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Subsurface Structural Mapping for Groundwater Resource Development of a Part of Tudun-Fulani North- Central Nigeria Using Radial Vertical Electrical Sounding Technique

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Abstract

The primary target for the development of groundwater resources in crystalline rocks of the basement complex are fractures which aid in enhancing their secondary porosities thus, making them aquiferous. It is to this end that Radial Vertical Electrical Sounding (RVES) in combination with detailed geologic and hydrogeologic mapping was employed to provide information about the subsurface structure and lithology with the aim of evaluating the groundwater potential of Tudun-Fulani area in Minna, North-central Nigeria. The study area is composed entirely of granitic rocks. A total of Nine RVES were made along three profiles of three sounding stations each within an area of 2km2. Geophysical sounding data obtained were used to produce Vertical Electrical Sounding (VES) curves, electrical pseudosections, geoelectrical sections and anisotropy polygons of the area. VES curves reveal that the area is generally characterised by three geo-electric layers. Resistivities and depths of top soil layer range from 15 Ωm to 167 Ωm and 1.3 m to 17.5 m respectively. The middle layer consisting of slightly weathered rocks have resistivity values ranging from 26 Ωm to 777 Ωm and depths of 4.6 m to 27.7 m. Generally, the area has not undergone appreciable weathering which is evident from the isopach map which showed that the average depth to basement is about 10 m. Iso-resistivty map show a trend of increasing resistivity values from the north-western portion of the map to the south-eastern part. Anisotropy polygons showed no definite joint direction which is in complete agreement with measurements made at the surface. RVES has been able to prove its usefulness in resolving the orientation of subsurface structures. However, the area does not have good groundwater potential because fractures mapped were not deep seated and interconnected.

Keywords: Subsurface Structures, Groundwater, Radial Vertical Electrical Sounding.

Introduction

The need for potable and adequate supply of water in modern civilization cannot be overemphasized. Public water supply has become a real challenge especially in urban centres. Its quality and supply has been grossly inadequate to meet the very increasing demand for this precious resource. Hence, people especially the inhabitants of Tudun Fulani in Minna, Niger State, have come to rely on groundwater as their main source of supply because water supply from the State Water Board has proven over the years to be grossly inadequate and most times, non-existent.

Groundwater is found everywhere but to get this resource in some areas is very difficult and complex. In Basement Complex terrains, groundwater is found in fractured and weathered crystalline rock formations. The challenge is to be able to have a sound knowledge of the geology of the area and to adopt appropriate geophysical methods to locate and characterize the subsurface fractures which are the target for groundwater exploration in the Basement Complex terrain. Many wells have failed and subsequently abandoned because boreholes were cited in areas that do not have the requisite secondary porosity created by the presence of interconnected fractures [1]. Radial geo-electric Sounding survey is a modified resistivity technique wherein the magnitude, intensity, and direction of electrical anisotropy are determined [2]. This method has proved very successful in the delineation of subsurface geology and structures, especially for effective identification and delineation of strike (orientation) of fractures [3].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 fractures [4]; [5].This study therefore employs Radial geo-electrical sounding technique in combination with detailed structural geology studies in locating and characterizing the subsurface fractures so as to delineate those with good ground water potential within the study area.

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Location and geology of the study area

The study area is located between latitudes 09^{0}39'00" and 09^{0}41'00"N and longitudes 06^{0}31'00" and 06^{0}32'00"E (Figure 1). The area lies within the south western part of Minna metropolis and is accessible through the Minna-Zungeru express road and other minor roads. The 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. Temperatures vary 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 [6].The study area is part of Minna Sheet 164 and 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. The Basement complex has been described by [7] as a heterogeneous assemblage, which include migmatites, para-gneisses, ortho gneisses, quartzites, paraschists and a series of basic to ultrabasic metamorphic 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. The study area which is composed entirely of granitic rocks (Figure 2), have massive texture and lack any form of visible intrusion. Joints on the exposed outcrops are few, shallow and tight. There was no evidence on faulting on the outcrops.

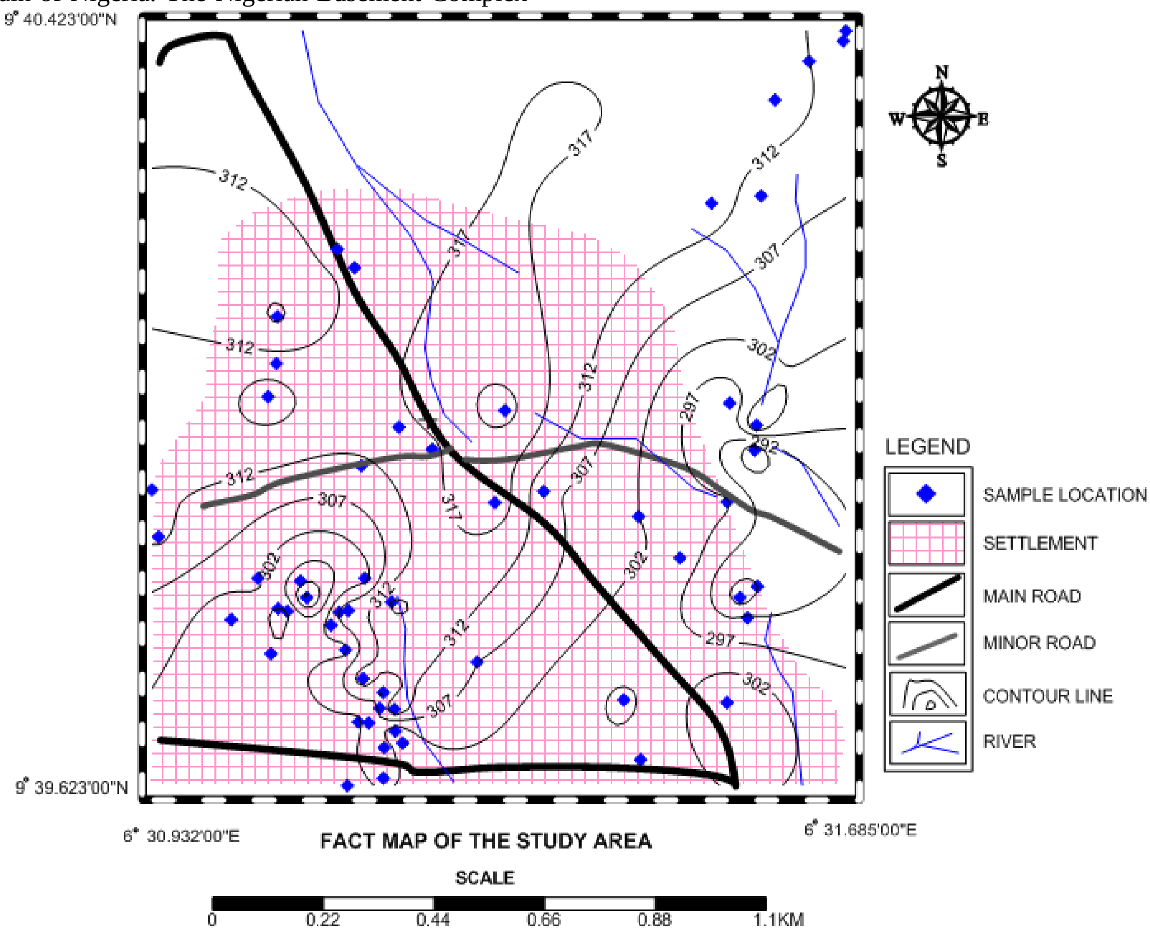

Figure 1: Fact map of the study area

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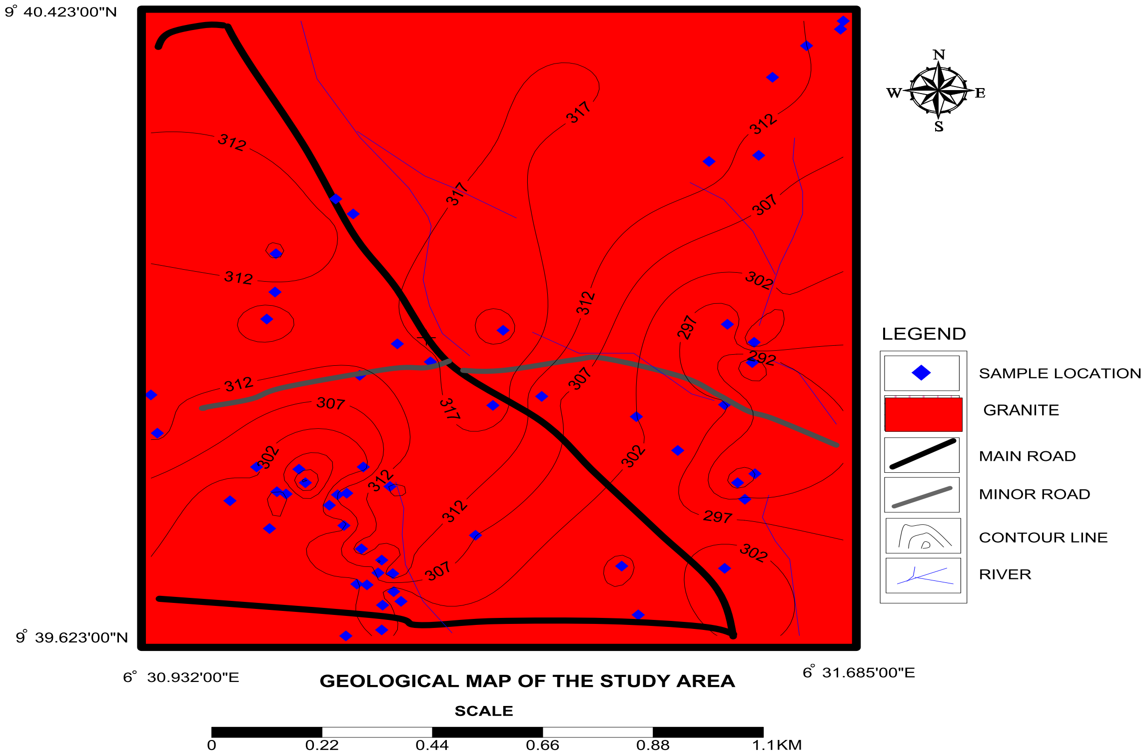

Figure 2: Geologic map of the study area

Materials and methods

Detailed geologic mapping of the study area was carried out to determine the main lithologies and joint directions were obtained that were used for the construction of the geological map and rosette diagram of the study area respectively. The major fracture patterns in the area were observed during the geological mapping. The values of the joint directions taken during the structural mapping with the aid of a compass-clinometer were used to plot the Rosette-diagram.

Radial vertical electrical sounding (RVES) was carried out in nine (9) different stations along three different profiles, three on each profile using a portable Avant-Garde terrameter with an in- built rechargeable power system. The instrument provides a digital readout of the current, resistance and self potential and several self-diagnostic checks are in built and error codes displayed for instrument, cable and electrode faults.

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. The resistivity values was then multiplied by the calculated geometric factors to obtain the apparent resistivity values which were plotted against the electrode spacing (AB/2) using WINRESIST– an automatic resistivity inversion software [8].

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 [9]. 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 [4]. It is an established fact that in geologic formations which are anisotropic due to the presence of factures, 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 [10].

Therefore, a useful parameter in determining the coefficient of anisotropy (λ) for an anisotropic medium is calculated using:

$$\lambda = \sqrt{r\,t/r\,s}$$

From the 27 RVES survey carried out, the apparent resistivity anisotropy polygon was plotted and coefficient of anisotropy was calculated for each

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station, using the methods of [11];[12];[13]; [10]; [9];[3] and [14].

The reflection coefficients (r) of the study area were calculated using the method of [15]; [16] and [17] :

$$r = \frac{(\rho n\ -\ \rho(n-1)}{(\ \rho n\ +\ \rho(n\ -1)}$$

Where ρn is the layer resistivity of the nth layer and ρ(n-1) is thelayer resistivity overlying the nth layer.

Other deductions made from the resistivity values, geologic and hydro-geologic data were used in the construction of the geo-electric section, pseudo-section of the study area.

Results and discussion

Rosette diagram

The principal joint direction in the area is trending NW-SE (Figure 3), with a minor one along NE-SW direction. It was however observed that the difference between the minor joint directions in the area are not very distinct, and also that the rosette-diagram gives the fracturing pattern of the surface which is likely to change with increase in depth. Hence conclusions cannot be drawn based on the findings from the rosette-diagram alone, it can however be used to support findings from other methods used in the study.

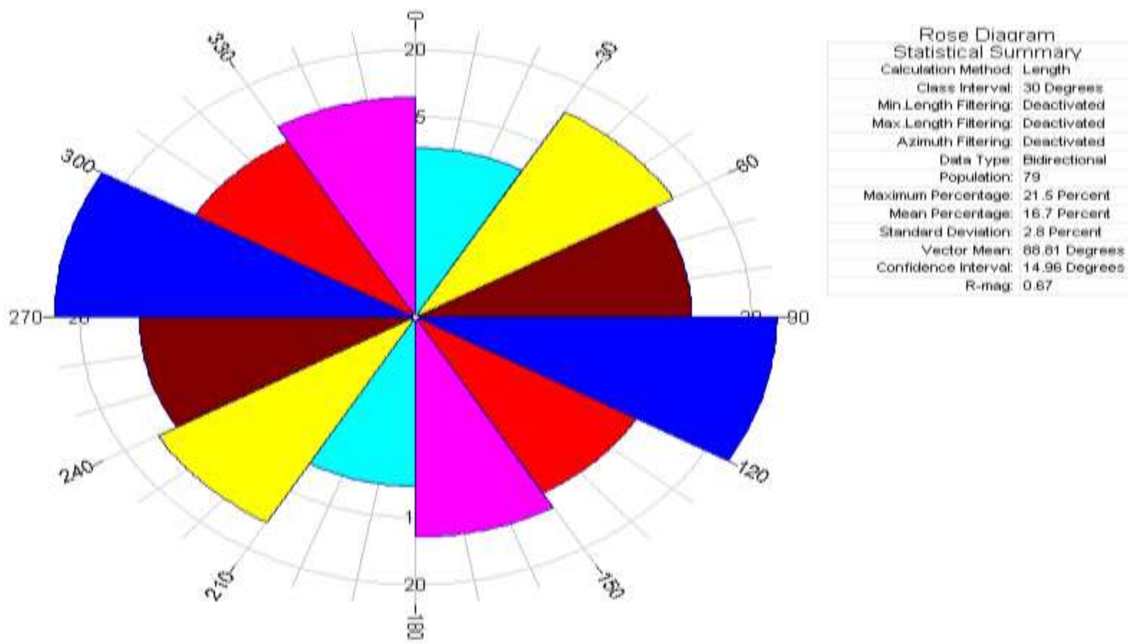

Figure 3: Rosette diagram of the study area

Description of VES curves

From the interpretation of the electrical sounding curves, it was observed that 67% of all the VES curves in the study area gave the A - type curves (Figure 4) while the H– type curves (Figure 5) make up the remainder. Hence, all VES curves reflect a 3 – layer structure. The layers include top soil layer, weathered/fractured layer and the fresh basement.

The top layer consists of sandy, clayey sand and lateritic soils and has resistivities ranging from 24 Ωm to 237 Ωm. The difference in the resistivity values is due to the composition and saturation of the top soil.

The thickness of the top soil layer ranges from 0.5 m to 4.1 m. This variation is due to the degree of compaction of the top soil.

The thickness of the topsoil layer is an important hydrogeologic consideration in groundwater development in the basement terrain [18].This is because water gets into the saturated zone through the top soil layer.

The second geo-electric layer consists majorly of clay and it has resistivities ranging from 3.8 Ωm to 300 Ωm. The thickness of this layer varies from 1.1 m to 4.2 m.

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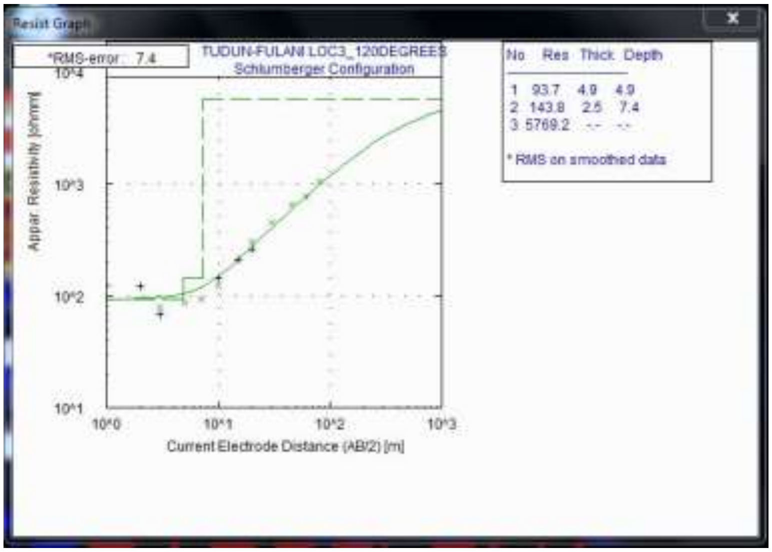

Figure 4: Typical A curves of the study area

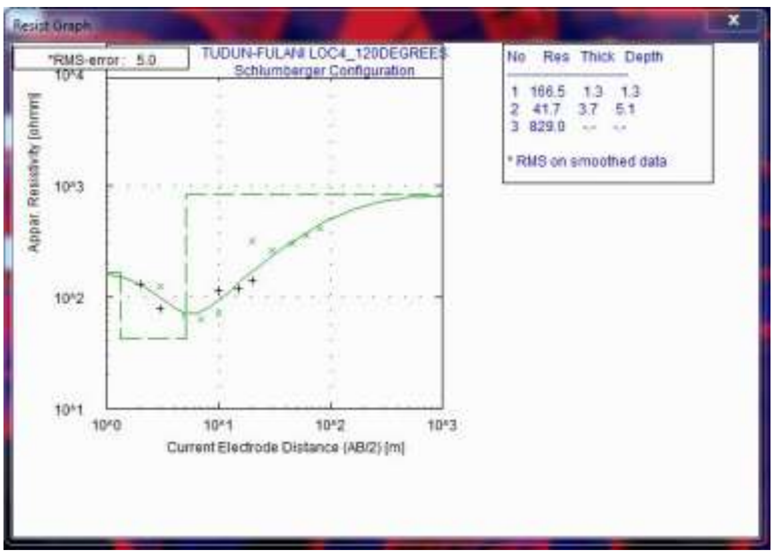

Figure 5: Typical H curves of the study area

The weathered/fractured layer is the third geo-electric layer and it has a resistivity ranging between 26.2 Ωm to 295.8 Ωm. the thickness of this layer varies from 1.2m to 8.6.

Fresh basement rock is characterized by high resistivity value of up to 100,000 Ωm. The fresh basement is made up of infinitely resistive rock in all the stations. It forms the bedrock. The rocks in this zone are hard with no permeability and hence, it is not a water bearing zone. The depth to fresh rock from the VES soundings is found to range between 3.7 m and 16.9 m.

In fresh non – fractured rock, the porosity is often less than 2.5% and as a result, runoff is high and infiltration rate is extremely too low. Hence, accumulation of groundwater is almost non-existent.

Electrical resistivity pseudosections

The electrical pseudosections of the study area were constructed along three different profiles trending N-S, with three sounding stations each and fractures maybe interpreted at places where contours get very closely spaced. Profile 1 (Figure 6) reveals a significant intrusion, and also highly resistive strata around VES 9. There seem to exist no significant fracturing around VES 6 and VES 8, as these portions have low resistive materials compared to VES 9.

Profile 2 (Figure 7) which have sounding stations 5, 7 and 3 reveal a uniform increase in resistivity with

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depth and also a comparative medium resistivity throughout the whole profile. A slightly closed packing of contour occurs around VES 7 between 10m and 20m depth. This is likely a local fracturing. Besides this, there is no deep fracturing observed along this profile.

Fractures are also inferred in profile 3 (Figure 8) around VES 4 at depth. However, the presence of competent formation at the top to the subsurface and an obvious lack of fracturing may impede percolation of groundwater.

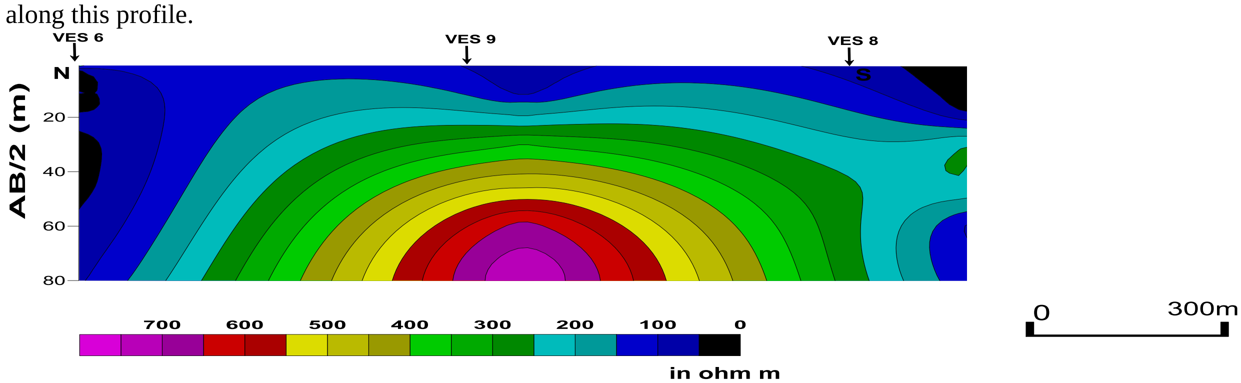

Figure 6: Pseudosection for profile 1.

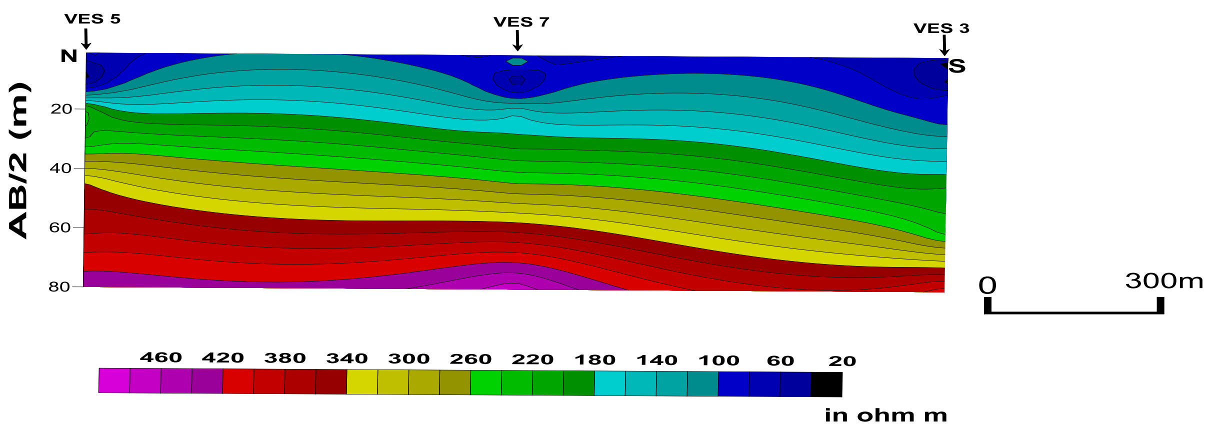

Figure 7: Pseudosection for profile 2.

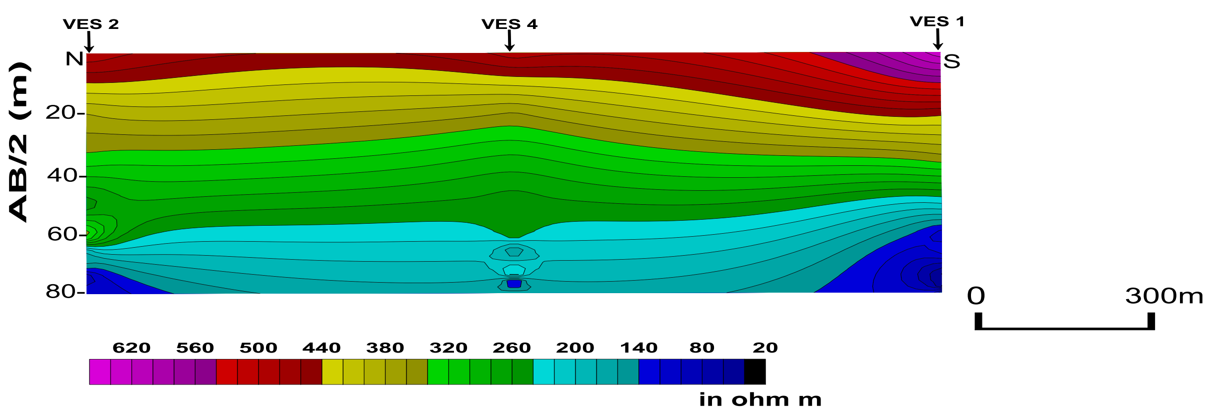

Figure 8: Pseudosection for profile 3.

Geo-electric sections

The geo-electric sections of each profile were drawn using appropriate software (Figure 9, 10 and 11). They show different geo-electric layers encountered in the subsurface with respect to its resistivity. The depth of each layer is shown and this enables a clear estimation of each layer's extent and proximity to fresh rock. The generated geo-electric sections reveal that the area is

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generally characterized by three geo-electric layers. The Resistivity of the top soil layer range from 15 Ωm to 167 Ωm and thickness range of 1.3 m to 17.5 m. The middle layer consisting of slightly weathered rocks have resistivity values ranging from 26 Ωm to 777 Ωm and depths of 4.6 m to 27.7 m. The third layer which is the fresh basement has a resistivity range of 256 Ωm to 5769 Ωm and is of infinite thickness. Hence it can be deduced from the result above that the area has not undergone appreciable weathering/fracturing.

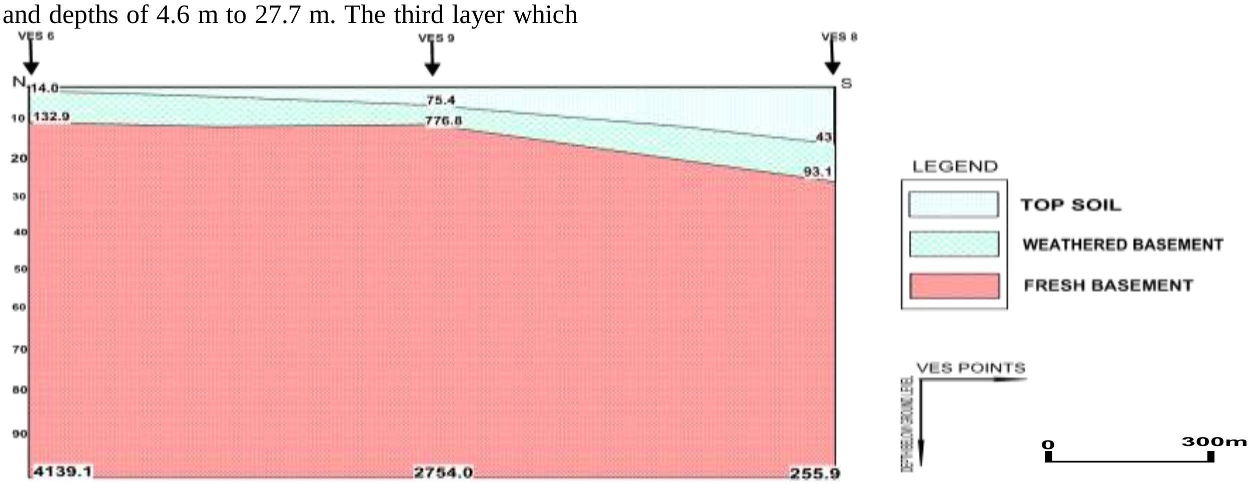

Figure 9: Geo-electric section along profile 1

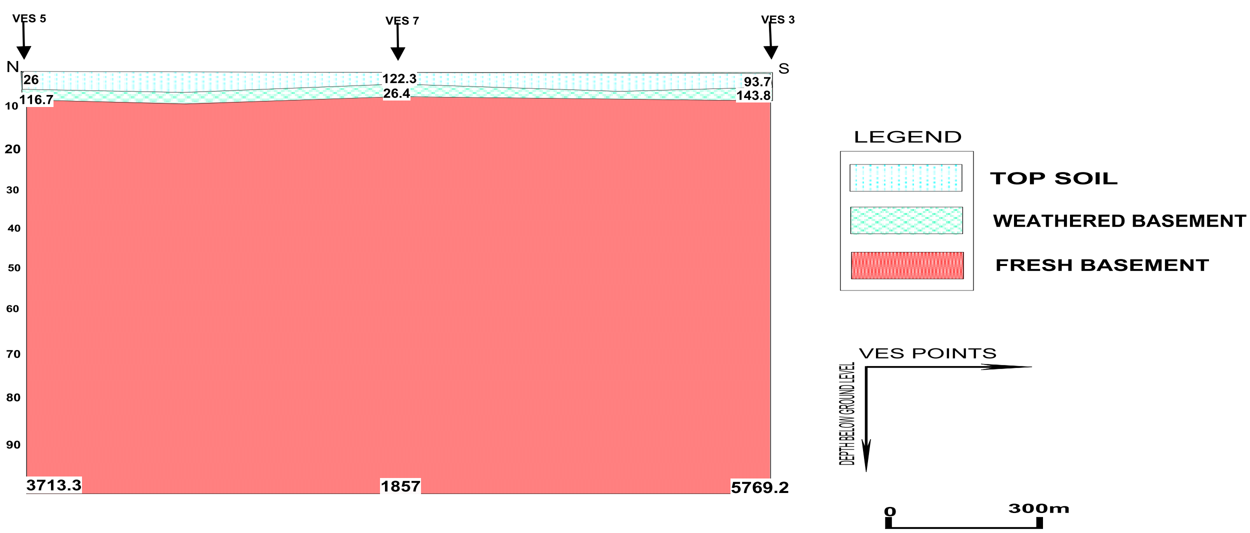

Figure 10: Geo-electric section along profile 2

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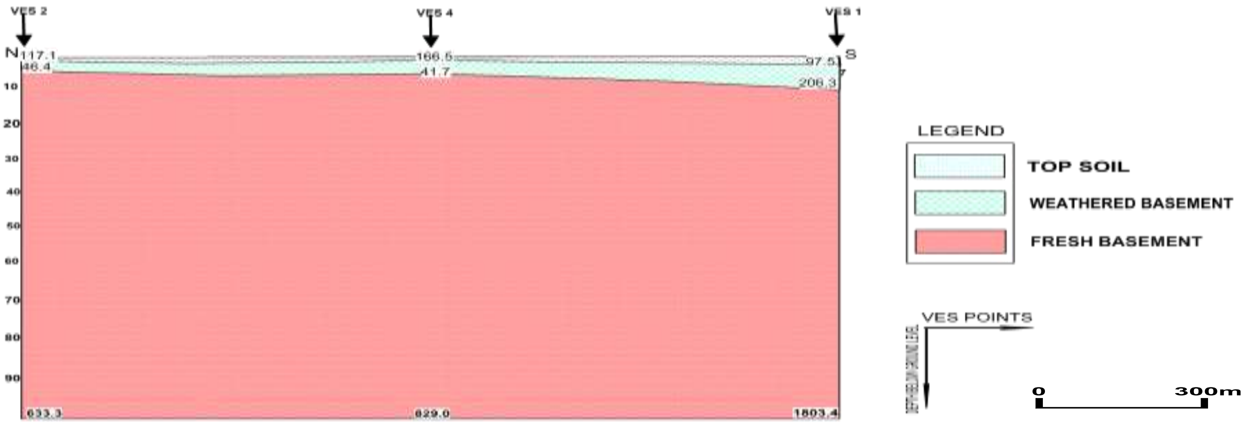

Figure 11: Geo-electric section along profile 3

Isopach map of depth to bedrock

The isopach map of the area (Figure 12), which is the depth to basement, show that the study area is dominated by shallow overburden thicknesses ranging from 5 m to 10 m. This is also an indication of very low amount of weathered and fractured rock units. Deep areas are found in the south-western portion of the map with depth values up to 35 m.

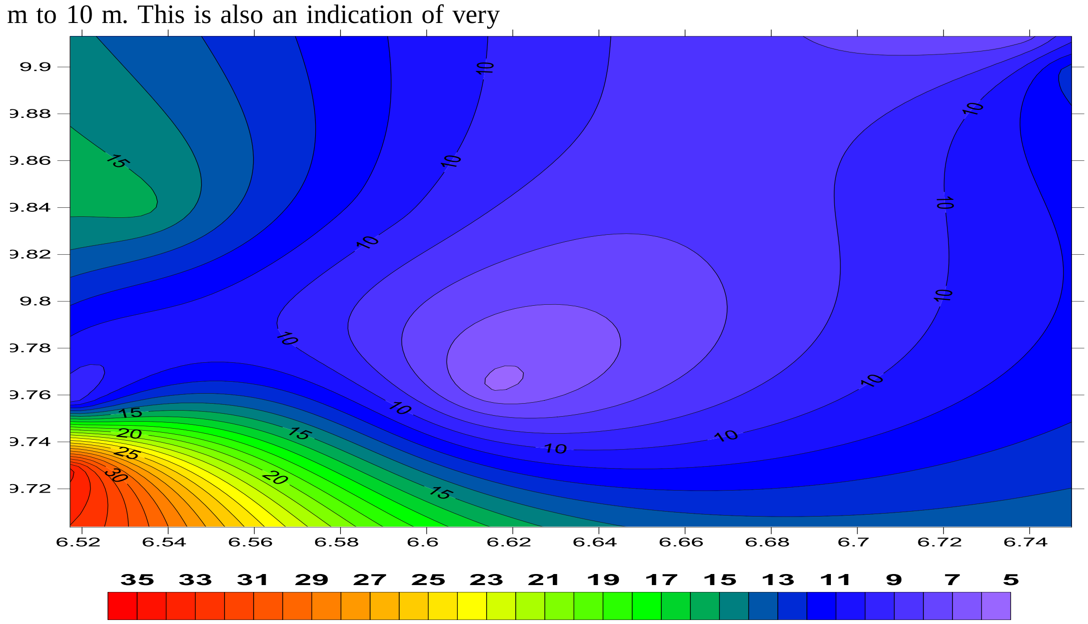

Figure 12: Isopach map of the overburden in the study area

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 [9]. The direction of the electrical anisotropy lies predominantly in the NW-SE direction at shallow depths (<30 m) while others lie in the NE-SW and direction. At depths from 60 m up to 80 m, it lies in the N-S direction. The NW – SE lineament is parallel to the Niger Basin (N60^0 – S60^0E). The NE – SW orientation of fractures is closely related to the Benue Trough and the Ifewara – Zungeru fault line. The preponderance of both fracture sets may be attributable to these fault lines. From the plot of the coefficient of apparent anisotropy values (λa) against various depth equivalents of different AB/2 separations (Figure 13), the behaviour of rock fracturing at various depths can be understood

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qualitatively. The decrease of anisotropy with increasing depth is an indication of diminution of fracture with depth [3]. These sets of results correlate effectively with results from surface structural mapping.

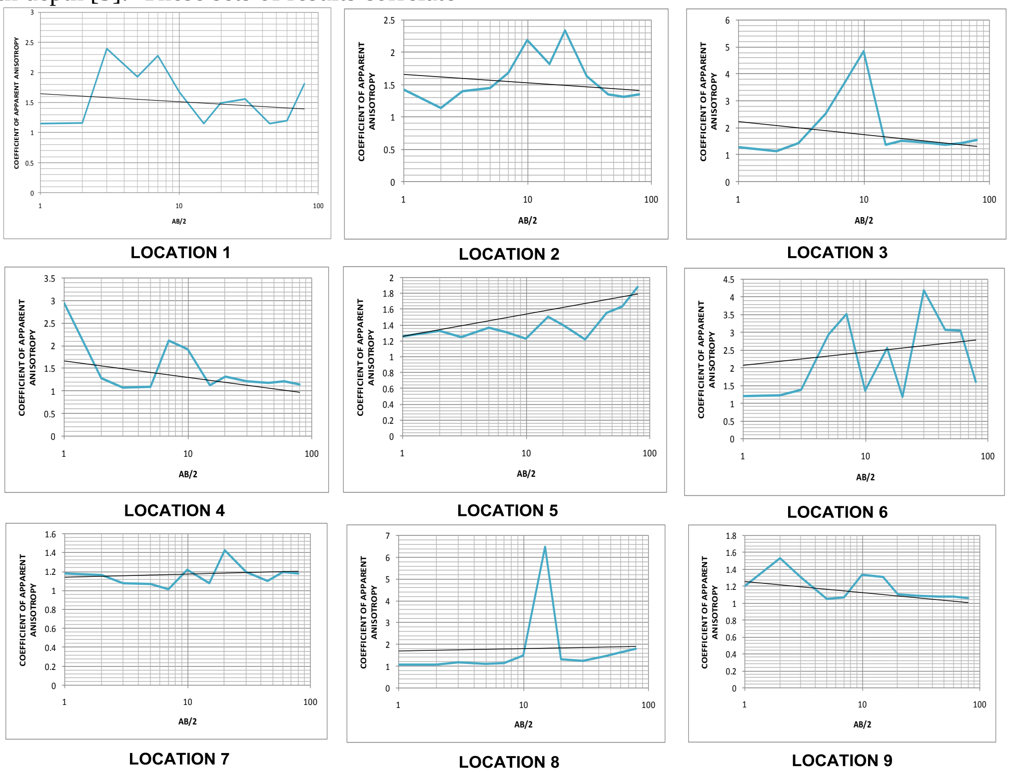

Figure 13: Degree of fracturing for all locations

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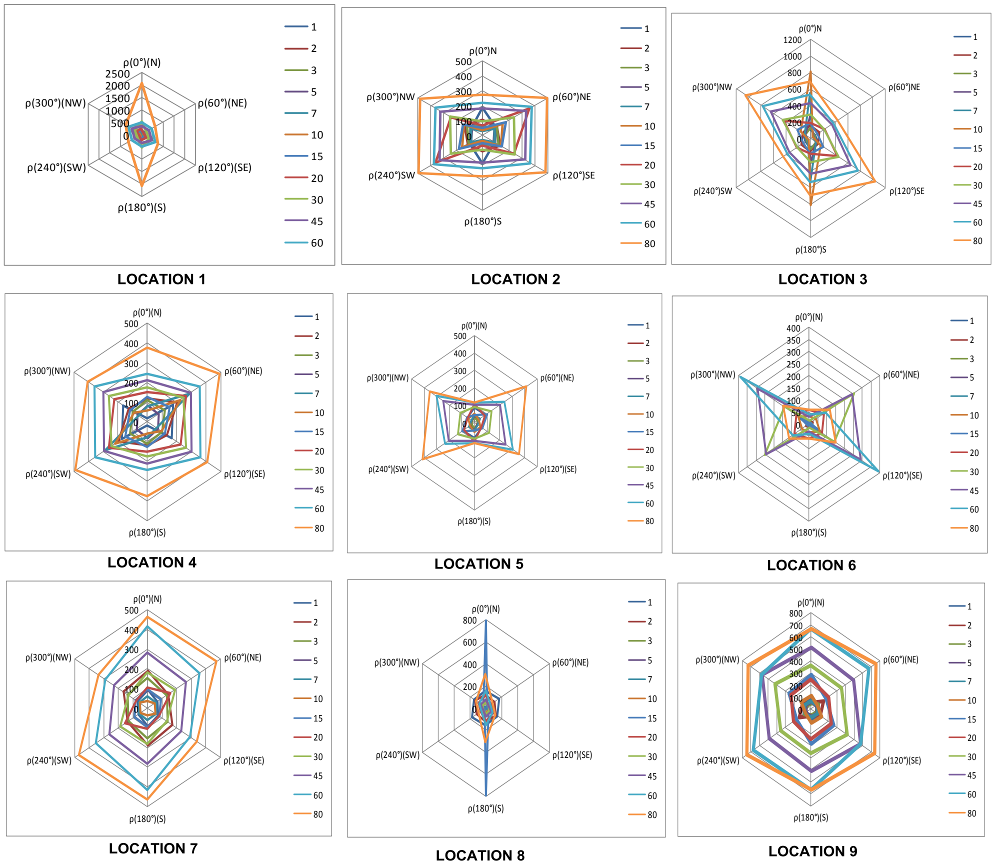

Figure 14: Coefficient of anisotropy polygons for all locations in the study area.

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

STATION	COEFFICIENT OF ANISOTROPY (λ)	INFERRED STRUCTURAL TRENDS
1	1.81	N-S
2	1.35	N-S,NE-SW
3	1.55	NW-SE,N-S
4	1.14	NE-SW
5	1.88	NE-SW,NW-SE
6	1.60	NW-SE
7	1.18	NE-SW, N-S
8	1.82	N-S
9	1.06	NE-SW,NW-SE

Reflection coefficient

The reflection coefficient map of the area is plotted and presented (Figure 15). The reflection coefficient map as indicated by [15] reflects the spatial distribution of reflection coefficient values of an area under study. These values exhibit a weathered or fractured nature of its basement rock. Thus, lower reflection values are an indication of higher degree of fracturing, hence, a higher groundwater potential of an area.

From the reflection coefficient map, it can be deduced that the study area is dominated by high reflection coefficient values. This is attributable to almost non-existent significant fracturing in the area. This lends

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credence to the numerous failures experienced in drilled boreholes in the study area.

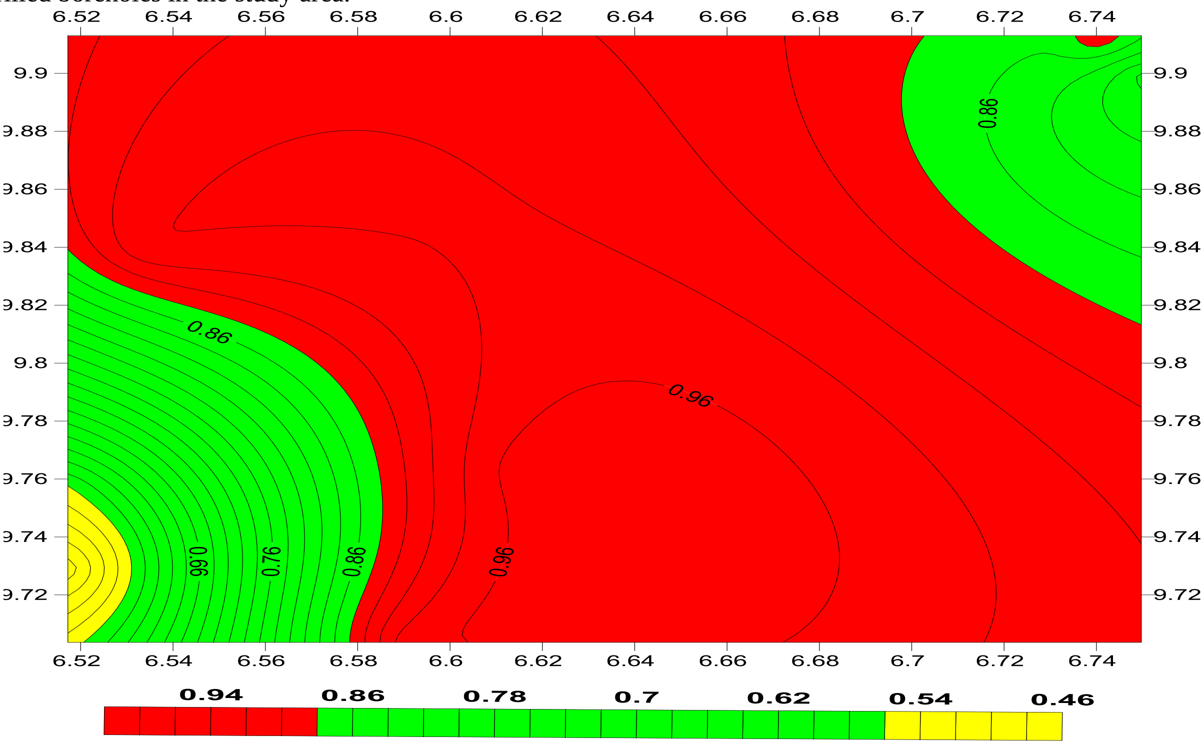

Figure 15: Reflection coefficient map of the study area

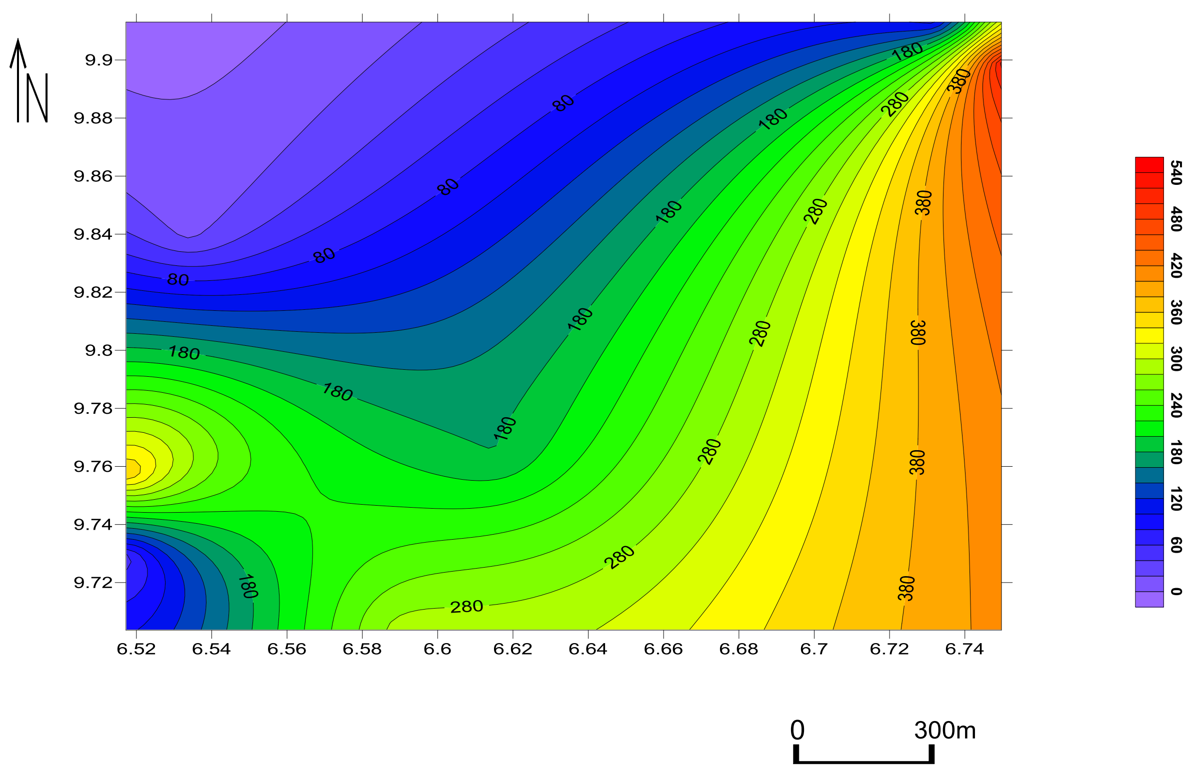

Figure 16: Iso-resistivity map of the study area at Ab/2=30m

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Conclusion

The general fracture pattern observed at the surface in the study area correlates well with those delineated using radial geo-electric sounding technique.The groundwater development potentials of the study area is not so viable, however a few points show very slight potential for groundwater development.

In the bid to develop the groundwater potential of an area, a combination of geologic, hydro-geologic and geophysical method of investigation is by far the most efficient means of exploration. In most cases it might be viewed as time consuming and uneconomical to combine all three methods, it however saves the grievous cost of embarking on a failed groundwater development project. At the end of it all, the end actually justifies the means.

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