FRACTURE DETECTION IN A HARD ROCK TERRAIN USING RADIAL GEOELECTRIC SOUNDING TECHNIQUE

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ABSTRACT

Groundwater exploration in the hard rock terrain of Nigeria primarily focused on the extent and type of the weathered mantle and fracturing. Fractures are lineaments in the subsurface which host a lot of mineral resources and groundwater. The present study is aimed at detecting fractures that were caused by recent tectonic activities around Lupma Hill in Paikoro Local Government area of Niger State, Central Nigeria. The tremor was reported to have a magnitude of 3.2 on the Richter's scale. The lateral extent of this fracturing was estimated to be about 400m. A combination of detailed geologic mapping and Radial Geoelectric Sounding Techniques were utilised to characterise the subsurface structural trends. The area is composed primarily of granitic rocks. These rocks occur as outcrops, hills and ridges. Joint directions observed on outcrops were measured, plotted as a Rosette diagram and revealed a predominant NE-SW trend. Radial geoelectric sounding was done using Schlumberger array configuration in three different orientations: 0°, 060° and 120° to a depth of 80m to obtain apparent resistivity values. Apparent resistivity values were plotted along three azimuths; 0°, 060° and 120° to obtain electrical resistivity anisotropy polygons. The sounding data were interpreted using WINRESIST software. Analysis of electrical resistivity anisotropy polygons indicated that fractures detected at shallow depths are oriented in NE-SW direction and at greater depths, fractures are oriented in the N-S direction. These results are similar to results obtained from the plot of the Rosette diagram. Generally, three geoelectric layers, consisting of thin topsoil, whose depth values range from 1 m to 3 m, and resistivity values ranging from 5Ωm - 63 Ωm, weathered mantle, whose depth values range from 3 m to 19 m and resistivity values ranging from 10Ωm - 512Ωm and finally, fresh basement having resistivity ranging from 200Ωm - 1539Ωm were found. These sets of results greatly favour groundwater development in the area. The use of Radial Geoelectric Sounding methods of investigating the subsurface with a combination of geologic mapping for unravelling fractures in the Basement Complex terrain has proven to be a very useful contribution in groundwater exploration in the Basement Complex.

Keywords: *Radial geoelectric sounding, groundwater exploration, Basement Complex, fractures.*

INTRODUCTION

Internal movements (tectonics) within the earth generate stresses that are capable of deforming rocks. The deformation may occur in brittle ways, where the rocks change shape by fracturing or by ductile deformation as folds. Joints and other brittle deformation structures are linear structures or lineaments. These lineaments can be studied on a large scale using seismic sections and satellite images, on a smaller scale, as as joints, faults and veins in outcrop and on a micro scale, in thin sections.

Fractures mapped on outcrops could be deep seated. Hence, it is possible to detect their orientations in the subsurface using electrical geophysical techniques
(Olasehinde and Bayewu, 2010).

Radial Geoelectric Sounding survey is a modified resistivity technique wherein the magnitude, intensity, and direction of electrical anisotropy are determined (Mallick *et al.,* 1983). This method has proved very successful in the delineation of subsurface geology and structures, especially for effective identification and delineation of strike (orientation) of fracture (Olasehinde, 1984). The identification and characterization of fracture is important in rocks with low primary (or matrix) porosity because the porosity and permeability are determined mainly by intensity, orientation, connectivity, aperture and infill of fracture (Skjernaa and Jørgensen, 1993; Watson and Baker, 1999). Hence, groundwater exploration in hard rock terrains primarily focused on the extent and type of weathered mantle and fracturing.

Therefore this study has attempted to use Radial Geoelectrical sounding technique to detect, determine the orientation, intensity and behaviour of fractures in the hard rocks as it concerns groundwater development.

STUDY AREA

The study area is located in Paiko, North Central Nigeria. It lies between latitudes 9°15’N and 9°30’N and longitudes 6°30’E and 6°45’E (Figure 1). The total area of coverage is about 10km^2. It is accessible through the Paiko – Lapai road.

The study area has a typical Guinea savannah climate with distinct wet and dry seasons: a dry season which usually last from December to March and a rainy season which last from April to October. Temperature varies between 24°C around December/January and 32°C in March/April. Average annual rainfall for a thirty year record in the area is about 1270 mm. (Nigerian Meteorological Agency, 2010).

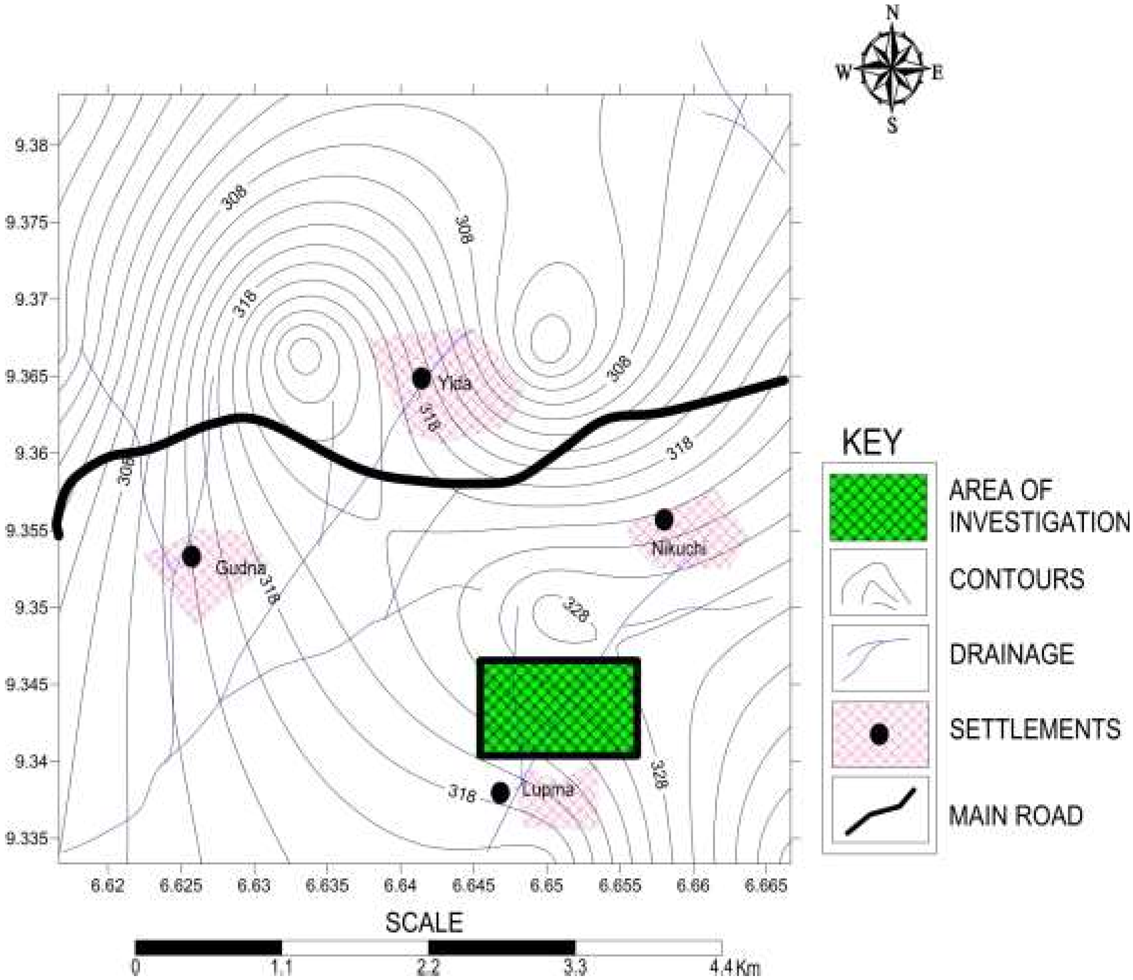


Fig. 1(a). Topographic map of the study area.

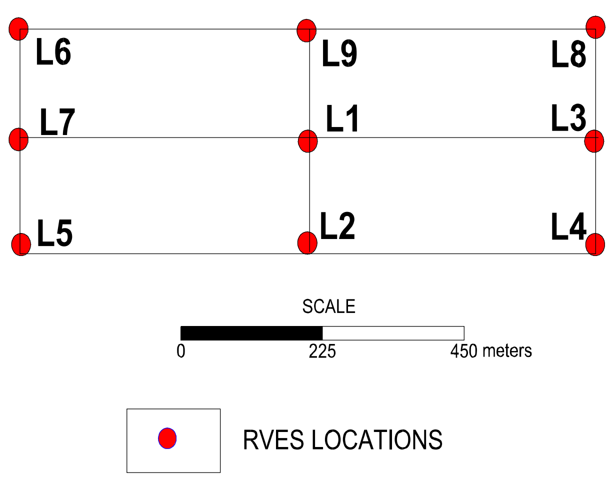


Fig. 1(b). Layout of profiles for the sounding locations.

GEOLOGY OF THE STUDY AREA

The study area is part of Paiko area Sheet 185 (Figure 2) and it falls within the Basement Complex Terrain of Nigeria. The Nigerian Basement Complex forms part of the ancient African shield, bordered to the west by West African Cratonic Plate and underlies about 60% of Nigeria's land mass (Obaje 2009).

The Basement complex has been described by Rahaman (1988) as a heterrogenous assemblage, which include migmatites, paragneisses, ortho gneisses, quartzites, paraschists and a series of basic to ultra basic metamorphosed rocks. Pan African Granites and other minor intrusions such as pegmatite and aplite dykes and veins, quartz veins and extrusive diorites and dolerites have intruded these rocks.

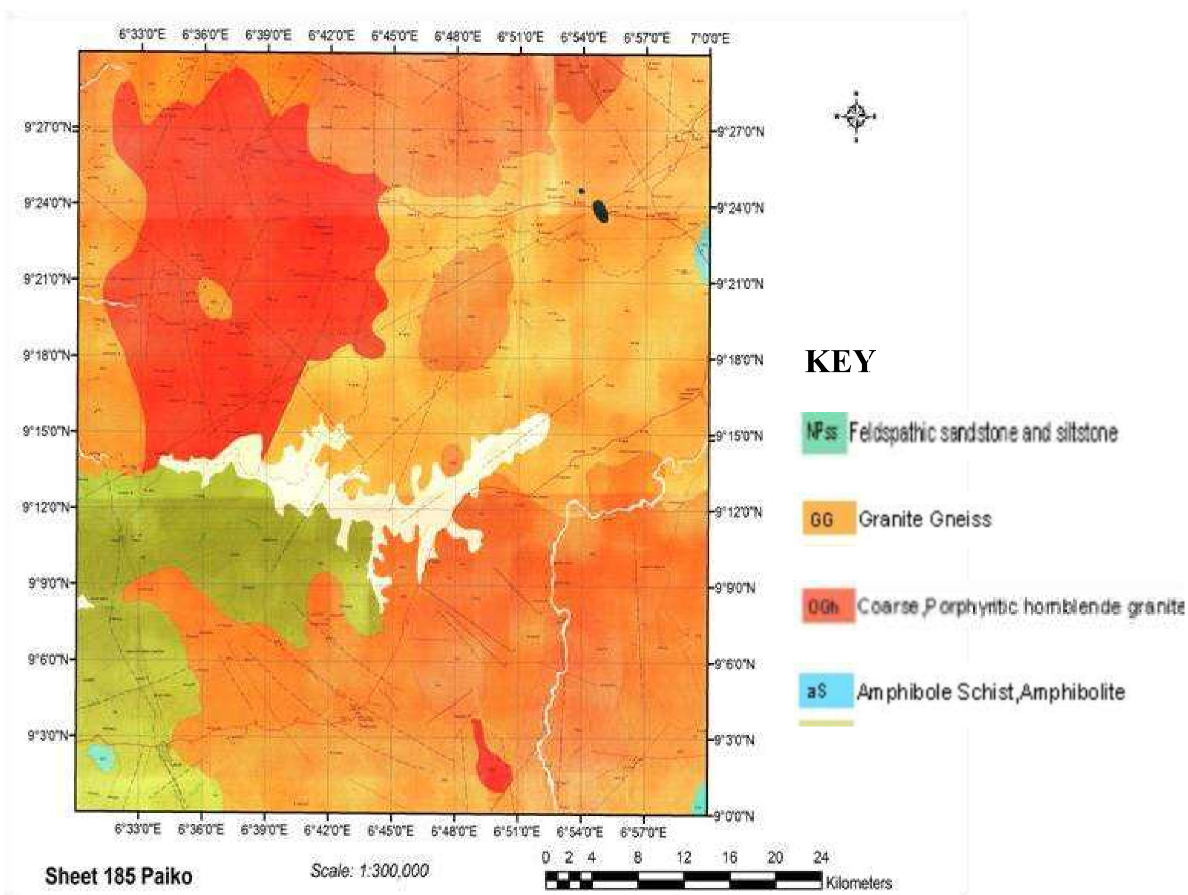


Fig. 2. Geological Map of Paiko Sheet 185.

Good descriptions of the rocks can be found in the works of Burke and Dewey (1972); Annor and Freeth (1985); Odeyemi (1988) who recognised four (4) major groups of rocks within the basement complex. These include:

1. Migmatite-Gneiss complex which comprise of biotite-hornblende gneiss, qurazite and quartz schist and small lenses of calc-silicate rocks;
2. The metasedimentary and metavolcanic rocks (i.e. ths Schist belts) which include slightly migmatised to unmigmatised paraschists, quartzites, amphibolites, talcose rocks, meatconglomerates, marbles amd clac-silicate rocks;
3. The Pan African granitoids (i.e. the older granites) which comprise rocks varying in composition from granodiorite to true granites and potassic syenite;
4. Unmetamorphosed dolerite dykes, believed to be the youngest.

The area under study belongs to the older granite suite which was emplaced during the Pan African Orogeny. These granite intrusives range in size from sub-elliptical plutons to large elongated ridges. They are texturally variable from fine to coarse textures. The exposed granites have quartz veins cross-cutting them and evidences of jointing and faulting were also observed. Significant exfoliation has also taken place. The structural mapping of the area shows that the principal joint direction is in the NESW direction (Figure 3).

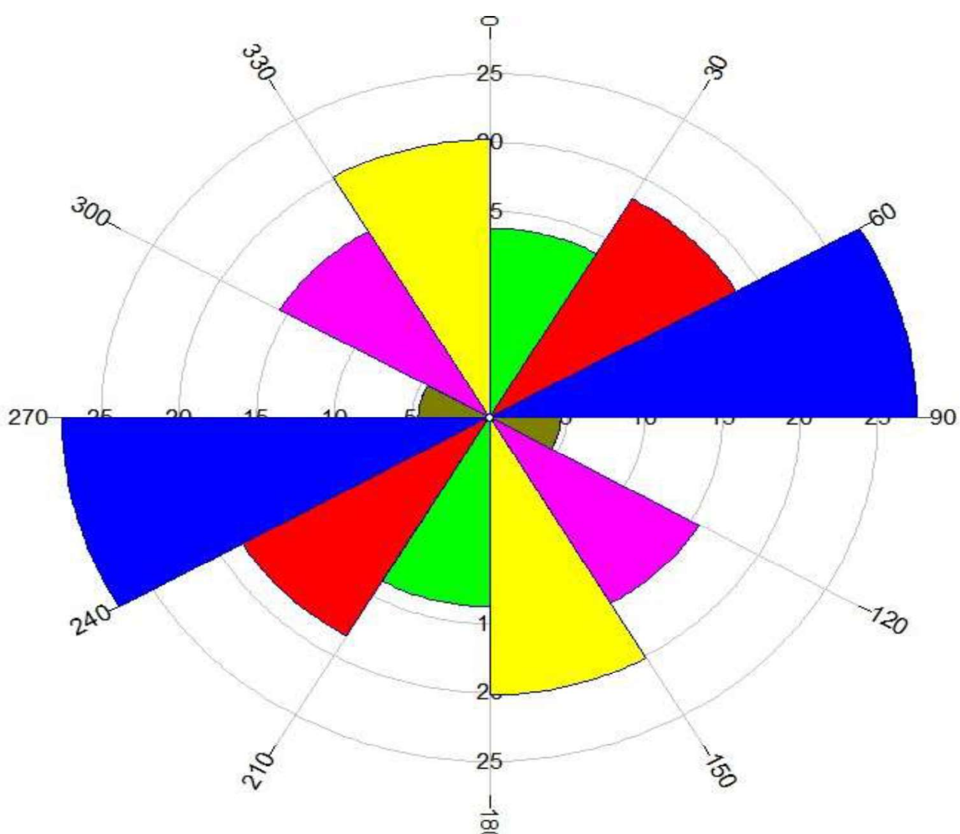


Fig. 3. Rosette Diagram showing the frequency of orientation of joints and fractures.

METHODOLOGY

Nine points were selected and placed in three profiles each with three stations. At each of these stations, Radial Vertical Electrical Sounding (RVES) was carried out along three directions; 0°, 60° and 120° so as to observe the correlation between the measured structural directions and the plotted anisotropy polygon directions. The maximum spread of AB/2 is 80 m. The results of the maximum spread were used to produce the iso-resistivity map.

It is known that in any formation which is anisotropic due to the presence of fractures, the apparent resistivity (r*t*) measured normal to its strike direction is greater than apparent resistivity (r*s*) measured along the strike direction, when Schlumberger or Wenner array is used but contrary when crossed square array method is employed (Lane *et al*., 1995).

A useful parameter of anisotropic medium is the co-efficient of anisotropy and is
calculated by: $\lambda = \sqrt{(r\,t / r\,s)}$

The apparent resistivity was measured along three different azimuths; N-S (0°), NE-SW (60°) and NW-SE (120°) for a given AB/2 separation and were plotted along their corresponding azimuths. Anisotropy polygons were generated from the apparent resistivity values at different AB/2 separations by joining lines of equal values along the different azimuths.

For an isotropic homogeneous formation, this polygon will assume a circular shape. Any deviation from a circle to an ellipse is indicative of anisotropic nature of the formation (Mallik *et al*., 1983). The direction of the longest axis of the polygon corresponds to the strike (orientation) of the fracture, and the ratio of the long to short axis is an indication of the presence of fractures (faults and joints system) in an area if high, and otherwise if low (Skjernaa and Jorgensen, 1993).

The co-efficient of apparent anisotropy (λa) (designated here as the degree of fracturing) is calculated from each anisotropy ellipse (fitted through each polygon) using the relationship:

$\lambda a = a / b$, where a and b are the semi major and semi minor axes of the element. All the calculated λa values are then plotted against the corresponding AB/2 separations. The behaviour of rock fracturing at various depth equivalents to different AB/2 separations can thus be understood qualitatively from the variation of λa (Habberjam, 1975).

From the nine (9) RVES survey carried out, the apparent resistivity anisotropy polygon was plotted and coefficient of anisotropy was calculated for each station, using the methods of Habberjam (1972, 1975, 1979), Lane *et al*., (1995), Mallik *et al*., (1983), Olasehinde (1984), and Okurumeh and Olayinka (1998).

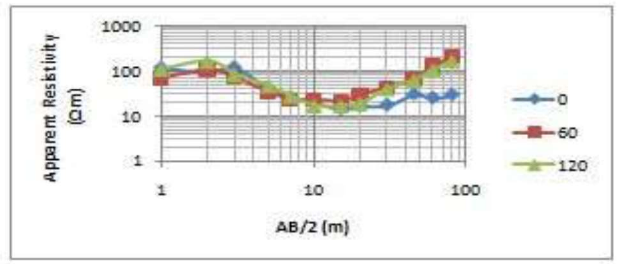
The data obtained were plotted against the electrode spacing on a double logarithm graph and a preliminary interpretation was carried out using partial curve matching involving two-layer master curves and the appropriate auxiliary charts of Rijkswaterstaat (1975). The resultant layered earth model now serves as input for WINRESIST – an automatic geophysical data inversion software, as a final stage in quantitative data interpretation.

RESULTS AND DISCUSSION RVES PLOTS

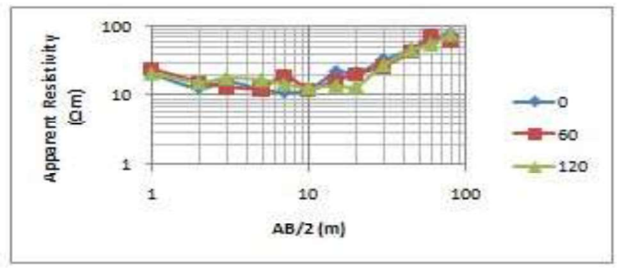
The result of the RVES data for the study area were plotted and interpreted. A typical graphical plot of RVES at stations 2, 4 and 7 is shown in Figure 4 and the geometry of the curves show that the effect of anisotropy is evident in these results, as the values of resistivity are changing with direction. The automatic interpretation of the VES data using the inversion software revealed that the curves are predominantly (70%) made up of three layers of A-type (that is, $\rho 1 < \rho 2 < \rho 3$), where ρ1, ρ2 and ρ3 are the resistivity of the first, second and third layer respectively. The remaining curves are of the H-type (that is, $\rho 1 > \rho 2 < \rho 3$) (Figure 5).

The top layer consists of sandy, clayey sand soils and has resistivities ranging from 5Ωm to 163Ωm. The difference in the resistivity values is due to the composition and saturation of the top soil layer. The thicknesses of the top soil layer ranges from 1.2 m to 4.5 m. This variation is due to the degree of compaction of the top soil.

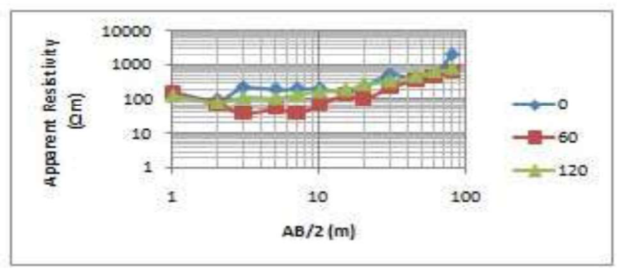
The weathered/fractured layer is the second geoelectric layer and it has resistivities ranging from 11 Ωm to 512 Ωm. The thickness of this layer varies from 5.1 m to 21.5 m. VES 1 has the highest thickness and VES 7, has the least thickness. The depth to fractured/fresh rock, which forms the bedrock, is found to range between 8 m and 24 m.



STATION 2



STATION 4



STATION 7

Fig. 4. Plot of RVES for stations 2, 4 and 7.

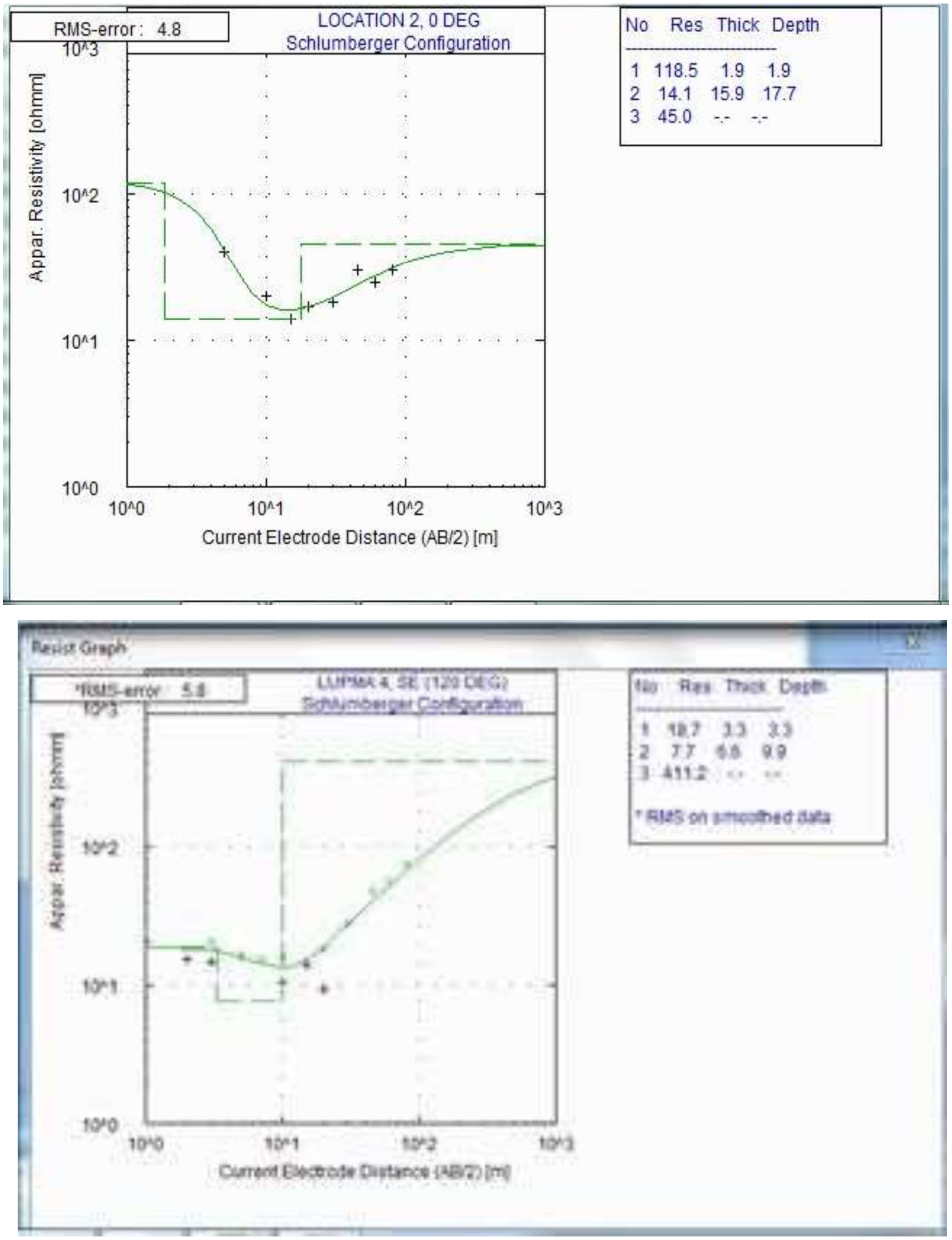


Fig. 5. Typical iterated curves types of the study area.

COEFFICIENT OF ANISOTROPY AND ANISOTROPY POLYGONS

The inferred structural trends and the coefficient of anisotropy are presented in Table 1. They are classified into three; N-S, NE-SW and NW-SE. The direction of the longest axis of the anisotropy polygon corresponds to the strike (orientation) of the fracture. A high ratio of the long to short axis is an indication of the presence of fractures (faults and joints system) in an area. If it is low, fractures are not significant or absent. The directions of the electrical anisotropy lie predominantly in the NE-SW directions at shallow depths (< 30 m) while others lie in the NW-SE directions. At depths of up to 80m, it lies in the N-S direction (Figure 6 and 7). This can be attributed to intersection of fractures and can as well be inferred to have tectonic significance and good indication for accumulation of groundwater

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Table 1: Coefficient of Anisotropy and inferred structural trends of the study area.

STATION	COEFFICIENT OF ANISOTROPY (λ)	INFERRED STRUCTURAL TRENDS
1	1.65	NW – SE, NE – SW
2	2.67	NE – SW
3	1.20	N – S
4	1.12	NE – SW, N – S
5	1.52	NE – SW, NW – SE
6	1.77	NE – SW, N – S
7	1.81	NE – SW
8	1.35	NE – SW
9	1.55	N – S

From the plot of the coefficient of apparent anisotropy values (λa) against various depth equivalents to different AB/2 separations (Figure 8), the behaviour of rock fracturing at various depths can be understood qualitatively. Most of the areas show an increase of anisotropy values with depth. This increase terminated at approximately AB/2=60 m and started decreasing from this depth. The decrease of anisotropy at this depth is an indication of diminution of fracture with depth (Olasehinde, 1999).

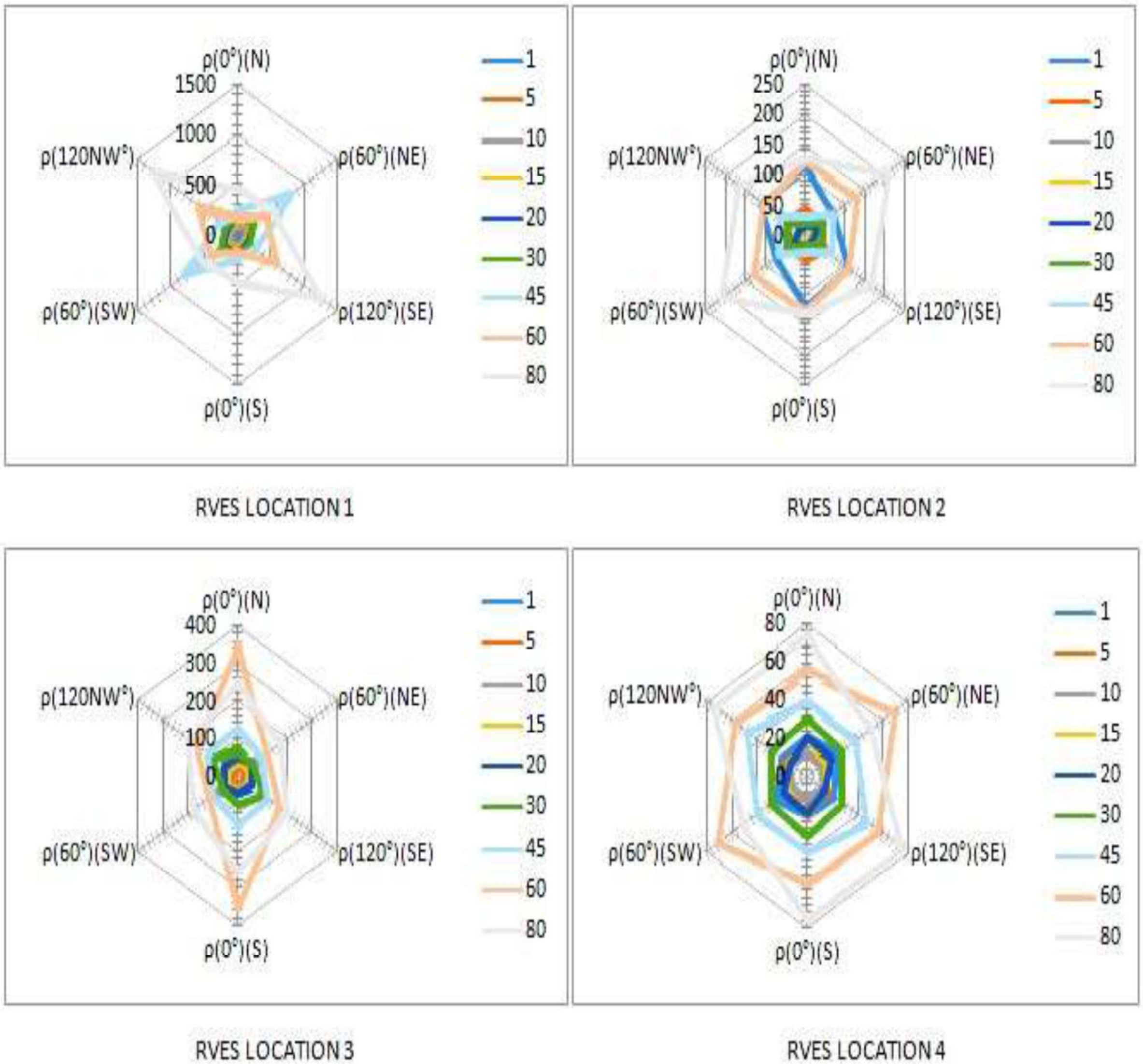


Fig. 6. Anisotropy Polygon for locations 1 – 4.

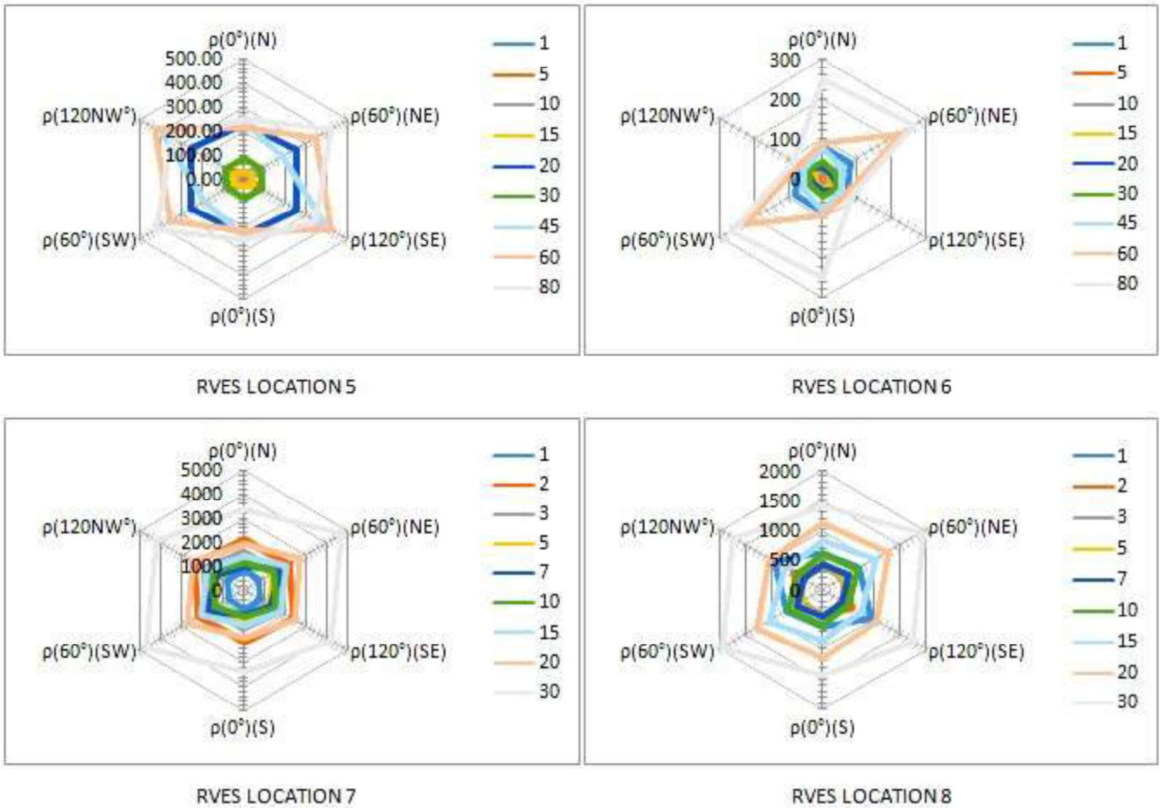


Fig. 7. Anisotropy Polygon for locations 5 – 8.

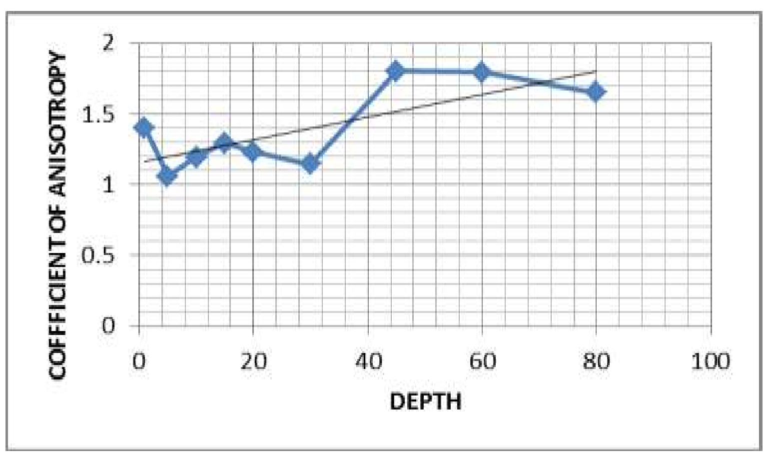


Fig. 8. Degree of fracturing with depth.

GEOELECTRIC SECTIONS

The iterated curves plotted for the direction of 60° along the profile lines were used to produce the geoelectric section. The geoelectric sections of the three profiles are made up of three geoelectric layers. The geoelectric section along profile 1 (Figure 9) revealed that the first layer is the top soil made up clay/sandy clay and has resistivity range of 52 Ωm to 74 Ωm, the second layer has a resistivity range of 14 Ωm to 1150 Ωm, while the third layer, which is the fresh bedrock has a range of resistivity of 852 Ωm to over 2000 Ωm. In profile 2 (Figure 10), the resistivity range from 15.6 Ωm to 296 Ωm, 36 Ωm to 431 Ωm and 315 Ωm to 702 Ωm for the top layer, weathered/fractured layer and the fresh basement layers respectively. Also, Profile 3 has resistivity range for the top layer, middle layer and bedrock layer to be 9.5 Ωm to 27.1 Ωm, 139 Ωm to 347 Ωm, 883 Ωm to 2931 Ωm respectively (Figure 11).

The geoelectric sections show that the thicknesses of the first layer is generally less than 5 m, while the thicknesses of the middle layer range from 5m to 20m. The fresh/fractured bedrock layer has infinite thickness. The orientations of detected fractures were superimposed on the geoelectric sections.

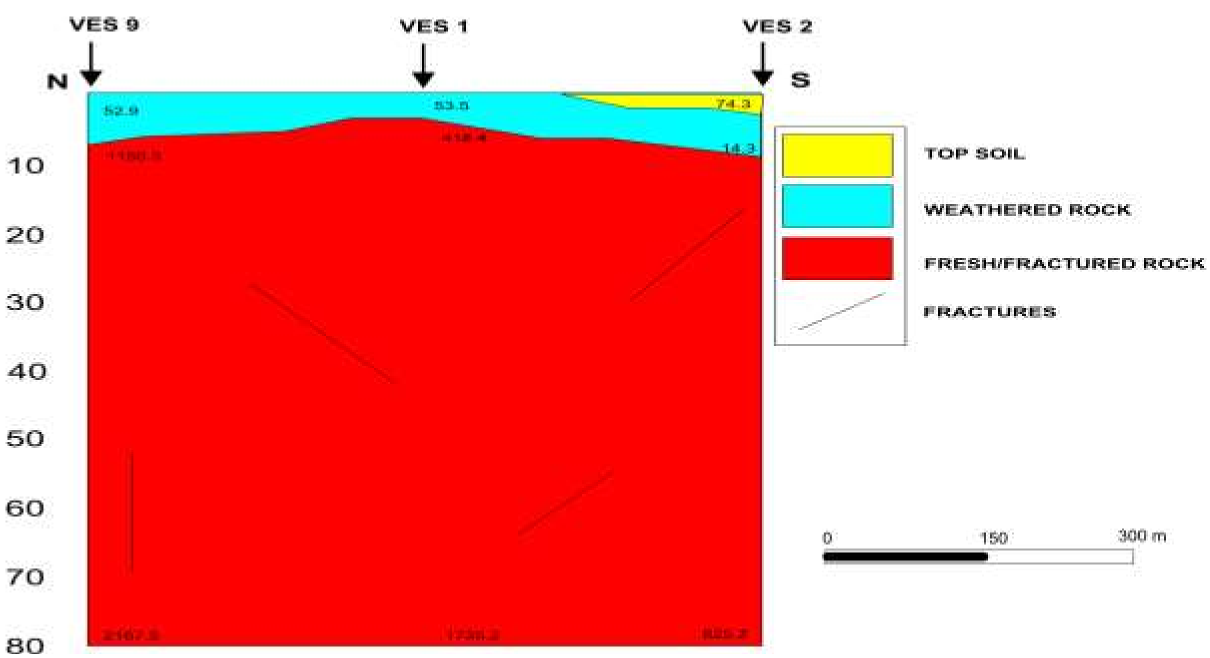


Fig. 9. Geoelectric Section for Profile 1.

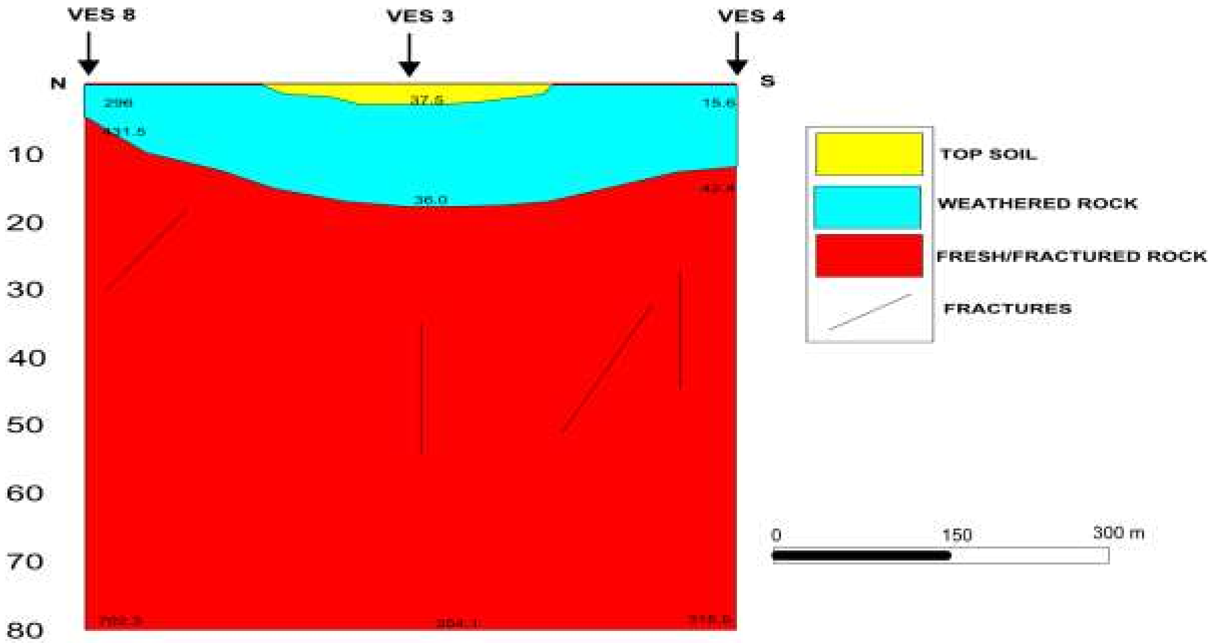


Fig. 10. Geoelectric Section for Profile 2.

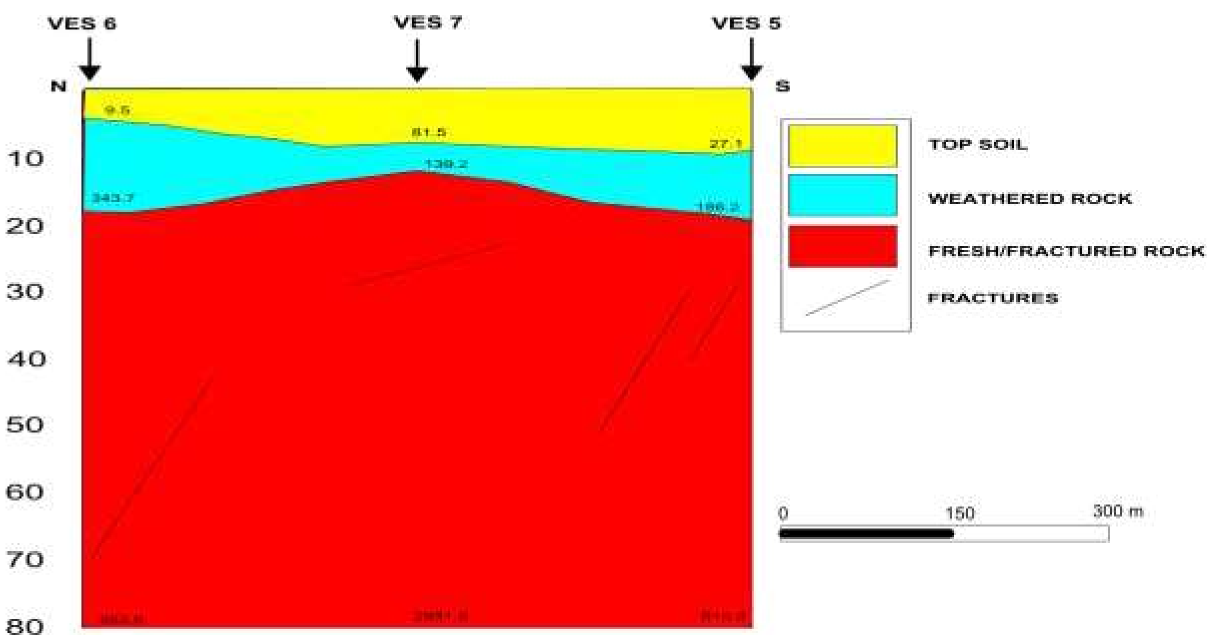


Fig. 11. Geoelectric Section for Profile 3.

PSEUDOSECTIONS

The central portion of pseudosection for profile 1 reveals a low resistivity substratum. The top layers of pseudosection for profile 2 and profile 3 show a general low resistivity anomaly (Figure 13 & 14). The low resistivity values may be due clay and aluvium. In the central portion of profile 2, (Figure 13) a high resistivity anomaly is seen. This may be attributable to a high resistive material, probably a dike.

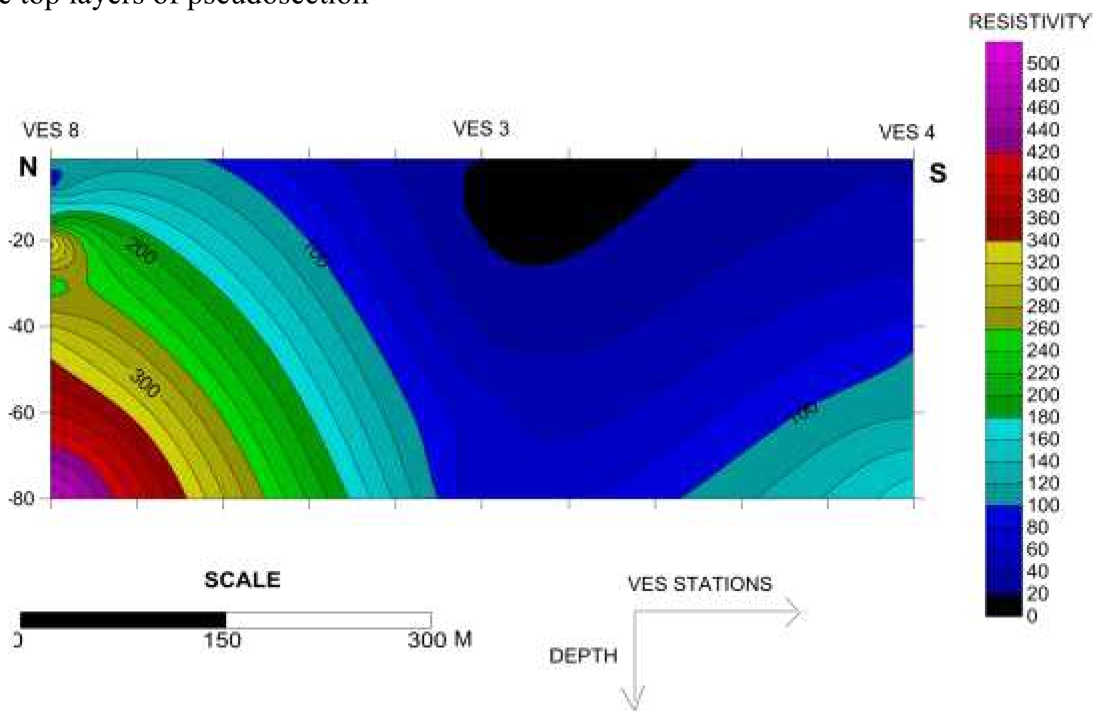


Fig. 12. Pseudosection for Profile 1.

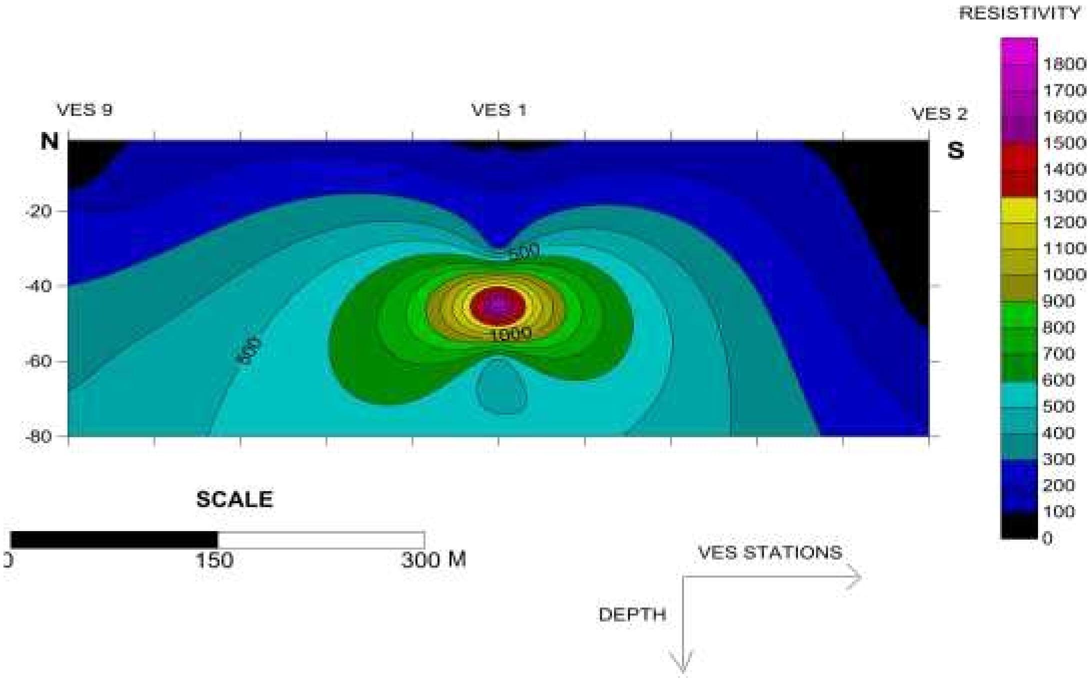


Fig. 13. Pseudosection for Profile 2.

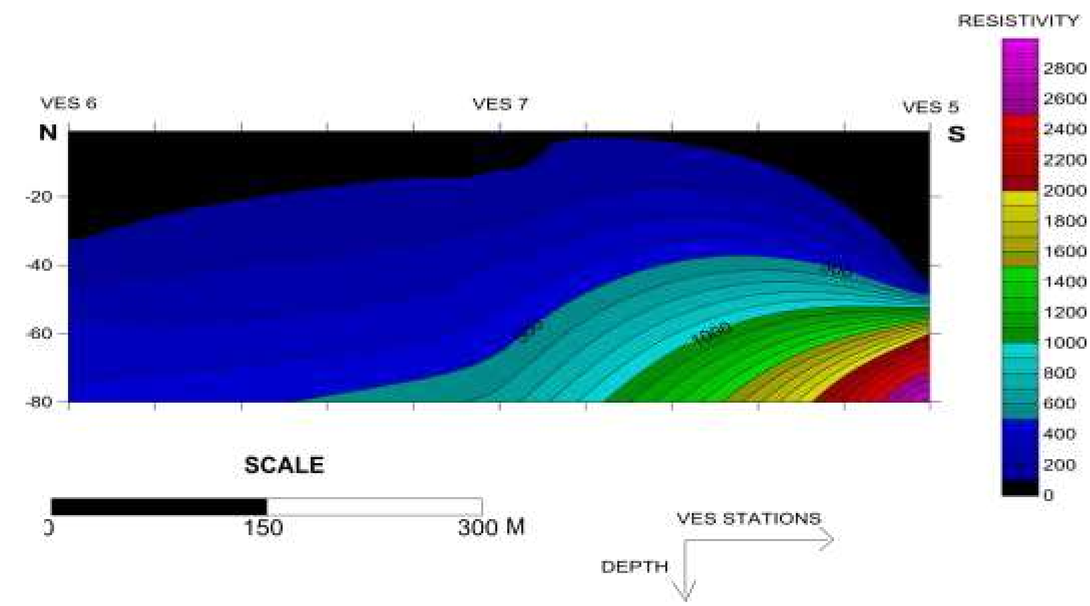
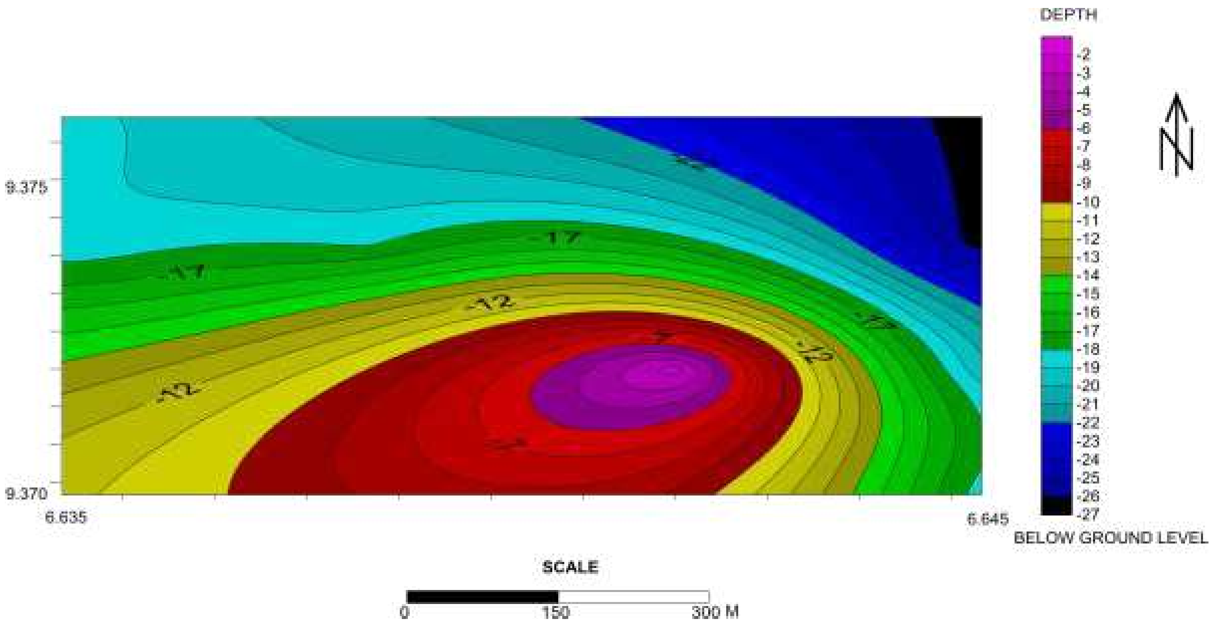


Fig. 14. Pseudosection for Profile 3.

ISOPACH MAP



The isopach map of the area (Figure 15) which is the thickness of the overburden (depth to basement) show that the shallow part is located at the southern portion of the study area while the deepest part in the area is at the North-eastern and northern part of the study area. Low bedrock resistivity is indicative of probable fracturing of the bedrock. This may be complicated due to the non-uniqueness of bedrock resistivities.

Fig. 15. Isopach map of depth to basement.

ISO-RESISTIVITY MAP

The result of the iso-resistivity map at 30 m depth (Figure 16) was prepared using the data of the radial geo-electric sounding at 60°. Resistivity contour maps display the lateral variation in the subsurface geology of the area. The area with low resistivity values indicates the occurrence of relatively good conductors while those with high values indicate poor conductors. The low resistivity values at this depth are an indication of fracturing of the rock units.

0 150 300

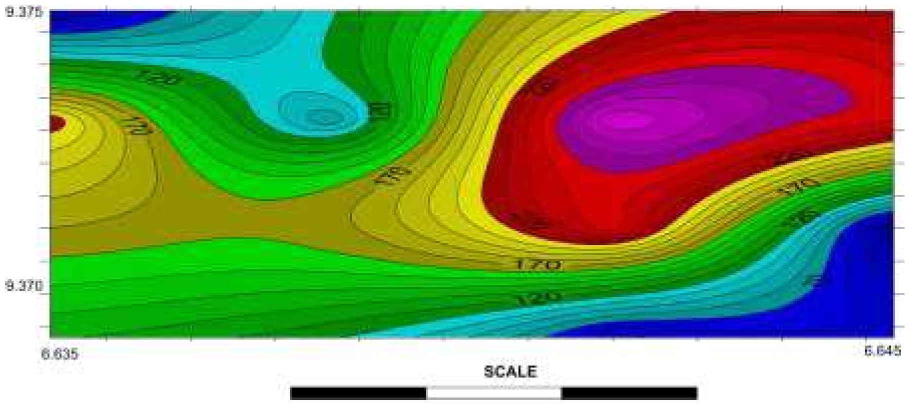
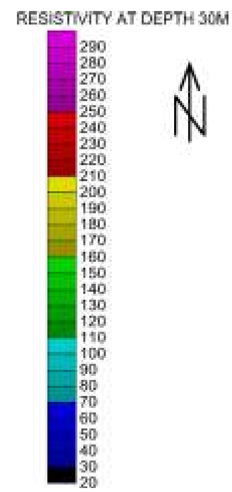


Fig. 16. Iso-resistivity map at AB/2= 30 m.



450 M

CONCLUSION

Radial geoelectric sounding techniques is a powerful tool for characterization of near subsurface geological structures, especially fractures. This study was aimed at characterizing and delineating the orientation of fractures. Fracture parameters obtained from field measurements are fracture orientation and coefficient of anisotropy. These parameters are useful in making preliminary inference on the degree of fracturing of the area. The dominant fracture orientations at depths of about 30m are oriented in the NE-SW direction. Other fracture orientations include the NE-SW and the N-S at greater depths. The opening of the fractures terminated at around 60m depths. Characterizing the orientations of fracture is an important study needed in evaluating the permeability and porosity of rock mass at macroscopic and microscopic scale, as they are indicator of possible earth tremor occurrence.

For the purpose of groundwater development, the coefficient of anisotropy (λ) which is a measure of the degree of inhomogeneity arising from fracturing, faulting, jointing, weathering and permeability of the rock mass among others is directly related with degree of secondary porosity. Therefore, the λ value is an index to degree of fracturing such that the higher the λ the higher the fracturing.

Other parameters measured and derived from the measurements like the VES curves, geoelectric sections, isopach map and isoresistivity map show good indication for successful groundwater development in the area.

It should be noted that it is important to combine other geophysical methods of investigations to validate the results of the radial vertical electrical sounding. Remote sensing techniques (satellite imageries) and petrographic studies should also be incorporated.

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