Groundwater Investigation Using Combined Geophysical Methods*

Amarachi R Alisiobi[1], and B. D. Ako[2]

Search and Discovery Article #40914 (2012)
Posted April 23, 2012

*Adapted from extended abstract prepared in conjunction with poster presentation at AAPG Annual Convention and Exhibition, Long Beach, California, April 22-25, 2012,

[1]Geology, Obafemi Awolowo University, Ile-Ife, Osun, Nigeria (alisiobia@gmail.com)
[2]Geology, Obafemi Awolowo University, Ile-Ife, Osun, Nigeria.

Abstract

A geophysical investigation involving the seismic refraction and the vertical electrical sounding (VES) electrical resistivity methods was carried out around Ajebandele quarters, Ile-Ife, Osun State, Southwest Nigeria. The study was carried out with a view to determine the subsurface layer parameters (velocities, resistivities, and thicknesses) and use same to categorise the ground-water potential of the area.

Five seismic stations were shot and six vertical electrical sounding locations, along each traverse for the refraction, a total of five (5) traverses, with traverses one and two trending north-south (N-S) and traverses three, four, and five trending east-west (E-W). Geophone separation of 2 m was used and an offset distance of 4 m along each traverse. A 12 channel BISON seismograph was used in recording the values of the arrival times at the geophones positions. The vertical electrical sounding stations were located based on the results of the refraction survey. The VES technique was employed for the resistivity method. A total of six VES stations were occupied with electrode separation (AB/2) varying from 1 m to 65 m. An ABEM terrameter SAS 300C was used in the survey. The results of interpretation of the seismic refraction time-distance graph and VES curve were used to construct geo-sections showing the subsurface layers, their corresponding velocities, and thicknesses.

The interpretation of results from seismic refraction showed three layer formations, the top layer with thickness ranging from 1.3 m to 3.6 m and velocities ranging from 352 m/s to 827 m/s. The velocity of the second layer ranges from 678 m/s to 2105 m/s with a thickness of 6.1 to 9.4 m and velocity of the third layer ranging from 2222 m/s to 3229 m/s. A discontinuity representing a fracture is observed on traverse four (4). Maximum of five (5) layers were delineated with H, HK, AA, and HAA curve types and showed the bedrock in the area occurs quite close to the surface. The topsoil had resistivities ranging from 105 Ωm- 412 Ωm to a depth of 0.5 m-1.4 m. The weathered layer had resistivities ranging from 102 Ωm- 224 Ωm to a depth of 3.4 m- 6.2 m and the fresh bedrock had resistivities ranging from 1161 Ωm- ∞. In VES four (4), a fractured

zone is observed at a depth of about 15 m. Although the number of layers delineated differ, both methods indicate viable aquifer at a fractured zone along traverse four.

General Overview

The availability of quality water resources has always been the primary concern of societies in semi arid and arid regions, even in areas of more abundant rainfall, the problem of obtaining adequate supply of quality water is generally becoming more acute due to ever increasing population and industrialization. As a result of this, surface water cannot be dependable throughout the year, hence, the need to look for other alternatives to supplement surface water. This makes the world depend on the largest available source of quality fresh water which lies underground and this is referred to as Groundwater. It is the water held in the subsurface within the zone of saturation under hydrostatic pressure below water table (Ariyo and Banjo, 2008).

Groundwater can be in sedimentary terrain where it is less difficult to exploit except for its chemical composition. It can also be in the Basement Complex terrain where it can be a bit difficult to locate especially in areas underlain by crystalline unfractured or unweathered rocks. The research for groundwater today has become essential, due to its relative low cost and its chance of obtaining quality water from the bedrock.

Therefore, the application of geophysics to the successful exploration of groundwater in sedimentary terrain requires a proper understanding of its hydro-geological characteristic. Evidence has shown that geophysical methods are the most reliable and the most accurate means of all surveying method of subsurface structural investigations and rock variation (Carruthers, 1985; Emenike, 2001).

Several methods employed in groundwater exploration include electrical resistivity, gravity, seismic, magnetic, remote sensing, electromagnetic, among others, out of which the resistivity method is the most effective for locating productive well and the Vertical Electrical Sounding (VES) technique can provide information on the vertical variation in the resistivity of the ground with depth and the Constant Separation Traversing (CST) provides a means of determining interval variation in the resistivity of the ground (Olayinka and Mbachi, 1992; Olorunniwo and Olorunfemi, 1987; Ariyo, 2003).

In view of the above, the Seismic Refraction and Vertical Electrical Sounding (VES) techniques were used to investigate groundwater potential in a local residential area in Ajebandele, Ile-Ife in Osun State, Southwest Nigeria.

Location and Accessibility of the Area

The study area is in Ajebandele area in Ife Central Local Government area of Osun State Nigeria. The survey area lies within longitudes 4.49410^0 E and 4.49483^0 E and latitudes 7.49882^0 N and 7.49967^0 N. The study area is accessible through network of roads and well developed footpaths.

Literature Review

A lot of geophysical investigations have been carried out in different parts of the world for groundwater investigation:

Brousse (1963) cited the effectiveness of the electrical resistivity method in the investigation for groundwater in complex granite areas. He used the method to map fractures, gorges gouge, and faults which act as water reservoirs.

Ako and Osondu (1986) carried out groundwater investigations at Darazo on the Kerri-Kerri Formation, they concluded that Dar-Zarouk parameters are related to borehole characteristics. Thus, they concluded that the highest traverse resistance (T) corresponds to the zone with the highest borehole yield.

Ajayi and Adegoke-Anthony (1987) investigated groundwater prospect in the Basement Complex rocks of southwestern Nigeria. They concluded that local geological condition play
an important role in the yield of boreholes located in the basement complex area of southwestern Nigeria.

Olorunfemi and Oloruniwo (1987) used the electrical resistivity method for groundwater investigation in parts of the Basement terrain in Southwest Nigeria and concluded also, that the weathered layer and the fractured Basement constitute the aquifer zones.

Olorunfemi and Fasuyi (1993) used the electrical resistivity method in investigation of geo-electric and hydro-geologic characteristics of areas in Southwest Nigeria.

Gnanasunder and Elango (1999) carried out groundwater quality assessment of a coastal aquifer lying south of Chennai City, Madras, India, using geo-electrical techniques. This study was able to delineate a fresh water ridge of good groundwater quality in the central portion of the coastal aquifer while the eastern and western margins of the aquifer however contained groundwater of poor quality.

Ayolabi et al. (2000) carried out groundwater investigation at Igbogbo, Lagos, using seismic refraction and electrical resistivity techniques. They correlated the results from each method and delineated aquifer zones.

Osuagwu (2009) used very low frequency electromagnetic and vertical electrical sounding techniques in delineating aquifer zones in Modeme area, Ife, Osun State.

Aims of Study

The research work was carried out to have an insight into the subsurface geology of the study area with the following objectives, to:

(1) detect subsurface layers, their thicknesses, and their resistivities;
(2) investigate the hydrological conditions of the area with the view of delineating the potential area for groundwater development;
(3) map geological structures e.g. faults and fractures, which are conductive bodies, thus may accommodate groundwater, and
(4) locate possible and suitable site for productive boreholes in the study area.

Methodology

The seismic refraction method was carried out first due to its ability to provide extensive and qualitative information on the velocities of different subsurface layers and also aid in the selection of specific potential areas in which the Vertical Electrical Sounding (VES) could be done (Figure 1).

For the refraction, a total of five (5) traverses were established, with traverses one and two trending North-South (N-S), and traverses three, four, and five trending East-West (E-W). Geophone separation of 2 m was used and an offset distance of 4 m along each traverse. A 12 channel BISON Seismograph was used in recording the values of the arrival times at the geophones positions. The Vertical Electrical Sounding (VES) stations were located based on the results of refraction survey. The VES technique was employed for the resistivity method. A total of six VES stations were occupied with electrode separation (AB/2) varying from 1 to 65 m. An ABEM terrameter SAS 300C was used in the survey.

The seismic refraction data were plotted as time-distance graphs, while the vertical electrical sounding (VES) data were presented as depth sounding curves. The interpretation results of the seismic refraction time-distance graphs were used to construct geo-sections showing the subsurface layers, their corresponding velocities and thicknesses. Also, the interpretation results of the VES curves were used to construct geo-electric sections showing the subsurface layers, their corresponding resistivities and thicknesses.

Geology and Hydrology of the Study Area

The attempt to describe the occurrence, structural, and stratigraphic relationships, classification and illustration of the metamorphic history and evolution of the rocks, led people like Oyawoye (1964), Rahaman (1973, 1976, 1988), Odeyemi (1978) and many others to carry out extensive study of the rocks of the Precambrian Basement Complex of Nigeria. Figure 2.1 shows the generalized geologic map of Nigeria. The Basement Complex is divided into two zones:

- The NS trending western zone elongated schist belts separated by migmatites, gneisses and granites.
- The eastern zone in which the schist belts are poorly represented, comprising mainly migmatites, gneisses, and granites.

Rahaman's (1976, 1988) classification of the rocks of the Precambrian Basement Complex recognizes six (6) lithologic groups. The lithologic groups include:

- <u>The Migmatite-Gneiss-Quartzite Complex</u>: This is regarded as the oldest. This unit covers over 30% of the total surface area of Nigeria (McCurry, 1976). It is called 'basement complex' by older workers. This comprises quartzite and quartz schist, biotite and biotite-hornblende gneiss, and small lenses of calc-silicate rocks. [Archean to upper Proterozoic, Kiberan and Eburnean orogenesis].
- <u>Slightly Migmatized to Non-migmatized Metasedimentary and Metaigneous rocks</u>**:** These have been called different names ranging from 'Newer sediments' by Oyawoye (1964), 'schist belts' by Ajibade (1976) to 'younger metasediments' by McCurry 1976) respectively [Achaean to upper Proterozoic, Eburnean orogeny].
- <u>Charnokitic, Gabbroic, and Dioritic rocks</u>: These rocks occur within the amphibolite facies, although their mineral assemblages indicate that they belong to the granulite facies (Rahaman and Ocan, 1981; Olarewaju 1981) [Pan African, 600 $\pm$ 150 ma].
- <u>Older Granites</u>**:** This comprises rocks of varying compositions ranging from granodiorite to true granites and potassic syenite [Pan African, 600 $\pm$ 150ma].
- <u>Metamorphosed to Unmetamorphosed Alkaline Volcanic and Hyperbasal rocks</u>: The most important lithologies which form these rock units include volcanic agglomerates, tuffs and rhyodacites [Pan African, 600 $\pm$ 150ma].
- <u>Unmetamorphosed Dolerite dykes, Syenite dykes</u>, etc: These are invariably the youngest of all. Dolerite dykes are widely distributed within the Nigerian Basement Complex (De-Swardt, 1953). Examples include the Ibadan dolerite dyke, whose emplacement is thought to represent the termination of the Pan-African Orogeny (Grant, 1970, 1971), the Igarra syenite dyke extensively studied by Rahaman and Odeyemi (1974), Odeyemi (1976), Obasa (1981), as well as others.

The rocks in the study area belong to the slightly migmatized to non-migmatized meta-sedimentary and meta-igneous rocks usually referred to as the Schist belts. The primary rock type constituting the local geology of the area is schist. The study area is on the slope of a low hill.

After sampling five wells in the area, it was deduced that the water table in the area occurs at about 5 m depth.

Geophysical Prospecting Methods

The essence of geophysical methods is to analyse the real picture of the subsurface geology of a particular area of interest. Devices used for these methods locate discontinuities caused by contrast in physical properties of the rocks. However, due to the complexity of the geophysical pattern and signature of these discontinuities in geophysical interpretations, an integrated survey or the correlation of two or more geophysical methods are used so as to reveal the subsurface geology of the area of interest, not leaving behind its ability to reduce the problems posed by inhomogeneous nature of the earth. In this project, an integrated geophysical survey was adopted which comprises of seismic refraction and electrical resistivity methods.

Seismic Refraction Method

Seismic refraction method is based on the principle of acoustic impedance which is the product of density and velocity of subsurface layers. Energy is sent through the source which could be a hammer, a weight dropping system, explosives, etc. The method used for this exercise is the hammer method. Energy sent into the subsurface is refracted, travels along the subsurface boundary and back to the surface and is recorded by receiver(s) called geophone(s). This method assumes that velocity increases with depth. So, if the velocity of the layer is less than the velocity in the layer overlying it, there will be velocity reversal. The layer having the low velocity will not be delineated by the refraction method. The factors that affect seismic velocity in rocks are age of the rock, porosity, and depth of burial etc.

Data Acquisition

The data are acquired along a traverse with definite and constant geophone-geophone spacing. The larger the geophone-geophone spacing and the offset employed, the larger the depth of investigation.

Many layers as possible can be mapped. The essential instruments are

- Sledge hammer (Seismic source) which generates a seismic pulse,
- Receivers / Transducers (in this case geophones were used since the survey was carried out on land) useful for detecting and recording the seismic waves through the ground,
- Compass – Clinometer
- 12 channel BISON seismograph.

For this project, an array of 12 geophones was used. On and Reverse shootings were also done, with offsets of 4 m along both shootings. A total of five (5) traverses were established, with traverses one and two trending North-South (N-S), and traverses three, four and five trending East-West (E-W). Geophone separation of 2 m was used and an offset distance of 4 m along each traverse. A 12 channel BISON Seismograph was used in recording the values of the arrival times received on the geophones which were laid on the surface.

The seismic data were plotted as Time – Distance (T-X) graphs, where the times picked as the first arrivals of the signal were plotted against the distance (station separation). The plots are segmented curves in which the number of segments represents the number of layers. The inverse of the slope of the individual segments is the velocity of the particular layer. Both the ON and REVERSE shootings were plotted on the same graph. The depths to the layers were computed using equation 1, that is, the intercept time method.

$$Z = \frac{t_i V_2 V_1}{2\sqrt{(V_2^2 - V_1^2)}} \qquad \textbf{(1)}$$

Where Z = depth to refractor,

V_1 = velocity of layer 1,

V_2 = velocity of layer 2, underlying layer 1, and

t_i = the intercept time.

The Electrical Resistivity Method

The electrical resistivity method measures both lateral and vertical variation in ground resistivity from different points on the earth surface. The resistivity of the ground is measured by sending current into the ground at the current electrodes and the corresponding potential difference is measured at the potential electrodes, which is then converted to apparent resistivity value by multiplying with an appropriate geometrical factor. Different factors affect the resistivity in the subsurface (Telford et al, 1990).

Pore spaces in rock particles may be in the form of intergranular voids, joint, or fracture openings and closed pores such as bubbles or vugs (in lavas). Only the interconnected pores effectively contribute to conductivity and the geometry of the interconnections. Also, the degree of saturation influences the resistivity of rocks. Moreover, as water forms a conductive electrolyte with the presence of chemical salts in solution, the resistivity varies inversely with to the salinity. Also, the effect of increase in temperature tends to decrease the resistivity of the electrolyte because the viscosity of the fluid decreases.

The large variations in the electrical resistivity values of different rocks and minerals make the Electrical resistivity method very useful. The Electrical resistivity method can be used in mineral exploration to map massive ores, in groundwater exploration to delineate aquifers, in geothermal exploration to locate geothermal fields, in engineering site investigation to determine depth to bedrock, and in environmental studies for environmental assessment.

Electrode Configuration

This is determined by the mode of arrangement of the current and potential electrodes. There are different types of electrode arrays that can be used in the resistivity method. These include the Pole-Pole, Pole-Dipole, Dipole-Dipole, Wenner, Schlumberger, Lee Partition, Square, Gradient, Crossed Square array, and others. Generally, two (2) potential and two (2) current electrodes are used in electrical resistivity surveys. An exception to this is the Lee Partition electrode array which uses five (5) electrodes. For this survey, the Schlumberger array method was employed.

Schlumberger Electrode Array

This is a collinear array of electrodes in which the potential electrodes are located within the current electrodes. This electrode array is symmetrical because the station of measurement is at the centre of the array.

Field Procedures

Instrumentation

The ABEM SAS 300C terrameter was used for the field data collection. This instrument measures and displays the resistance of the subsurface averaged over a number of cycles (four cycles for the purpose of this study). Other instruments used include; metal electrodes, measuring tape, labelled tag (used in locating station position), hammer (used in driving the electrodes into the ground), compass, and connecting cables.

Survey Techniques

The survey technique used for this study is the Vertical Electrical Sounding (VES) technique. The Vertical Electrical Sounding technique measures the vertical variations in ground apparent resistivities with respect to a fixed centre of array. The VES technique employs the collinear arrays designed to output a one- dimensional (1-D) vertical apparent resistivity versus depth model of the subsurface at a specific observation point. In this method, a series of potential differences are acquired at successively larger electrode spacing while maintaining a fixed central reference point. The induced current passes through progressively deeper layers at greater electrode spacing. Apparent resistivity values calculated from measured potential differences can be interpreted in terms of overburden thickness, water table depth, and the depths and thicknesses of subsurface strata (Telford et al., 1990).

For this study, the Schlumberger configuration was used to acquire VES data at five (5) sounding points, one along each traverse. The electrode separation (AB/2) varied from 1 to 65 m. Current was passed into the ground through the current electrodes, and the resulting potential was measured through the potential electrodes, and was converted to resistance, which was recorded by the terrameter.

Data Presentation

The apparent resistivity data obtained from the VES survey were presented as depth sounding curves by plotting the apparent resistivities along the ordinate axis and the half current electrode spacing (AB/2) along the abscissa. This plot was made on bi-log paper. The resistivity depth sounding curves were classified based on layer resistivity combinations.

For a three (3) layer case, there are four type curves, the H, K, A, and Q type curves. Any type curve can be derived from any combination of these type curves. The curves obtained in the study area were H (VES one, two, and three), HK (VES four), AA (VES five) and HAA (VES six)

Data Interpretation

The Depth sounding curves were interpreted both qualitatively and quantitatively.

<u>Qualitative Interpretation</u>

Qualitative interpretations of the depth sounding curves involve:

- Classification or grouping of depth sounding curves based on distinctive geo-electric characteristics and determination of percentage of each group.
- Lithological identification aided by lithologic logs where available (e.g. Olorunfemi and Olorunniwo, 1985; Ako and Osondu, 1986; Okhue and Olorunfemi, 1991; Idornigie and Olorunfemi, 1992). On the basis of this, the VES curves were interpreted in terms of lithologies.

<u>Quantitative Interpretation</u>

The quantitative interpretation of the depth sounding curves was carried out by adopting the partial curve matching technique (Bhattacharya and Patra, 1968). In order to do this, the VES data were plotted on a transparent overlay. The partial curve matching technique involved the use of a standard two (2) layer master curve and four (4) auxiliary type curves (H, K, A, and Q).This procedure required segment-by-segment curve matching starting from the position with shorter electrode spacing and moving towards those with longer spacing.

The results of the VES curves obtained from the partial curve matching were then used to constrain the interpretation by the computer using iteration software known as WINRESIST. This invariably reduces overestimation of depths.

Results and Discussion

Seismic Refraction Results

The seismic survey was carried out on the five traverses shown in the base map. From the *ON* and *REVERSE* data gathered during the survey, Time (T) – distance (X) curves were plotted for each traverse. The numbers of line segments on these curves correspond to the number of layers in the subsurface. The reciprocal slopes for these line segments give layer velocities. From the T-X plots, the following parameters were derived: layers velocities V_1, V_2, and V_3, and the thicknesses of the overlying layers, Z_1, Z_2, and Z_3. Table 1 gives a summary of the refraction results. Geo-sections were constructed for each traverse based on the velocities and thicknesses calculated from the T-X curves. The thicknesses were converted into depths by adding up the overlying thicknesses. The results obtained indicate three layers for traverses one and four, and two layers for traverses two, three, and five.

Deductions from Results

In traverses one and four, the top layer has velocity ranging from 353 m/s – 483 m/s, and has a thickness of 1.3 m – 3.6 m from the ground surface. In traverses two, three, and five, the top layer's velocity ranges from 458 m/s to 827 m/s with a thickness of 1.7 m – 3.1 m.

In traverses one and four, the second layer has velocity 678 m/s – 789 m/s and is 6.1 m – 9.4 m thick. In traverses two, three, and five, the second layer has velocity 860 m/s – 1593 m/s. This layer is seen as a lateral variation in traverses three and five. A discontinuity is observed in traverse two, which is indicative of a septic tank dug along this traverse.

In traverses one and four, the third layer has velocity 2222 m/s - 3229 m/s. Along traverse four as shown by the Time – Distance curve, there is a discontinuity in the ON shot direction, which is indicative of a fracture along this traverse.

Potential aquifers in this area are the fracture zones and layers with low - medium velocities.

Vertical electrical Sounding (VES) Results

A total number of six (6) VES were carried out, one on each traverse. The results obtained were plotted to get a curve on a bi-log graph, with apparent resistivity, (ρ_a), on the y-axis, and current electrode separation, (AB/2), on the x-axis. The depth sounding curves were interpreted quantitatively to determine depth to fresh basement bedrock. The results of the VES curves obtained from the partial curve matching were then used to constrain the interpretation by the computer using iteration software known as WINRESIST. A total number of four layers were depicted from each VES curve. Table 2 shows an overview of the VES results obtained. A false interpretation was gotten for VES six which shows the topography of the area as a result of moving the electrodes along a slope.

Deductions from Curves

Geo-electric Section Trending SW-NE

The geo-electric section trending SW-NE connects VES 2, 4, and 5. The section reveals the presence of three to four layers. The resistivity of the first layer ranges from 105 to 425 ohm-m while its thickness varies from 0.7 m to 1.4 m. This layer constitutes the topsoil. Underlying this topsoil is a sandy clay layer which has a resistivity of 123 to 224 ohm-m, and a thickness of 3.0 m – 6.2 m. This sandy clay layer overlies the fresh bedrock, with velocity 3580 to ∞ m/s. In VES four, at a depth of 22 m, a fractured zone occurs. This zone is the main aquifer in this area. The sandy clay layer, may serve as a minor aquifer, although the recharge would be very low due to the low to moderate porosity and permeability of the layer. Taking into consideration, the water table at 5 m, the sandy clay aquifer is only about 0.7 m in VES two, and 2.6 m in VES five. The yield from wells dug in these locations, would be insufficient, even for domestic use.

Geo-electric Section Trending NW-SE

The geo-electric section trending SE-NW connects VES 2, 1, and 3. The section reveals the presence of three (3) layers. In VES 2 and 1, the resistivity of the first layer ranges from 217 to 380 ohm-m while its thickness varies from 0.7 to 1.4m. This layer constitutes the topsoil. In VES 3, the resistivity of the first layer is 910 ohm-m and is 0.5 m thick. This layer also constitutes the topsoil. The high velocity recorded, may have been due to the effect of massive building materials and rubbles, which were randomly scattered and around this VES station. The resistivity of the second layer ranges from 109 to 128 ohm-m, while its thickness varies from 3.4 to 5.0 m. This constitutes the sandy clay zone. Underlying the sandy clay zone, is the fresh bedrock with resistivity ranging from 1181 to ∞ ohm-m. The aquifer in this area is the sandy clay zone. Thus, since the water table in this area is 5 m, the aquifer thickness is about 0.4 m in VES 1 and about 0.7 in VES 2 which would give very low yield.

Correlation between the Seismic Refraction Results and the VES Results

The VES positions were selected, based on the seismic refraction results. Seismic refraction sections and electrical resistivity geo-electric section are shown along traverses one to five. Comparison of the figures shows that even though the cross-sections look alike, a depth variation exists between the electrical and seismic refraction results (Figure 2). This may be due to the fact that the two methods respond to different properties of the earth. It is seen that the thickness of the overburden material varies from 0 m to 7.9 m, and consists of loose materials.

Conclusion

The results of the seismic refraction survey and electrical resistivity sounding carried out at a local residence area in Ajebandele, Ile-Ife, Osun State, Southwest Nigeria have been reported. The main aquifer unit recognised is a fracture in the basement of VES four at a depth of about 19 m. Other minor aquifer units include the sandy clay zones in VES one, two, and five. In these locations, the groundwater yield is so unappreciable and low even for domestic supply. There is no groundwater potential in VES 3. The correlation between Seismic refraction and Electrical resistivity geo-electric sections shows that even though the same number of layers are obtained, a depth variation exists, due to the different properties measured by the methods. In VES six, it appears like a fault exists, but the data and results are false, due to the fact that during the fieldwork, the electrodes were moved along the sloppy road, instead of in the perpendicular direction, thus the resulting profile depicts the topography of the area, not the subsurface geology.

Recommendation

It is recommended that a borehole be drilled at VES station number four, to a depth of about 30 m. The fracture in traverse four may also extend to any area parallel but close to the traverse. Such location can also be drilled. Other geophysical methods like the Electromagnetic (VLF) Method and Dipole-dipole electrical resistivity survey can be used to complement the methods used for this study.

References

Ako, B.D., and V.C. Osondu, 1986, Electrical resistivity of the Kerri-kerri Formation, Darazo, Nigeria: Journal of African Earth Sciences, v. 5/ 5, p. 527-534.

Archies G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Trans. A.I.M.E, v. 146, p. 54-62.

Ariyo, S.O., 2005, Geoelectrical characterisation of aquifers and Geochemical study of groundwaters in the basement complex/sedimentary transition zone around Ishara, Southwest Nigeria: Unpublished Master’s Thesis, University of Ibadan, Ibadan, Nigeria, p. 139.

Ariyo, S.O., and A.A. Banjo, 2008, Application of electrical resistivity method for groundwater exploration in a sedimentary terrain: A case study of Ilara-Remo, Southwest Nigeria: Continental Journal of Earth Sciences, v. 3, p 53 – 58.

Ayolabi, E.A., L. Adeoti, N.A. Oshinlaja, I.O. Adeosuni, and O.I. Idowu, 2009, Seismic Refraction and Resistivity Studies of part of Igbogbo Township, Southwest Nigeria: Journal of Science Research Development, v. 11, p. 42–61.

Bernard, J., 2003, Short notes on the depth of investigation of electrical methods, p. 2-4. Web accessed 4 April 2012. http://www.heritagegeophysics.com/papers/Depth_of_investigation.pdf

Bhattacharya, A.P.K., and H.P. Patra, 1968, Direct current geo-electric sounding: Principles and interpretations: Methods of Geochemistry and Geophysics, v. 9, p. 133.

Brousse, J.J., 1963, Modern geophysical methods for subsurface water exploration: Geophysics, v. 28/4, p. 634-635.

Carruthers, R.M., 1985, Review of geophysical techniques for groundwater exploration in crystalline basement terrain: British Geological Survey, Regional Geophysics Research Group, Report 85/3, 30 p.

De Swardt, A.M., 1953, The Geology of the country around Ilesha Nigeria: Bulletin Geological Survey Niger, v. 23, p. 54.

Emenike, E.A., 2001, Geophysical exploration for groundwater in a Sedimentary Environment: A case study from Nanka over Nanka Formation in Anambra Basin, Southeastern Nigeria: Global Journal of Pure and Applied Sciences, v. 7/1, p. 1-11.

Falconer, J.D., 1911, The Geology and Geography of Northern Nigeria. Macmillan Publication, London, 295 p.

Gnanasundar, D., and L. Elango, 1999, Groundwater quality assessment of a coastal aquifer using geo-electrical techniques: Journal of Environmental Hydrology, v. 7, paper 2.

Grant, N.K., 1970, Geochronology of Precambrian basement rocks from Ibadan Southwest Nigeria: Earth and Planetary Science Letter, v. 10/1, p. 29-38.

Grant, N.K., 1971, A Compilation of radiometric ages from Nigeria: Journal of Mining and Geology, Nigerian Mining, Geological and Metallurgical Society, v. 6/1-2, p. 37-54.

Hubbard, F.H., I.K. Ogbukagu, A.M.J. De Swardt, and J.D. Van Coppenhagen, 1966, The geological map of Ife-Ilesha area: Geological Survey of Nigeria. 1:250,000 series Iwo sheet 60.

Idornigie, A.I., and M.O. Olorunfemi, 1992, A Geo-electrical mapping of basement structures of the South-central part of the Bida Basin and its hydrogeological implications: Journal of Mining and Geology, v. 28/1, p. 93-103.

Kollert, R., 1969, Groundwater exploration by the electrical resistivity method: ABEM Geophysical memorandum, v. 3/69, p. 1-8.

Obasa, O.O., 1981, Petrology and Geochemistry of a composite dyke south of Igarra:. Unpublished Bachelor of Science Thesis, University of Ife, p. 58.

Odeyemi, I.B., 1976, Preliminary report on the field relationships of the basement complex rocks around Igarra, Midwest Nigeria, *in*, C.A. Kogbe (ed.), Geology of Nigeria: Elizabethan Publishing Company, Lagos, Nigeria, p. 59-63.

Odeyemi, I.B., 1978, Orogenic events in the Precambrian basement of Nigeria, West Africa: Geol. Rdsch, v, 70, 879-909. (Can't locate what this means.)

Okhue, E.T., and M.O. Olorunfemi, 1991, Electrical resistivity investigation of a typical basement complex area: Journal of Mining and Geology, v. 26/2, p. 243-250.

Olarewaju, V.O., 1981, Geochemistry of the charnokitic and granitic rocks of the basement complex around Ado-Ekiti-Akure, Southwest Nigeria: Unpublished Ph.D. Thesis, University of London, p. 383.

Olayinka, A.I., and C.N.C. Mbachi, 1992, A technique for the interpretation of electrical sounding from crystalline basement areas of Nigeria: Journal of Mining and Geology, v. 27, p. 63-69.

Olorunfemi, M.O., and S.A. Fasuyi, 1993, Aquifer types and the geoelectric hydrogeologic characteristics of parts of the central basement terrain of Nigeria, Niger State: Journal of African Earth Sciences, v. 16/3, p 309-317.

Olorunfemi, M.O., and M.A. Olorunniwo, 1985, Geoelectric parameters and aquifer characteristics of some parts of Southwest Nigeria: Geologia Applicata Indrogeologia, v. 20, p. 99-109.

Olorunfemi, M.O., and M.A. Opadokun, 1986, On the application of surface geophysical measurement in geological mapping – the basement complex of Southwest Nigeria as a case study: Journal of African Earth Sciences, v. 6/3, p 287-291.

Olorunniwo, M.A., and M.O. Olorunfemi, 1987, Geophysical investigation for groundwater in Precambrian terrain, A case history from Ikare, Southwest Nigeria: Journal of African Earth Sciences, v. 6, p. 787-796.

Osuagwu, B.C., 2009, Geophysical investigation for groundwater in a difficult terrain around Modomo Area, Ife, Osun State: Unpublished Bachelor of Science Thesis, Obafemi Awolowo University, Ile-Ife, Osun State, p. 88.

Oyawoye, M.O., 1964, The Geology of the Nigerian basement complex: Journal of the Nigerian Mining, Geological and Metallurgical Society, v. 1, p. 87-482.

Oyawoye, M.O., 1972, The Basement Complex of Nigeria, *in*, T.F.J. Dessauvagie, and A.J. Whiteman, (eds.), African Geology: University of Ibadan, Nigeria, p. 67-99.

Rahaman, M.A., 1973, The Geology of the district around Iseyin, Western Nigeria: Unpublished Ph.D Thesis, University of Ibadan, p. 268.

Rahaman, M.A., 1976, Review of the basement geology of Southwest Nigeria, Geology of Nigeria, *in*, C.A. Kogbe (ed.), Geology of Nigeria: Elizabethan Publishing, p. 41-58.

Rahaman, M.A., 1988, Recent advances in the study of the basement complex of Nigeria: Precambrian Geology of Nigeria, G.S.N, p. 11-41.

Rahaman, M.A., and O.O. Ocan, 1981, The nature of granulite facies metamorphism in Ikare area, Southwest Nigeria: Journal of Mining and Geology, v. 15/1, p. 23-32.

Rahaman, M.A., and I.B. Odeyemi, 1974, Petrology of a potassic syenite dyke from south of Igarra, Abstract: Journal of Mining and Geology, v. 12/1, p. 15-18.

Telford, W.M., L.P. Geldart, R.E. Sheriff, and D.A. Keys, 1990, Applied Geophysics (Second Edition: Cambridge University Press, p. 344-536.

Wilson, A.F., 1922, Geology of the Western Railway: Geological Survey of Nigeria Bulletin, No. 2.

Selected Website

University of the Witwatersrand, Johannesburg, South Africa: Web accessed 4 April 2012. http:// www.wits.ac.za/

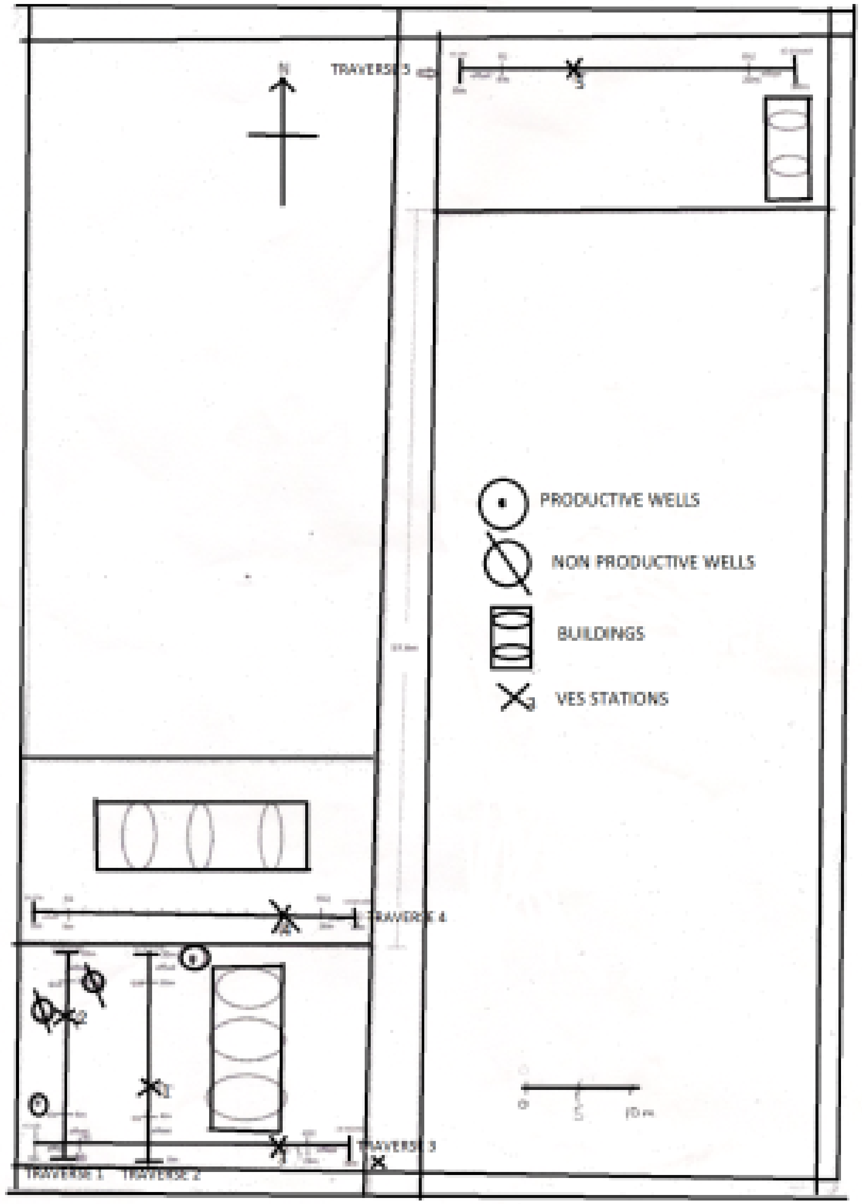

Figure 1. Sketch site map of the study area showing geophysical traverses.

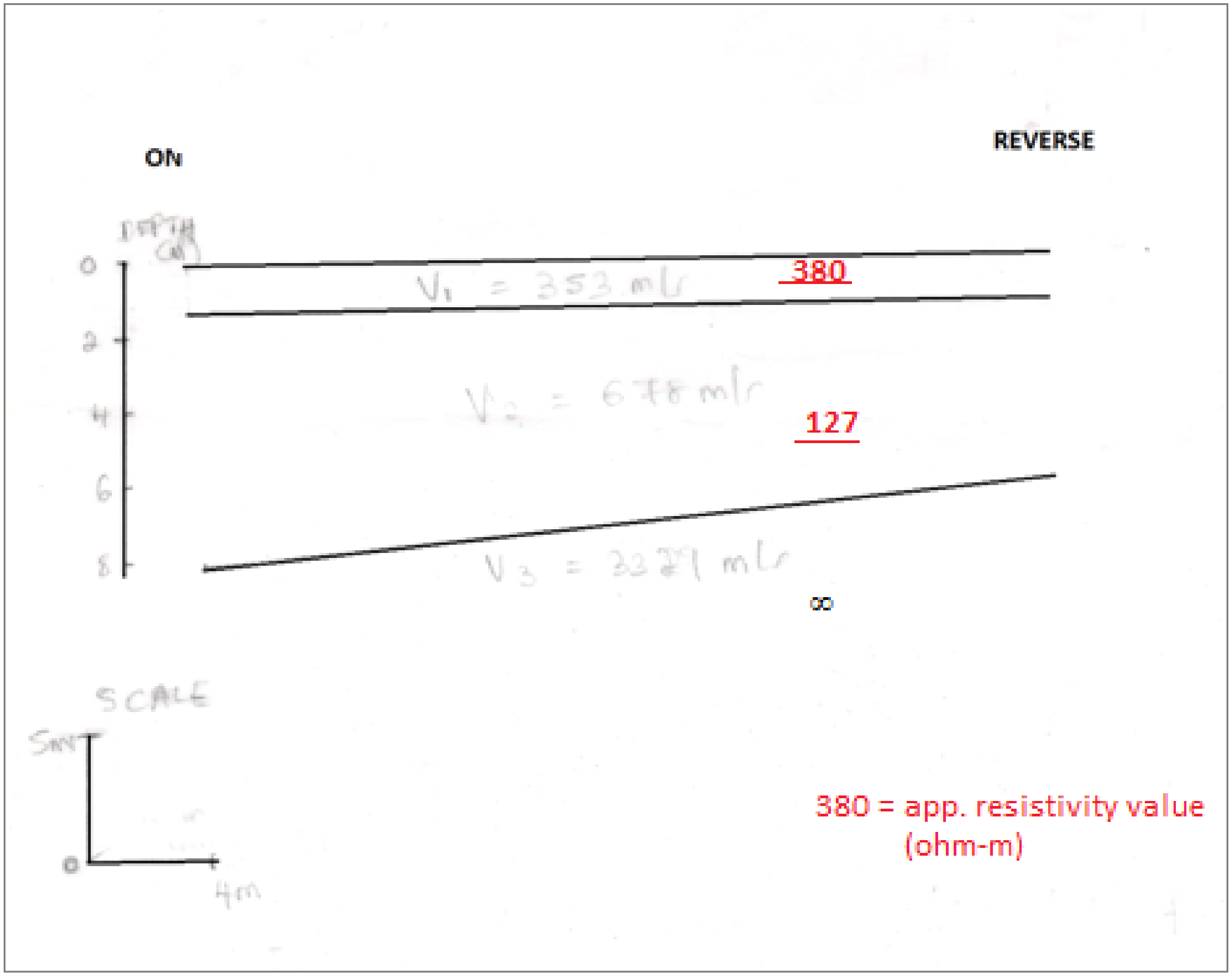

Figure 2. Correlation of electric and seismic geo-sections in traverse one.

TRAVERSE NO	LAYER 1			LAYER 2			LAYER 3
	Velocity (m/s)	Thickness (m)		Velocity (m/s)	Thickness (m)		Velocity (m/s)
		Forward	reverse		forward	reverse	
1	353	1.3	1.2	678	6.5	6.1	3229
2	458	2.3	2.1	860	-	-	
3	827 238.1	-	3.1	2105	-	-	-
4	483	2.0	3.6	789	5.7	9.4	2222
5	708	1.7	-	1088	-	-	-

Table 1. Summary of the Seismic Refraction Results.

VES STATION NUMBER	GEOGRAPHIC LOCATION	LAYER RESISTIVITY	THICKNESS	DEPTH	TYPE CURVE
		ρ_1 / ρ_2 / --- /ρ_n (ohm-m)	h_1 / h_2 / --- / h_n (m)	D_1/D_2/--/D_n (m)	
1	N 07^o,29.959$^/$ E 004^o,29.602$^/$	217 / 109/ 5200	1.4 / 4.0	1.4 / 5.4	H
2	N 07^o,29.965$^/$ E 004^o,29.599$^/$	380 / 127 / ∞	0.7 / 5.0	0.7 / 5.7	H
3	N 07^o,29.952$^/$ E 004^o, 29.617$^/$	910 / 128 / 1161	0.5 / 3.4	0.5 / 3.9	H
4	N 07^o, 29.973$^/$ E 004^o,29.611$^/$	425 / 123 / 2920 / 1310	0.9 / 2.1 / 19.0	0.9 / 3.0 / 22.0	HK
5	N 07^o,30.000$^/$ E 004^o,29.611$^/$	105 / 224 / 3580	1.4 / 6.2	1.4 / 7.6	A
6	N 07^o,29.950$^/$ E 004^o, 29.622$^/$	67 / 52 / 149 / 2006 / 6637	0.9 / 1.0 / 1.1 / 15.5	0.9 / 1.9 / 3.0 / 18.5	HAA

Table 2. Summary of VES Results.