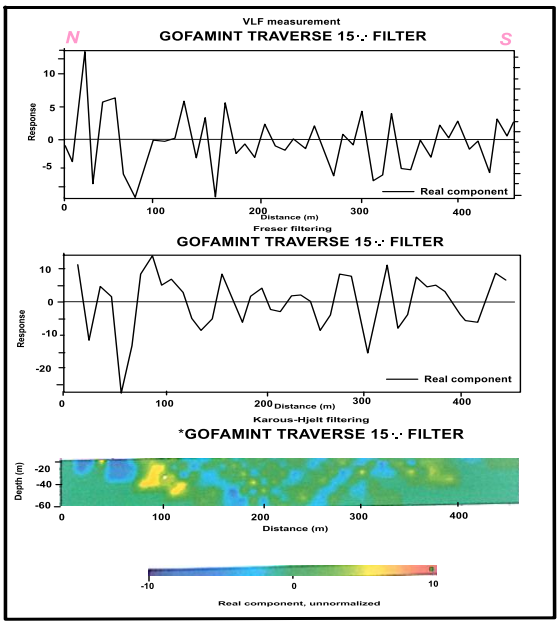

Figure 15: Plot of Filtered Real, Fraser filtered Real and Karous-Hjelt Filtering.

5. Conclusion and Recommendation

5.1 Conclusion

The study area was investigated using geological and geophysical techniques (VLF-EM) to reveal the subsurface geology and characterize the basement aquifers and or potentially mineralized zones.

Topography investigation reveals that the ground surface slope northward towards the stream while geological study shows an outcrop of Migmatite-gneiss striking NW-SE and dipping in Western direction. They are characterized by structural features such as joints, fractures, minor faults and foliation. Other rock types such as Schist unit and quartzite were also encountered around the environs of the study area.

The result of Electromagnetic method (VLF-EM) reveals some pockets of conductive zones which were interpreted as a steeply dipping water-bearing fracture, weathered zone or conducting weakly mineralized zone. They are not all that prominent in some area.

The VLF-EM results serve as the basis for the characterization of the basement aquifer and mineralization potential. Regions with high conductivity (from VLF-EM) are delineated as the basement aquifer and or conductive ore body and vice versa.

5.2 Recommendation

The use of LAND SAT IMAGERY / RADAR SENSING should be used in conjunction with other geophysical methods such as induced polarization (IP), resistivity, seismic refraction, magnetic and gravity. These methods are also capable of detecting fractures, contacts, joints and depressions which tend to harbour groundwater and mineralization within the basement terrain.

Finally, geochemical exploration should be carried out in conjunction with these geophysical investigations to give more details on the mineralization potential of the area.

References

Abdulbariu, I., Baba Aminu, M., and Achonwa, K. O., 2023b. Frequency-Domain Electromagnetic and VLF Data with an Application of Modeling Basement Structures: A Case Study within Ibadan Area, Southwestern Nigeria, International Journal of Research and Innovation in Applied Science (IJRIAS), volume 8, issue 6, Pp. 156-175. DOI: https ://doi.org/10.5184/IJRIAS.202 3.8616

Abdulbariu, I., Izge, H. I., Baba Aminu, M., Ayinla, A. H., 2023a. Applications of Vertical Electrical Sounding (VES) and Two-Dimensional (2-D) Imaging Methods for Groundwater Exploration and Basement Configuration at GOFAMINT Church Camp, Ibadan, Southwestern Nigeria. Science Forum, Journal of Pure and Applied Sciences. 23 (2023) Pp. 336 - 356

ABEM. 2007: A Nitro Consultant company, international frequency list, ABEM printed matter No. 93062: WWW. Abem.se/products/wadi/vlf-freq.pdf. accessed June 18, 2007.

Andarawus, Y., Nur, A., Musa. N., Adamu, A., Mu'awiya, B.A., 2022. Geoelectric Investigation for Aquifer Characterization in Boi and Environs, Bauchi State, Northeast, Nigeria. Dutse Journal of Pure and Applied Sciences (DUJOPAS), Vol. 8 No. 2a June 2022

Anomohanran, O., 2011a. Determination of Groundwater in Asaba, Nigeria using Surface Geoelectric Sounding. International Journal of Physical Science 6: Pp. 7651-7656

Anomohanran, O., 2011b. Underground Water Exploration of Oleh, Nigeria using the Electrical Resistivity Method. Scientific Research Essays, 6: Pp. 4295-4300.

Atakpo, E. and Ofomola, M. O., 2012. Hydrologeologic Investigation using Vertical Electrical Sounding Method in Agbarha Otor, Delta State Nigeria. Nigeria Journal of Science Environment 11: Pp. 95-103.

Babale, S. I., Haruna, A. I., Baba Aminu, M., Salisu, S. M., Sale, M. B., Simon, D. C., Changde, A. N., Adinoyi, E. S., Dung, P. D., Dahiru, A. J., Tobias., Paca, F. S., 2022. Communication in Physical Science 8(4): Pp. 652-666.

Changde, A. N, Aminu M. B, Simon D.C, Ernest O. A, Kizito O. M, Godwin O. A and Okiyi, I. M., 2022. Electric Resistivity for Evaluating Groundwater Potential Along The Drainage Zones in The Part of Jos North, Plateau State, Nigeria. European Journal of Environment and Earth Sciences Vol 3 | Issue 6 | November 2022

Cm-Tryck A.B., Bromma, 1989. (ABEM WADI) Interpretation Guide; Theory, practice and case stories for WADI operators.Issued by ABEM AB, Box 20086, S-161 02 Bromma Sweden. Telex: 13079 ABEM S, Telefax: +468 28 11 09.

Ezeh, C. C. and Ugwu, G. Z., 2010. Geoelectrical Sounding for Estimating Groundwater Potential in Nsukka L.G.A. Enugu State, Nigeria. International Journal of Physical Science 5: Pp. 415-420.

Fisher, G., B. V. Le Quang, and I. Muller, 1983, VLF ground surveys, a powerful tool for the study of shallow two-dimensional structures: Geophysical Prospecting, 31, Pp. 977–991.

Fraser, D. C., 1969. Contouring of VLF-EM data Geophysics 34. Pp. 958–967.

Hayles J G and Sinha A K. 1986, A portable local loop VLF transmitter for geological fracture mapping: Geophysical prospecting, 34, Pp. 873 - 896.

Hutchinson, P. J., and L. S. Barta, 2002, VLF surveying to delineate long wallmineinduced fractures: The Leading Edge, 21, Pp. 491–493.

Iserhien – Emekeme, R. E., E. A. Atakpo, O. L. Emekeme and O. Anomohanran, 2004. Geoelectric Survey for Groundwater in Agbede Etsako West L.G.A., Edo State. Advanced National Applied Science Resource 2: Pp. 65-72.

Kaikkonen, P., 1979. Numerical VLF modeling Geophys. Prospect. 27. Pp. 815–834.

Karous M.R. and Hjelt, S.E 1983. Linear Filtering of VLF Dip Angle MeasurementsGeophysical Prospecting, 31:Pp. 782-794.

McNeil J.D., Labson V.F., 1991 Geological mapping using VLF radio fields. In Nabighian, M.C. (Ed.), Geotechnical and Environmental Geophysics Review and Tuto ri al, vo l 1. Society of Exploration, Tulsa, Pp. 191-218.

Molua, O. C., Emagbetere, J.U., 2005. Delineation of Water Table using ElectricalSounding Technique: A Case Study of Afuze, Edo State, Nigeria. Journal of Nigeria Association of Mathematics and Physics 5:Pp. 457-464.

Nurudeen, S.I, and Amadi, UMP, 1990. Electromagnetic survey and search for Groundwater in the Basement Complex of Nigeria. Journal of Mning and Geology 26 (1), Pp. 45-54.

Ogilvy R D and Lee A C 1991 Interpretation of VLF-EM in-phase data using current density pseudosections Geophys. Prospect. 39 567–580.

Olayinka, A.I., 1990. EM Profiling for groundwater in Precambrian basement complex area of Nigeria. Nordic Hydrology 21, Pp. 67-76.

Parker, M. E., 1980. VLF electromagnetic mapping for straband mineralization near Aberfeldy Scondland Trans. Inst. Mining Metall. B 89 B123–133.

Paterson, N. R., and Ronka, V., 1971. Five years of surveying with the very low frequency electromagnetic method: Geoexploration, 9, Pp.7–26.

Payne, M.I., 1988. Electromagnetic Traversing method of Groundwater exploration in Crystalline Rock Terrain. Journal of Mining and Geology 15(2) 863-874.

Phillips, W. J., and Richards, W. E., 1975. A study of the effectiveness of the VLF method for the location of narrow mineralized zones Geoexploration 13 Pp. 215–226.

Ramesh Babu, V., Ram, S., and Sundararajan, N., 2007 Modeling of magnetic and VLF-EMwith an application to basement fractures: a case study from Raigarh, IndiaGeophysics 71. Pp. 133–140.

Saydam, A. S., 1981. Very low frequency electromagnetic interpretation using tilt angle and ellipticity measurements Geophysics 46. Pp. 1594–1606.

Sundararajan, N., Chary, M. N., Nandakumar, G., and Srinivas, Y., 2007. VLF and VES—an application to groundwater exploration, Khammam, India The Leading Edge 26. Pp. 708–716.

Tijani, M.N., Osinowo, O.O., and Ogedengbe, O., 2009. Mapping of sub-surface fracture System using intergrated electrical resistivity profiling and VLF-EM methods: A case study of suspected gold mineralization; RMZ – Materials and Geoenvironment, Vol.56, No.4, Pp. 415-436.

Wright, J. L., 1988. VLF Interpretation Manual (Concord, Ontario: EDA Instruments, now Scintrex, Ltd).