Very low frequency - electromagnetic (VLF-EM) and Offset Wenner resistivity survey of spring sources for groundwater development

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Geophysical mapping involving VLF Electromagnetic profiling along seven profiles, ten Offset Wenner and two azimuthal soundings were employed in the study of perennial spring sites at Iloyin community in Akure metropolis, southwest Nigeria. Geophysical methods are useful in mapping areas of natural water resource for groundwater abstraction or construction of containment such as dam or fishpond. Linear inversion of the Electromagnetic measurements involved application of the Fraser and Karous-Hjelt filter on the measured real components of the field data and generation of pseudo sections. The azimuthal sounding data were presented as azimuthal graphs in both Cartesian and Polar coordinates in conjunction with the polar plots of the Offset Wenner resistances (RD1 and RD2). The topsoil is generally thin with resistivity values ranging between 65 to 612 Ohm-m and thickness from 0.5 to 2.9 m. The underlying layer with resistivity value ranging from 25 to 468 ohm-m is the main aquifer recognized as quartzite bed and quartzite impregnated clayey aquifer. The Aquifer layer thickness varies between 0.9 to 32.6 m. The basement rocks, which graduate from highly weathered/fractured to fresh bedrocks, are characterized by resistivity values ranging from 827 to 11064 Ohm-m. Aquifer units in the area comprise brecciated quartzite, clayey sand and fractured bedrock. The topsoil is highly loose and unprotected which makes the aquifer in the study area susceptible to infiltration and groundwater being prone to pollution.

Key words: Spring, electromagnetic, Offset Wenner, Azimuthal resistivity, filtering.

INTRODUCTION

The survey area is a new developing settlement located within northwestern part of Akure and forms part of the basement complex of the southwestern Nigeria. It lies between longitudes 5° 08' 48.46" E to 5° 08' 59.7" E and latitudes 7° 17' 19.7" N to 7° 17 28.8" N (Figure 1). The urbanization of this area and neighbouring communities is greatly influenced by the location of the Federal University of Technology, Akure close to these communities in 1987. Despite good groundwater yield from the wells in the area during the raining season, some areas still have problems of in adequate groundwater yields.

Two springs in the area serve as recharge sources with water percolating through brecciated and scattered conglomerates of quartzite having high permeability and porosity. Their occurrence may also be attributed to tilted strata of permeable and well-jointed quartzites juxtaposed by clayey layers. Groundwater may percolate downwards until it reaches joints or emerges at the base of the permeable layers or at the interface between quartzite and underlain bedrock. The surface water from the stream channels flow predominantly in the NE-SW direction along depressions at the central part of the study area. The streams are structurally controlled as they flow along lithologic boundaries and fracture zones in the area. The stream channel at the central part remains alive throughout the season and empties its water into the valley at the western part, via the depression at the central part of the area. The distribution of the hydraulic head in Figure 2 shows a predominant easterly to westerly trend of groundwater flow. A localized convergence of the water head levels in form of
Figure 1. Location map of the study area (inset geological map of Ondo state, Nigeria showing the study area, after NGSA, 2006).

Figure 2. Hydraulic head levels and groundwater flow pattern of the study area.
channels at the central part suggest transmissive zone, while divergence of flow lines to the northern and southeastern flanks suggested zones of low transmissivity (Worthington and Baker, 1977). Thus, the natural groundwater recharging potential of the springs in the area can greatly be exploited for construction of groundwater containment such as dam or fishpond.

Very low frequency electromagnetic induction (VLF-EM) and electrical surveys are effective geophysical tools in hydrogeological studies. The VLF-EM method is a geophysical technique that is usually employed as a reconnaissance tool in locating steeply dipping or vertical structures in bedrock (Palacky et al., 1981; Adepelumi et al., 2006).

The ability to provide necessary information on the subsurface geology, in groundwater prospecting, of electrical resistivity over other methods has been demonstrated by various authors (Zohdy, 1974; Olorunfemi and Okhue, 1992; Olajuyigbe, 2003). Watson and Barker (1999) demonstrated the use Offset-Wenner electrical soundings to differentiate anisotropy, dipping layers and lateral electrical variations within the subsurface. The directional electrical resistivity surveys are increasingly being used by hydrogeologists in identification and characterization of fractured zones or in areas characterized by (1) steeply dipping interface, (2) a gradational lateral change in resistivity or (3) any combination of these (Watson and Barker, 1999; Taylor and Fleming, 1988; Matias and Habberjam, 1986; Keller and Frischnecht, 1966). VLF method is an attractive geophysical technique which is usually employed in locating steeply dipping or vertical physical structures in bedrock (Palacky et al., 1981; ABEM, 1990; Telford et al., 1990). These structures may be several hundred meters long or deep, have better electrical conductivity than the surrounding rocks, and often contain water. Contacts between beds of contrasting resistivity produce profiles that are rather different from crossover associated with dipping-sheet conductors (Telford et al., 1990).

This paper presents the use of VLF-EM induction and offset Wenner sounding methods for hydro-geophysical evaluation of groundwater resource potentials in Iloyin Community, Akure. This study will provide information on the basic geology and geological structures within the study area. The scope of the study includes understanding the basic geology of the survey area, location of conductive zones, identification and delineation of lithological boundaries, shear or weak zones and other structures that would provide information on the suitability of the area for groundwater development scheme.

Physiography and geological setting

The topography is steeply undulating and hilly, with surface elevations ranging from 337.16 to 352.66 m above mean sea level (msl). Vegetation is of the rain forest type with dense evergreen trees, shrub, and grasses. Much of it has been cleared for physical development. The total rainfall is between 100 and 150 cm and the region has up to four months of dry season. Relative humidity is over 80% in the morning and falls to between 5 and 70% in the afternoon, while temperature ranges between 24 to 30°C (NIMET, 2011).

The area is characterized by coarse-grained, Biotite-rich Charnockitic rocks associated with Quartzite, biotite migmatized-gneiss or granitic gneiss intrusions. It is believed that the area has been greatly disturbed structurally in various ways, which may be associated with both primary and secondary geological events such as tectonic processes that include multiple folding, fracturing or development of joints, metamorphism and recrystallisation (Rahaman, 1976). From various works (Adeyeka, 1990; Adeyeka et al., 2003) the Pan-African Basement complex of southwestern Nigeria have been found to be comprised of four-fold tectono-stratigraphic division: the migmatite-gneiss-quartzite complex; the Schist Belt; the Pan African granites with associated granite rocks; and the minor felsic and mafic intrusive.

The relationships of the Charnockite bodies to the surrounding rocks however are obscured due to the scarce outcrops of the older rocks in the area and mostly due to influence of severe weathering of the rocks along the stream channels and in area associated with hybrid rocks. In Many rocks, which are similar lithologically may not be of the same geological age or even related (Cooray, 1970).

Field occurrences of outcrops of low lying migmatized-gneiss comprising of Quartzite, transition gneiss and Charnockite in the area reveal weak to strong evidence of intrusions of feldspathic biotite gneisses which are as well as strongly foliated. The granitic gneisses appear to be weakly foliated in some outcrops of transition gneisses or hybrid rocks of Charnockite and Biotite banded gneisses. These rocks are structurally deformed and consequently show micro-joints, micro-faults and high degree of weathering. Pockets of porphyritic granites also occur in many places around the study area. Rocks in the study area are cut by quartzofeldspathic veins with random orientations, having width up to 15 to 20 cm in some places, while dominant foliation trends in the E-W, NE-SW or NW-SE with dips towards northwest suggesting that the rocks have been probably subjected to the Pan-African thermotectonic events (Ekwueme, 2003; Ephraim et al., 2006).

MATERIALS AND METHODS

Field equipments

The geophysical surveys include the use of VLF electromagnetic profiling and DC electrical soundings. The VLF survey was carried out using ABEM WADI VLF instrument, while the RD-50 resistivity meter was utilized for resistivity data collection. The WADI utilizes
the magnetic component of the electromagnetic field generated by
to military radio transmitters that use the VLF (Very Low Frequency)
band, that is, 15 to 30 kHz commonly used for low distance
communication. The WADI measures this field strength and phase
displacement around a fracture zone or any conductive body in the
rocks (Telford et al., 1990; ABEM 1990). It detects the ratio (in
percent) between the vertical and the horizontal components. Other
data include information on the static water level and surface
elevations. Geographic locations of measured data were obtained
using Garmin Global Positioning System (GPS-72). Surface
elevation data in the area was derived from the topographic map of
Akure Northwest copied on a scale of 1:50,000 by the Federal
Surveys of Nigeria.

The methodology employed was the VLF profiling technique
which involved collection of data along existing road network in the
study area and data presented as profiles, pseudo-sections and
maps (Figures 3, 4 and 5). A total of seven traverses were occupied
during the field measurements. The main parameters measured in
VLF are the dip angle, that is, inclination of the bigger axis of
polarization ellipse (\(\alpha\)) and the ellipticity (\(\epsilon\)), or quadrature (ratio of
major to minor axis). Measurements from VLF surveys are usually
difficult to interpret and are always less intuitive, especially than
does of apparent resistivity. Although several filtrate techniques are
available that can be used to improve the representation of the
anomalies and make them more readable, they still lack the ability
to provide a physical parameter that can be compared directly with
the results of other electric or electromagnetic methods (Telford et al.,
1990; Chouteau et al., 1996). Difficulties involved in visualizing
and to correlate their results with those obtainable from other
methods, the data of the in-phase component (\(\alpha\)) are not usually
appropriate for the design of isovalue maps (ABEM, 1990; Telford
et al., 1990).

The interpretation of WADI data is generally based on the filtered
real part with the aid of the Karous-Hjelt filter, which enables the
distribution of the current density responsible for the secondary
magnetic field to be displayed as the isovalues maps and
interpreted as maps of current density (Benson et al., 1997). The
filter therefore provides a pictorial indication of the depth of the
various current concentrations and hence the spatial dispositions of
subsurface geological features, such as mineral veins, faults, shear
zones and stratigraphic conductors (Ogilvy and Lee 1991; Khalil et
al., 2009). Information on the nature of overburden can be deduced
from the filtered imaginary part.

The six-length linear Karous-Hjelt filter in its simplest form can be
expressed as:

\[
\left( \frac{\Delta Z}{2X} \right) I_x \left( \sigma \Delta Z / 2 \right) = -0.205H_2 + 0.323H_3 - 1.446H_4 + H_5 - 0.323H_2 + H_3 F_2 \left( \sigma \Delta Z / 2 \right)
\]

where \(\Delta Z\) is the assumed thickness of the current sheet, \(I_x\) is the
current density, \(X\) is the distance between the data points and also
the depth to the current sheet, with the location of the calculated
current density beneath the centre of the six data points. The
values of \(H_2\) through \(H_5\) are the normalized vertical magnetic field
anomaly at each of the six data points.

Another smoothing technique similar to the Karous-Hjelt filter is
the Fraser Filter, which transforms the VLF anomalies to contours in
such a way that proper crossovers are transformed to positive peak
readings, while reverse crossovers become negative values,
thereby enhancing the signals of the conductive components (Telford
et al., 1990). The centre of the anomalous structure may fall directly
under the peak of the Fraser filtered data.

The contour value \(C_{23}\), plotted midway of stations 2 and 3 is given by:

\[
C_{23} = (\alpha 3 + \alpha 4) \cdot (\alpha 1 + \alpha 2)
\]

where \(\alpha 1, \ldots, \alpha 4\) are the tilt angles (raw real) obtained at stations 1,
\ldots, 4. The sign of \(C_{23}\) is positive near proper crossovers and
negative for slopes in opposite direction.

According to Sundararajan et al. (2006), the advantages of the Fraser
filter include: (1) complete removal of DC bias and great
 attenuation of long wavelength signals; (2) complete removal of
Nyquist frequency related noise; (3) phase shifts in all frequencies
by 90° and (4) having the band-pass centered at a wave length of
five times the station spacing. Fraser filtering converts somewhat
noisy, non-contourable in-phase components to less noisy,
contourable data, which ensures greatly the utility of the VLF-EM
survey (Khalill et al., 2009).

The geoelectrical soundings comprise of ten Offset Wenner
electrical soundings, with additional two azimuthal soundings at
VES 3 and 6 along the central river channel. The use of offset
Wenner soundings in reducing effects of lateral contrast has been
demonstrated by Fielitz (1995) and well discussed by Watson and
Barker (1999).

The offset Wenner system of measurement as demonstrated by
Nunn et al. (1983) involves the use of collinear arrangement of five
equally spaced electrodes (Figure 6). Measurement of earth
resistance to the applied current is done in two phases: first with the
left four electrodes (\(R_{01}\)) and secondly with the right four electrodes
(\(R_{02}\)).

Analyses of the relative behaviours of the two Wenner
resistances as a function of both azimuth and electrode spacing
then forms the basis for differentiating between true anisotropy and
other geologic effects such as dipping layers and lateral electrical
variations within the subsurface (Watson and Barker, 1999). Two
other parameters that may be employed in differentiating true
anisotropy and geologic models are the offset error (Barker, 1981)
and range (Watson and Barker, 1999) described below. The offset
error, which provides estimates of the magnitude of lateral resistivity
effect along specific orientation, at electrode spacing \(a\), is
expressed as:

\[
e_f(\alpha) = \frac{R_{01}(\alpha) - R_{02}(\alpha)}{R_D(\alpha)} \times 100\%
\]

(2)

The differences between the maximum and minimum resistances
observed in \(R_{01}\) and \(R_{02}\) provides estimates of the magnitude of
lateral resistivity effects within a radius of electrode spacing \(a\), is
given by the expression:

\[
r(\alpha) = \frac{1}{2} \left( \left[ \frac{R_{D_1}(\text{max-min})}{R_{D_1}(\text{mean})} \right] + \left[ \frac{R_{D_2}(\text{max-min})}{R_{D_2}(\text{mean})} \right] \right) \times 100\%
\]

(3)

where \(R_0\) is the mean of the two resistances.

The number of the azimuthal resistivity was limited by built-up
areas and extensive vegetation. The electrode separation (AB/3)
varies between 1 and 64 m.

The azimuthal sounding data were presented as azimuthal
graphs in both Cartesian and Polar coordinates in conjunction with
the polar plots of the Offset Wenner resistances (\(R_{01}\) and \(R_{02}\)) in
Figures 6 and 7. Results of the Offset Wenner soundings were
presented as curves, model resistivity sections and lithologic models
in Figures 8, 9 and 10.

RESULTS AND DISCUSSION

VLF-EM survey

Characteristic pattern and nature of the anomalies
Figure 3. VLF-EM profiles; (a) In-phase component (raw real) and equivalent current density (Filtered data using Karous-Hjelt filter), (b) In-phase component (raw real) and smoothed in-phase using Fraser filter.
Karous-Hjelt filtering
"Traverse 1"

Karous-Hjelt filtering
"Traverse 2"

Karous-Hjelt filtering
"Traverse 3"

Karous-Hjelt filtering
"Traverse 4"
presented by various rock types and how they vary with the conditions of the pattern (depth, dip, presence of a conductive intrusive bodies and lateral variations of the resistivities at depths, etc.) are displayed in the profiles and isovalues maps of the real (the in-phase) and imaginary (quadrature) components. The data collected along the existing routes were filtered using both Fraser and Karous-Hjelt filters, thereby providing a means of removing geologic and noise originating from the transmitter. The choice of these filters is informed by the fact that the Karous and Hjelt (1983) filter computes approximate current density of the subsurface giving rise to a relative data across the resulting profiles (Benson et al., 1997). In a similar way, the Fraser filter transforms the VLF anomalies to contours in such a way that proper crossovers are transformed to positive peak readings, while reverse crossovers become negative values (Telford et al., 1990).

**EM-Profiles and current density section**

Qualitative and semi-quantitative interpretations of the VLF-measurements profiles (Figure 3) were made to map occurrence of localized alterations of conductive and resistive rocks as well as contacts among materials of different conductivity (Figures 4). Figures 3a and 3b demonstrate characteristic anomalies at Iloyin layout, Akure, Nigeria, while Figure 4 shows typical inverted current density sections using the Karous-Hjelt’ 2D-inversion program named KHFiiit Version 1.1a (Pirttijärvi, 2004). The pseudo sections are displays of the equivalent current density estimated from the filtered real component of the VLF data. The colour pane indicates a bluish to green colour for the resistive medium, while yellowish to red colour range indicates conductive medium.

The locations of the conductors are specified by cross
over points in the in-phase and a positive peak in the filtered-real (current density) plots as shown in Figure 3a, while location and identification of proper cross over points are enhanced in the Fraser filtered data in Figure 3b. The Fraser filtered data improves identification of the conductive anomalies and removes false impression from the false cross-over points that usually make interpretation of the measured data difficult.

Along profile 1, the current density profile shows existence of two anomalies located at 100 and 150 m. A shift in the location of the 100 m anomaly is indicated in the in-phase component plot. The first anomaly has the appearance of a complete anomaly over a conductive sheared zone with southward orientation. The other anomaly is indicative of boulder-like resistive materials with northward orientation. The corresponding filtered real using Fraser filter helps to delineate the location of these anomalies as well as collapsing the false cross over point that are usually makes interpretation of the measured data difficult. Series of shallow and near surface bodies, which were recognized as conductive bodies on the pseudo section (Figure 4a) have low

Figure 5. Isovalues maps of EM data in the study area; (a) Fraser filtered VLF in-phase map. (b) Karous-Hjelt Equivalent Current density map [Transmitter Station: Cutler Maine (Power = 1000 Kw; freq. = 24 kHz)].
<table>
<thead>
<tr>
<th>Electrode spacing (m)</th>
<th>(a) Cartesian Azimuthal Graphs</th>
<th>(b) Polar Azimuthal Graphs</th>
<th>(c) Polar graph of RD</th>
<th>(d) Analysis of Offset error</th>
<th>(e) Analysis of range</th>
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Figure 6. Offset Wenner sounding diagrams of azimuthal resistivity survey at VES 3.
(a) Cartesian Azimuthal Graphs

(b) Polar Azimuthal Graphs

(c) Polar graph of RD

(d) Analysis of Offset error

(e) Analysis of range

Figure 7. Offset Wenner sounding diagrams of azimuthal resistivity Survey at VES 5.
Figure 8. Typical computer iterated results of the interpreted Offset Wenner sounding curves of the study area.
amplitude anomalies between 180 and 240 m along the profile.
Along profile 2, the appearance of 2 conductive sections at distances of about 55 to 80 and 160 to 220 m corresponding to 2 broad positive peaks in Figure 3a, while Figure 3b revealed existence of four anomalies with relative cross over distance at approximate 48, 80, 110 and 205 m. It was discovered that the cross over points towards the northern end actually originated from closely spaced anomalies, which occur relatively at intermediate depth and dipping southward, while the anomaly towards the northern end is shallower in appearance (Figure 4b).
Profile 3, with E-W orientation shows characteristic anomalies indicating three sources in Figure 3a, which

Figure 9. Offset Wenner pseudo section across the traverses in the study area.
Figure 10. Model geoelectric sections across the traverses in the study area.
were later recognized as extensive sheared section with a resistive boulder at shallow depth close to 110 m mark along the profile in the current density section in Figure 4c. The anomalies were also identified with similar signature in Figure 3b relatively at distance of 50, 125 and 170 m. The characteristic amplitude of these anomalies revealed that the conductors are relatively nearer to the surface. The pseudo current density section also revealed a near surface boulder-like resistive medium close to the western end at a 50 m mark.

Along profile 4, Figure 3a and 3b show occurrence of relatively broaden conductive materials close to 40 and 80 m marks from the southern end, while another presumed to originate from an extending dipping source has characteristic positive anomaly peak between 215 and 215 m distance from the beginning of the profile. These anomalies were recognized to correspond to shear zones in current density section (Figure 4d).

Typical anomalies along profile 5 in Figure 3a and b indicate presence of sheared or conductive bodies close to the western end of the profile with relatively positive amplitude peak around 80 to 115 and 200 m marks. The later happens to be shallower and narrow body due to its characteristic sharp anomaly with respect to the former which has a broaden anomaly signature. In Figure 4e, the current density section shows that these anomalies are relatively conductive materials which are diagnostic of sheared zones.

Profile 6 reveals presence of two anomalies with the in-phase component showing characteristic extensive and broader amplitude between 50 and 135 m marks (eastward). Another incomplete anomaly is situated at a distance of 255 m towards the western end. In Figure 4f, the current density section reveals these conductive anomalies as sheared zones with tabular appearance at various depths along the profile.

Profile 7 is a very short easterly W-E profile characterized by deep seated anomalies at approximate distance of 60 and 120 m from the west on the profiles in Figure 3a and b, which were recognized as near vertical and dipping conductive sheared zones in the current density section (Figure 4g).

Isovalue maps

Figure 5 presents the outputs of the filtered real component data as maps of the Fraser-filtered in-phase and equivalent Karous-Hjelt filtered (current density) maps. The two maps clearly show the contacts between various rock types in the area as indicated by various zones with varying conductivity contrast. Although, it is difficult to differentiate the rocks based on the observed anomalies, however, the identification of location and lateral extent of these rock types can be easily realized from these maps.

The location of the quartzite rocks recognized as sheared zones and lithological boundaries between the quartzite and other rocks are clearly visible in the two maps. The charnockite boundaries are better resolved in the current density map where the neighbourhood rock is resistive than the slightly conductive quartzite rocks. Some of these bodies have a round or circular appearance of intruding boulders that were confirmed to be outcrops of other rocks in the area.

Both maps were used to identify more resistive rock type in the northern flank of the study area. From the observed field occurrence, this rock is likely to be younger biotite gneiss intrusions. In addition, the Fraser filtered in-phase map was able to differentiate areas with more conductive shared zones, which coincide with brecciated quartzite around the study area, though the Karous-Hjelt current density map was able to pick response from the more resistive rocks better. However, the pockets of outcrops of the transition or hybrid gneiss characterized by highly foliated gneisses with coarse grains of plagioclase and other minerals observed on the field cannot be resolved in these maps. These rocks are believed to have relatively similar conductivity with the brecciated quartzite. Thick veins close to 4 to 6 inches wide and extensive foliations trending approximately NW-SE were also noticed at the surface of these rocks.

Offset Wenner technique

Azimuthal soundings

The azimuthal resistivity results presented as graphs of the Offset resistances $R_{d1}$ and $R_{d2}$ and the mean resistance, RD-polar diagrams (Figures 7 and 8) help to differentiate the anisotropy (fracture) which has a 180° a symmetry from the dip and lateral effects with a 360° symmetry in the study area. These diagrams are discussed as follows:

Azimuthal diagrams: the azimuthal diagrams clearly demonstrate both effects of the near surface anisotropy and lateral variation of the subsurface dipping layers. Figure 5 presents the result of the Offset-Wenner azimuthal resistivity survey at VES 3. Both effects of near surface gradual lateral variation and strong anisotropic effects were observed at small electrode spacing. Both $R_{d1}$ and $R_{d2}$ rise and fall together at small electrode spacings (AB/3 = 1 and 4m) suggest the increase in lateral variation with depth.

In the azimuthal graphs, the effect of dipping interface is much evident as the electrode spacing increases. The maximum variations delineating the strike of the beds occurred at 20°/200° for the electrode spacing of 1 m and at 20/200 and 140°/320° with cross over points at 175 and 225° for the electrode spacing of 4 m, respectively. The principal fracture axis is perpendicular to these directions of greatest lateral change. The principal axis of fracturing anisotropy is observed to lie in the NE-SW
direction, which conforms to the major geologic trends in basement complex of south western Nigeria. This pattern demonstrates similar anisotropic effects described by Watson and Barker (1999) in a study carried out over anisotropic dipping interface.

Both offset error and range analyses show anomalous and alternation of low and high values usually greater than 5.0% at small electrode spacings, with further percentage rise in errors and range values at larger electrode separation up to 48 m. The coefficient of anisotropy is significant at this location, with $\lambda$ equal to 1.22, 1.57, 2.14 and 2.66 corresponding to electrode spacings of 1, 4, 12 and 48 m respectively. The results displayed in Figures 4 and 8 also suggest the occurrence of lateral variations in resistivity arising from intrusive rocks or dykes as well as relatively thick overburden.

Similarly, the Cartesian diagrams for VES 7 in Figure 8 reveal a similar trend to what is observed at VES 3. In the same manner, the graphs corresponding to electrode spacing of 1 and 4 m are characterized by rise and fall of $R_{D1}$ and $R_{D2}$ together. The maximum resistance occurs consistently at 20°/200° for the electrode spacing of 1 m and at 20/200 and 140°/320° with cross over points at 175° and 225° for the electrode spacing of 4 m, respectively.

These variations delineate the same strike of beds as indicated by VES 3. The coefficients of anisotropy corresponding to 1, 4, 12, and 48 m electrode separations are 1.43, 1.39, 1.15 and 1.22. Random offset errors with maximum occurring at electrode spacing of 24 m and characteristic appearance of the Cartesian and polar diagrams demonstrate the possibility of fracture anisotropy at shallow and intermediate levels. On the other hand, the range analysis displayed in Figure 7e does not reflect the source of lateral effects. The effects of the near surface fracturing, lateral resistivity variations and shallowness of the bedrock at VES 5 are substantiated by the VLF isovalue maps and Offset Wenner pseudo section across traverse 3 (Figures 5 and 10).

### Table 1. Interpreted geoelectric parameters.

<table>
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<tr>
<th>VES location</th>
<th>Layer resistivity (ohm-m)</th>
<th>Layer thickness (m)</th>
<th>Over-burden thickness (m)</th>
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### Interpreted curves and model resistivity sections

Typical sounding curves, pseudo sections and the inferred model lithologic sections obtained from the interpreted Offset Wenner soundings are shown in Figures 9, 10 and 11. The sounding curves (Figure 9) reveal occurrence of three geoelectric sequence in the area (Tables 1 and 2).

The inferred geologic stratigraphy in the model sections based on the geo-electric parameters revealed thin topsoil with resistivity values ranging between 62 and 523 Ohm-m, characteristic of clayey to sandy materials impregnated with quartzite rubbles. Thickness of this layer ranges from 0.5 m at the shallowest point (VES 5) close to the outcrop within the river channel to 2.9 m at VES 2. In Figure 9 the second unit however is slightly difficult to resolve, due to observed strong lateral variations of the resistivity value at shallow depth (Figures 10 and 11).

However, the use of VLF-pseudo sections and isovalue maps (Figures 4 and 5) in conjunction with the Offset Wenner pseudo sections (Figure 11) have greatly assisted in resolving the ambiguity. It was discovered that the there is overlap in the geo-electric parameters of the quartztite bed and quartzite impregnated clayey aquifer. At VES 3 location, the thickness of quartzite bed beneath the highly clayey second geo electric layer cannot be resolved due to large thickness of the medium.

The basement rocks, which graduate from highly weathered/fractured to fresh bedrocks, are characterized by resistivity values ranging from 827 to 11064 Ohm-m at VES 2 and 10 respectively.

### Conclusion

The VLF-EM and Offset Wenner resistivity mapping of the sites of springs in Iloyin Estate in Akure metropolis have successfully revealed the underlying geologic structures of the area. The interpretation results of the combined
geophysical methods were successfully used to locate locations of conductive zones, identify and delineate lithological boundaries in the area of study.

The VLF – EM measurements revealed lateral variation in conductivity, with relatively high conductive zones associated with shear zones diagnostic of brecciated quartzite, joints and fractures in the outcropping underlying bedrocks. The impact of severe weathering in the area makes the EM response from the pockets of outcrops of the transition or hybrid gneiss in the area to be resolved. The Fraser-filtered real component map of the EM measurements gives better resolution of the boundaries between the rocks than the isovalues map of the equivalent current density obtained from the Karous-Hjelt flittering.

The Offset Wenner survey has proved useful in differentiating effects of macro anisotropy (the near surface fracturing) and pseudoanisotropic lateral effects (lateral resistivity variations), and shallowness of the bedrock in the area, especially close to the stream channels have been substantiated by the Offset Wenner pseudo section and isovalues of the VLF measurements. Principal fracturing orientations is in the NE-SW direction, perpendicular to the direction of maximum dip in the area that conforms to the striking of the quartzite veins in the area.

The aquifer in the area is composed of brecciated quartzite, clayey sand and fractured bedrock. The overlying thin topsoil in the area is mainly composed of non-protective clayey to sandy materials impregnated with quartzite rubbles with thickness lying between 0.5 and 2.5 m. The loose nature of the topsoil makes the unprotected aquifer to be highly susceptible to infiltration of run-off water and pollution from septic tanks in the area. This is confirmed by consistent dirtiness of wells in the area, especially during raining season. The springs in the area could however serve as an alternative source of potable water if developed into local dam. The spring could also be developed for agricultural purpose whereby groundwater from the springs can be harnessed for irrigation or fish pond development.

**ACKNOWLEDGEMENTS**

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**REFERENCES**


<table>
<thead>
<tr>
<th>Geoelectric sequence</th>
<th>Layer parameter</th>
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<tr>
<td>Topsoil</td>
<td>Resistivity</td>
<td>Thickness</td>
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<tr>
<td></td>
<td>62 – 86</td>
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<td>Average Overburden</td>
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<td>Bedrock</td>
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