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Borehole Failure Investigation in a Typical Basement Terrain of Southwestern Nigeria using Lineament Mapping and Geophysical Method

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Abstract

The exploitation of groundwater involves the sinking of boreholes at sites, which sometimes are chosen arbitrarily. In several cases this resulted in abortive boreholes, extremely low yield and total failure of some supply wells. Thus proper precautions must be taken to reduce the risk of spending large sums of money in sinking abortive boreholes. Therefore this research work demonstrated the application of lineament studies and geophysical survey (Vertical electrical sounding) in borehole failure investigation. Out of six existing boreholes in the studied area which are mechanized with sophisticated submersible pumps, only two are working effectively according to their life expectancy as calculated by the design engineer/driller. Some of the lineaments observed are faults, fractures and joints. Two major structural trends observed are in an approximate NE – SW and NNE – SSW structural trend, typical of the Nigerian basement complex. The lineament density around the area is low. The lineament intersection map of the study area indicates low/very low intersection in the same areas where there are very low lineaments. The result of the vertical electrical sounding shows that the weathered layer and unconfined fractured basement are the two aquiferous units in the area. Therefore the failures of most of the borehole in the area can be attributed to the fact that they were drilled into the fractured basement aquifer with resistivity values above 100 Ω-m indicating a less fractured density zone with low porosity and permeability, unlike others which have a resistivity values below 100 Ω-m. Other factor like poor drilling technique; design and construction; and operational and maintenance failures could be other reasons for their failure; as it is possible for one factor to lead to the other.

Keywords: *Aquifer, Borehole, Fracture, Geophysical, Groundwater, Lineament*

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Background to the Study

Groundwater is derived from surface precipitation (rain), surface water and melted snow which percolate into the subsurface earth through pore spaces, jointed and fracture planes, filtered by the earth medium and store in the pore spaces of the sediments and weathered zone. Groundwater is abstracted through hand-dug wells, hand-pump operated shallow wells and submersible pump operated deep wells (Olorunfemi, 2007). Groundwater is one of the most important natural resources. Because of the ever increasing population growth, the requirement for water supply for various purposes have increased the demand for groundwater since large number of communities depend majorly on groundwater through hand dug wells and boreholes as a supplement to supply from surface sources. Over the years, boreholes have usually been drilled with or without previous knowledge of the subsurface stratification. As a result of multiple failed boreholes, research intensified on ways of minimizing failed wells thereby reducing both the risk as well as the cost of drilling.

The groundwater potential of a basement complex area is determined by a complex interrelationship between the geology, post-emplacement, tectonic history, weathering processes and depth, composition of the weathered layer, aquifer types and combination, groundwater flow pattern, climate, recharge and discharge processes (Olorunfemi, 2007). Geophysical techniques have been employed over the years to characterize aquifer in different geologic environment and to map the fractures in the basement areas (Afolabi *et al.,* 2003).

Alile *et al.,* (2008) applied the use of vertical electrical sounding method to decipher the existing subsurface stratification and groundwater occurrence status in a location in Edo North of Nigeria. The study showed that the main lithologic units penetrated by the sounding curves are laterite, sandstone, sandstone (dry with some clay/shale). This study revealed the possibility of having a maximum drill depth to water table of 260 m (865.80 ft).

Hydro geological deductions from geoelectric survey in Uvwiamuge and Ekakpamre communities, Delta State, Nigeria was carried out by Atakpo (2009). The vertical electrical resistivity survey (VES) utilizing the surface Schlumberger electrode array with a maximum current electrode spacing varying from 50 - 500 m has been used to provide valuable information on the hydrogeologic system of the aquifers and the subsurface lithology in the area.

Omosuyi *et al.,* (2007) used Electromagnetic (EM) profiling and geoelectric sounding to locate fissured zones and associated groundwater containing media at Afunbiowo, near Akure, Nigeria. The VES interpretation delineated three groundwater target areas within EM localized zones: (i) the overburden, with thickness varying from 1.1 to 39.1m (ii) the weathered zone, with thickness ranging from 0.9 to 38.2m and layer resistivity of 29 to 1136 ohm-m (iii) the fractured zone.

Objective of the Study

The objective of this study is to demonstrate the application of lineament studies and geophysical survey (Vertical electrical sounding) in borehole failure investigation.

Description of the Project Environment

Rufus Giwa Polytechnic, Owo, Ondo State, is located in Owo (Fig. 1), which is within the south western part of Nigeria. The institution (Fig. 2) is situated in Owo local Government of Ondo State. It lies within longitudes 6 ° 00? E and 5 ° 30? E and latitudes 7 ° 30? N and 7 ° 00? N.

Geomorphology, Climate and Vegetation

Owo is relatively flat, as the terrain ranges from 940 ft to 1100 ft (Fig. 3). However in Rufus Giwa Polytechnic Owo, the topography ranges from 311 m to 342 m above the sea level. The study area has a gently undulating topography. The area lies geographically within the tropical rain forest belt of hot and wet equatorial climatic region. The available rain data shows that mean annual rainfall ranges from 1000 mm - 1500 mm and mean temperature of 24 ° C to 27 ° C. The vegetation of the area (especially in undeveloped areas) is dense and made up of palm trees, kolanut trees and cocoa trees.

Regional Geological Setting

Nigeria lies between longitude $2^{o}40^{1}$E and $14^{o}40^{1}$E and latitude $4^{o}20^{1}$N and $13^{o}15^{1}$N in the West Africa sub region, which is part of the African shield, an ancient stable continental crust. It consists of different/diverse rock types that can be divided into two major groups; basement complex and sedimentary rocks (Fig. 4). The two groups of rocks underline the surface area of the country in approximately equal proportions, i.e. the crystalline rocks and sediments, each covers nearby half of the total area of Nigeria. The study area of study falls within the Southwestern basement rock which is part of Nigerian Basement complex. The Basement Complex of Southwestern Nigeria lies to the east of the West African Craton in the Region of Late Precambrian to early Paleozoic Orogenesis.

Local Geological Setting

The study area is underlain mainly by rocks of the Migmatite – Gneiss Complex (Fig. 5), which is generally considered as the basement complex (Dada, 2006) and is the most widespread of the component units in the Nigerian basement. It has a heterogeneous assemblage comprising migmatites, orthogneises, paragneisses, and a series of basic and ultrabasic metamorphosed rocks. Figure 6 displays the geological disposition of the study area. It is predominantly underlain by quartzite (Plate 2.1 – 2.4), granite and granite gneiss (Plate 2.5 – 2.10). Quartzite is the most dominant rock; which mineralogically contains quartz dominating mineral, other minerals such as muscovite, tremolite, microcline and biotite are common as well. Quartzites which are prominent as ridge vary in texture from massive to schistocity due to the presence of flaky minerals like mica.

Hydrogeology of the Area

The geological structure of Nigeria gave rise to two types of groundwater: pore-type water in sedimentary cover and fissure-type water found in crystalline rocks. Below are the aquifer types in Nigeria:

1. Fissure type water in Precambrian crystalline rocks
2. Pore-type water in sedimentary deposits
3. Pore-type water in superficial deposits.

Water Supply Units

1. Topsoil/Overburden Unit

This is loose unconsolidated layers which have the tendency of supplying borehole with near surface water. The level of supply of water from the overburden to the subsurface groundwater units depend on its thickness.

2. Weathered Layer

This is bedrock formation zone that has undergone weathering process in-situ which in most cases serves as the groundwater bearing zone.

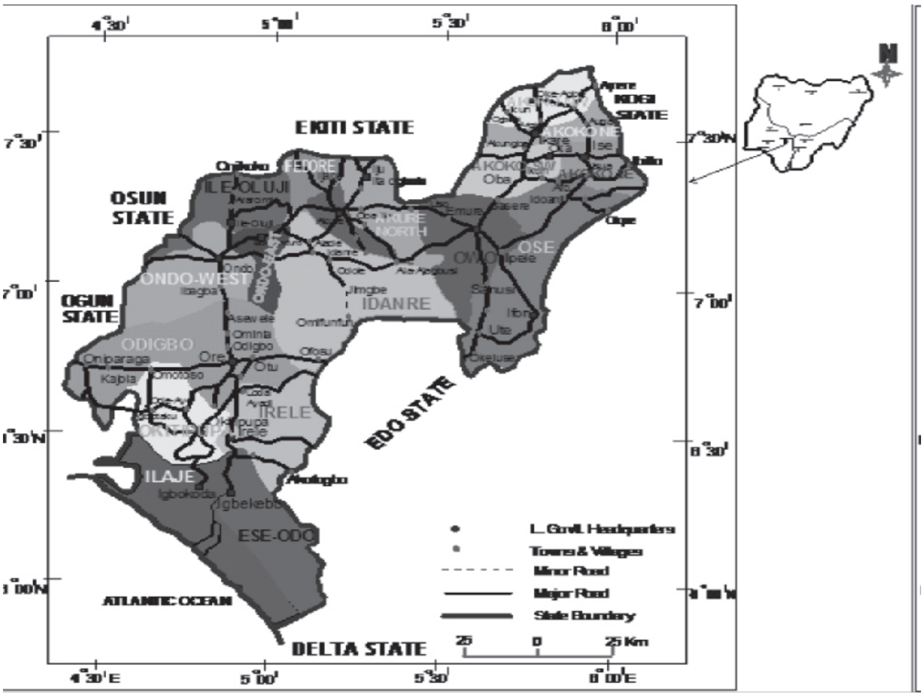


Fig. 1: Road/Administrative Map of Ondo State

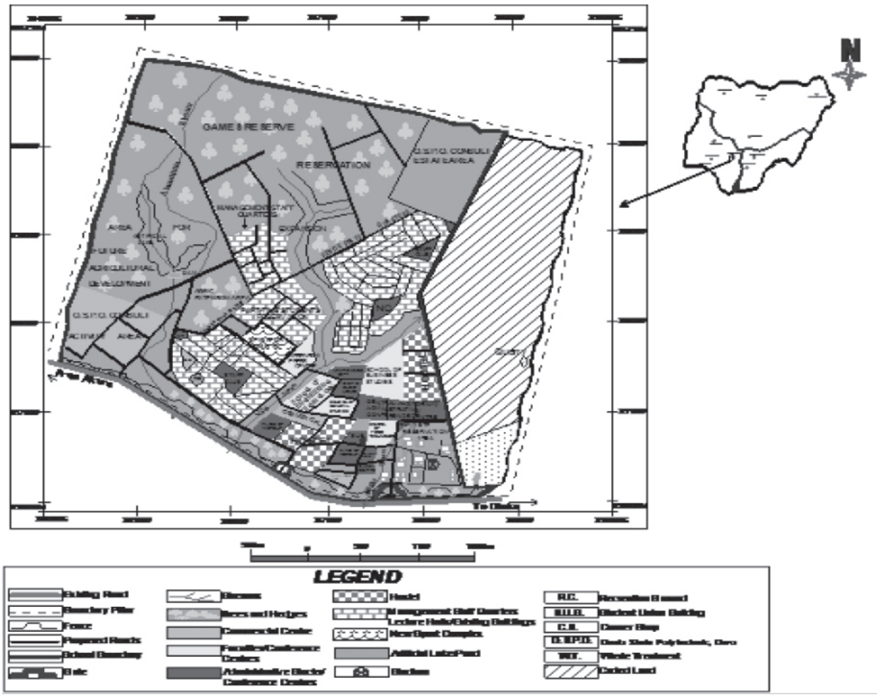


Fig. 2: Land-Use Master Plan of the Study Area

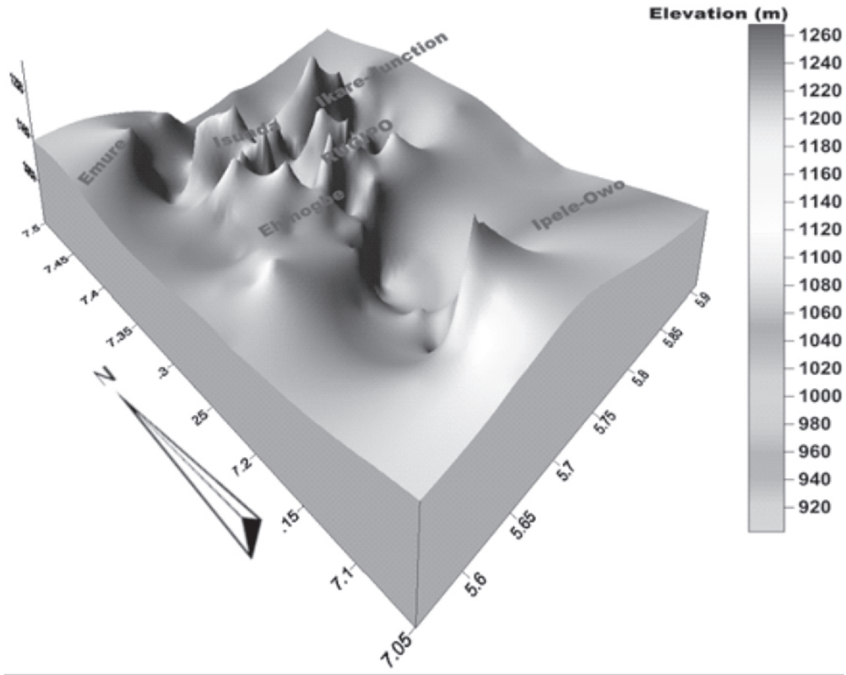


Fig. 3: 3-D Surface Elevation Map Around the study Area

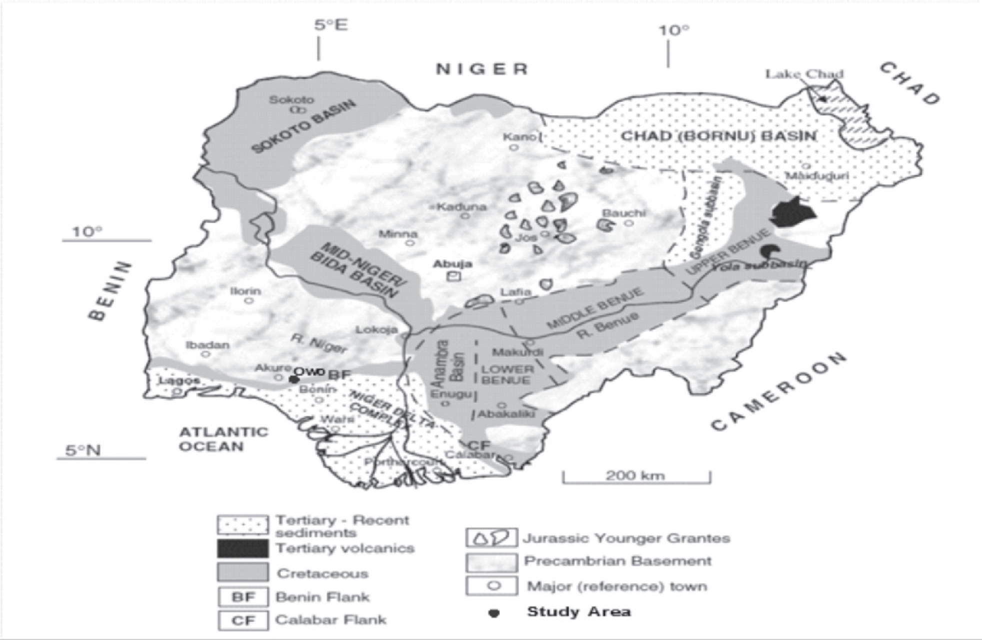


Fig. 4: Geological sketch map of Nigeria showing the major geological components; Basement, Younger Granites, and Sedimentary Basins (Modified After Geological Survey Division, 1974)

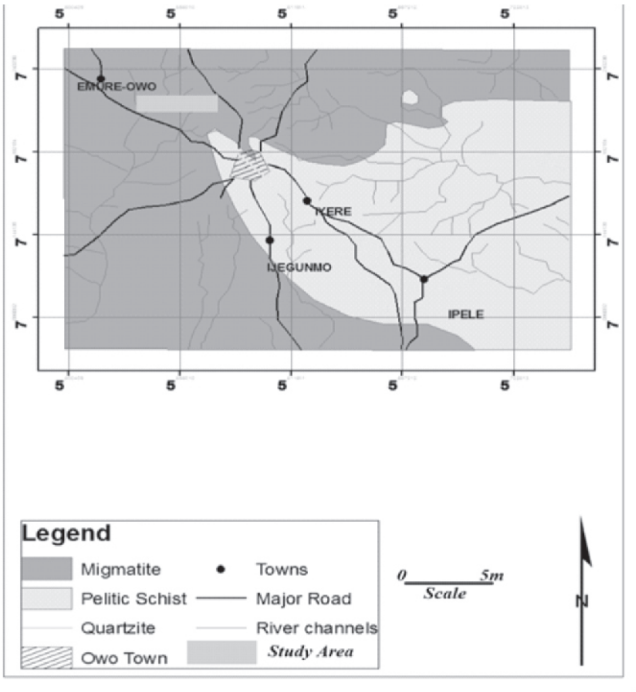


Fig. 5: Geological Map of Owo and Environ, Showing the Study Area Underlain by Migmatite. (Modified After Geological Survey of Nigeria, 1984)

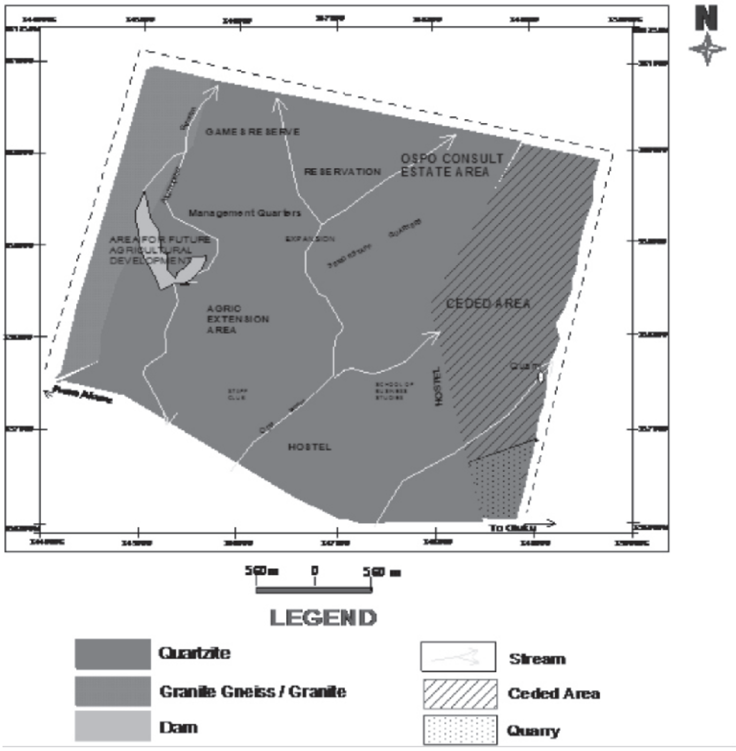
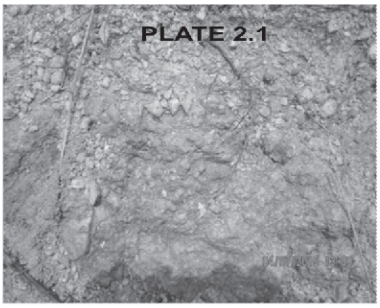
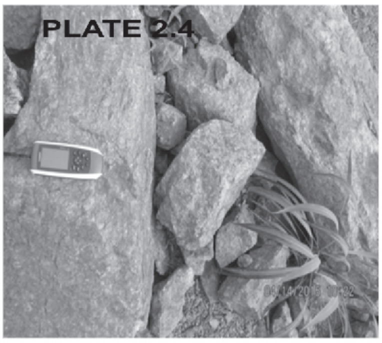


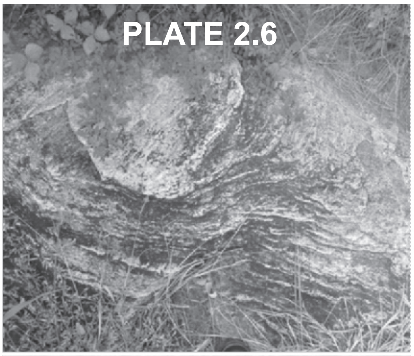
Fig 6: Geological Map of the Study Area, showing granite gneiss / granite and Quartzite rocks which is the most predominant in the area?

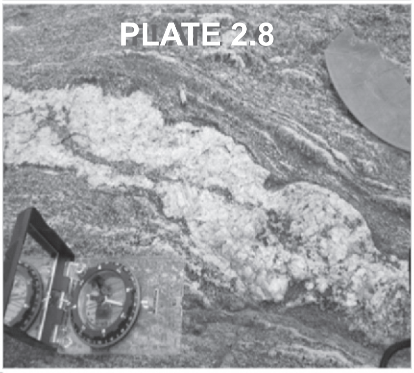


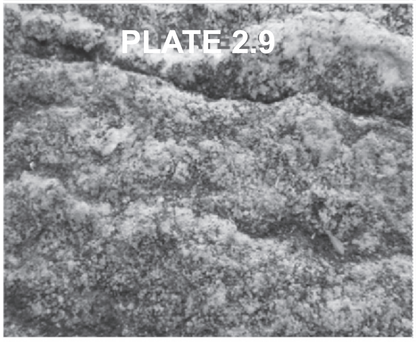


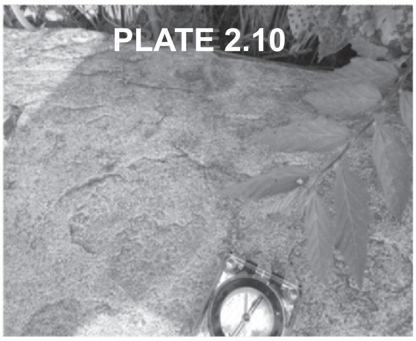
Plates 2.1- 2.2: Portions of surface exposures of Quartzite observed in the Study Area Showing different texture ranging from the massive to schistocity.

Plates 2.3 – 2.4: Portions of Quartzite rocks occurring as boulders and weathered rock material









Plates 2.5-2.6: Portions of Banded gneiss showing intercalation of light and dark mineral bands

Plates 2.7-2.8: Portions Granite showing concordant vein orientations of varying thickness

Plates 2.9-2.10: Portions of Granite observed in the Study Area showing fine grained and porphyritic texture with intrusion of Quartzo-feldspathic veins.

3. Bedrock

The unweathered rock below the weathered layer and drifts cover which can accumulate groundwater through its fractured units. Groundwater can also be found/trap along shear zones, lithological boundary, fracture/joints zones, fault zones etc.

Although the weathered layer and the fractured basement column constitute the two major aquifer units in a basement complex area, the aquifers can occur in five different forms. These include the weathered layer aquifer, the weathered/fractured (unconfined), the weathered/fractured (confined), the weathered/fractured (unconfined)/fractured (confined) and the fractured (confined) (Olorunfemi, 2007).

Drainage Pattern

The overall surface water drainage exhibited in the study is controlled by the underlying geological materials. The radial drainage characterized the surrounding hilly crystalline rocks of the area. This is interrupted by the presence of alluvial cover, such that they direct the flow of streams relatively within their course and exhibit dendritic drainage pattern. The study area is drained by three major streams: Atamopere stream, Ope stream, and Aaunke stream. These streams are some of the tributaries of Ogbese River. The flow directions of the streams are toward the northern and north-eastern parts of the study area (Fig. 6).

Methodology

The research work involved literature review of texts, technical journals, various articles, past projects thesis e.t.c., as related to the uses of geophysics as a tool in borehole failure investigation. The reconnaissance survey was in form of site visitation as this assisted in taking notes of the geologic setting of the area, taking of photography of the six existing boreholes in the areas (as this helped in accessing the conditions of the borehole). Personal interview was carried out with the staff in the institution in connection with the relevant information which assisted in carrying out the study successfully. Geophysical investigation involving electrical resistivity (Vertical Electrical Sounding (VES). The geographic co-ordinates of data stations were taken using GARMIN'S GPS 12 - Channel model. The geophysical data were interpreted qualitatively and quantitatively, as related to the objectives of the study.

During the course of structural field mapping, Strike and Dip of structural features such as joints, faults, and veins were measured on exposed outcrops. Furthermore, the attitudes of the structures were plotted on rose diagrams and stereographic projections in order to understand the trend of the major tectonic forces in the region. For the subsurface geological study, Vertical Electrical Sounding (VES) was adopted because information on the variation of geophysical characteristics of the subsurface layers with depth was desired. VES were conducted along five traverses established along the five existing borehole sites and the Sounding stations were marked and pegged along the traverses at varying intervals. The interval was chosen in view of the high degree of spatial resolution desired. In the Vertical Electrical Sounding (VES) technique, vertical variations in the ground apparent resistivity are measured with respect to a fixed center of array. RMS between the field curves and computer generated curves is generally less than 10 %; as it ranges between 1.8 – 10.7.

Results and Discussion

Lineament Maps

The structural elements delineated in the project area are mainly lineaments. The term lineament, as used in this study, is as defined by O' Leary *et al.,* (1976) as a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumed to reflect subsurface phenomenon. This can be generally equated with structural elements such as joints, fractures and faults (Viljoen *et al.,* 1983). The mapped structural lineaments were mapped and analysed using the lineament density (LD), lineament frequency (LF) and lineament intersection (LI) parameters. The results of the analysis are presented as the Lineament map (Fig. 7), Rose diagram (Fig. 8), Lineament density map (Fig. 9) and Lineament intersection map (Fig. 10).

Figure 7 shows the lineament map of Owo area, which encompasses the study area. This map shows that the drainage pattern is significantly controlled by the lineaments; hence the major rivers may have been structurally controlled. Some of the lineaments may be faults particularly those that show relative displacement. Other linear features are suspected to be fracture and fissure zones. As shown by the rose diagram (Fig. 8) four major structural trends that are typical of the Nigerian basement complex (Rahaman, 1989) are all represented in this area. These include the NE – SW, NW – SE, N- S and E – W trends. This clearly shows the polycyclic nature of the processes that brought about the origin and architecture of the basement complex. However, an approximate NE – SW and NNE – SSW lineament trend are the dominant structural trends in the study area.

The lineament density variation map shows the lineament numbers to be in the range of 0 and 0.1443 (in yellow colour). This implies that the lineament density around the study area is low. This indicates the low degree of hydraulic interconnection within the quartzite units as surface water circulates through these discontinuities. The density of lineaments along with the degree of lineament intersection determine the degree of anisotropy of groundwater flow in the fracture network, environments with a high degree of interconnection where groundwater flow is smoother and more uniform. Fracture intersection density is a map showing the frequency of intersections that occur in a unit area. The purpose of using intersection density maps is to estimate the areas of diverse fracture orientations. The lineament intersection map of the study area (Fig. 10) indicates low and very low intersection in the same areas where there are very low lineaments. The zones of low lineament intersection over the study area are non-feasible zones for groundwater potential evaluation.

Hydrogeological Measurement

Hydro geological measurements and information about the depth of the six existing boreholes in the study area are presented in Table 1 and 2. The static water level, water column and depth to water level vary between 316.9 m and 330.5 m, 1.3 m and 4.8 m, and 8.1 m and 10.5 m respectively. The average depth to the water level was 9.4 m. This implies that the vadose zone is fairly thick. The average water column is 3.1 m indicating a medium water column. The information obtained from the existing boreholes in the area revealed that the depth of those boreholes vary from 20 m to 45 m.

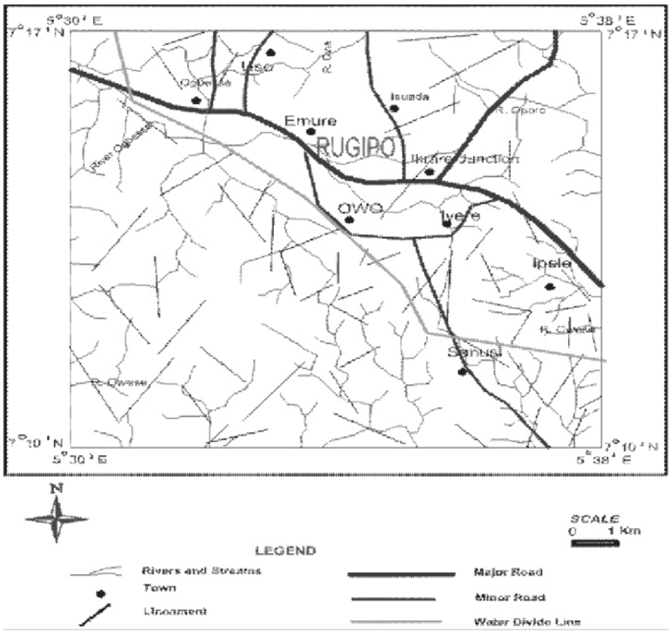


Fig. 7: **Lineament Map around the Study Area (Modified After Adewumi *et al.*, 2015)**

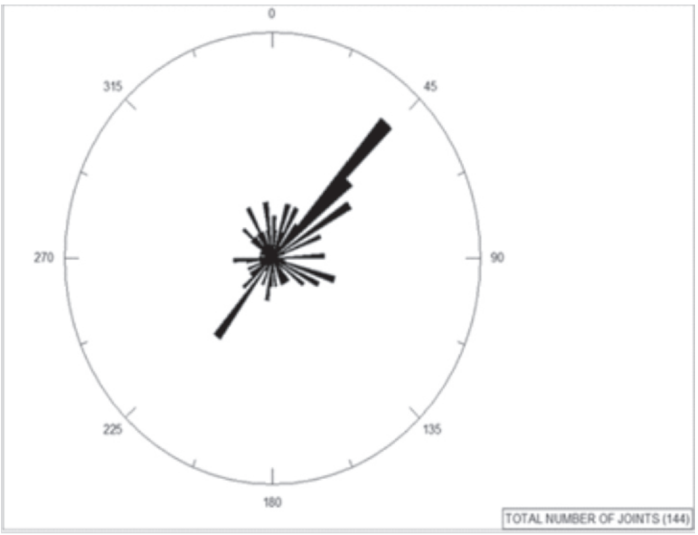


Fig. 8: **Rose Diagram of Joints Observed on Quartzite and the Migmatite Rocks in the Study Area**

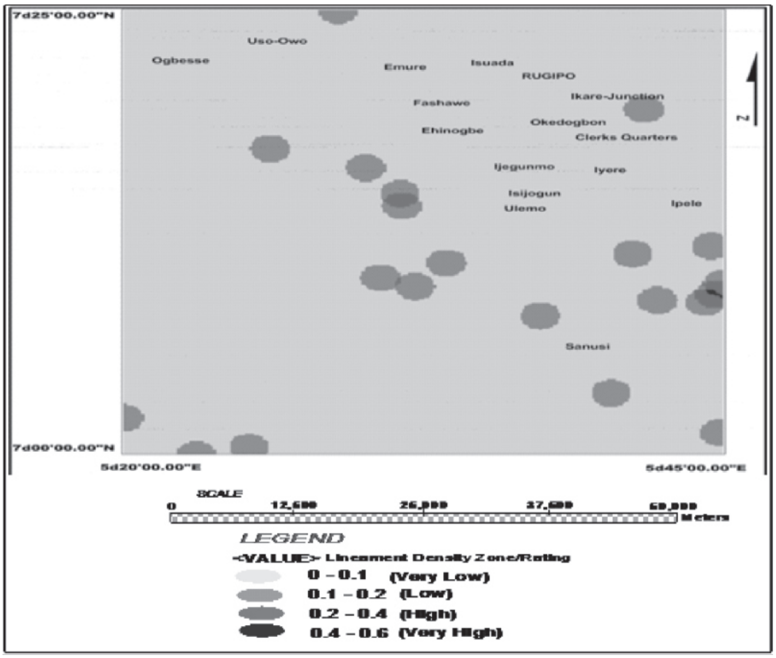


Fig. 9: Lineaments Density around the Study Area

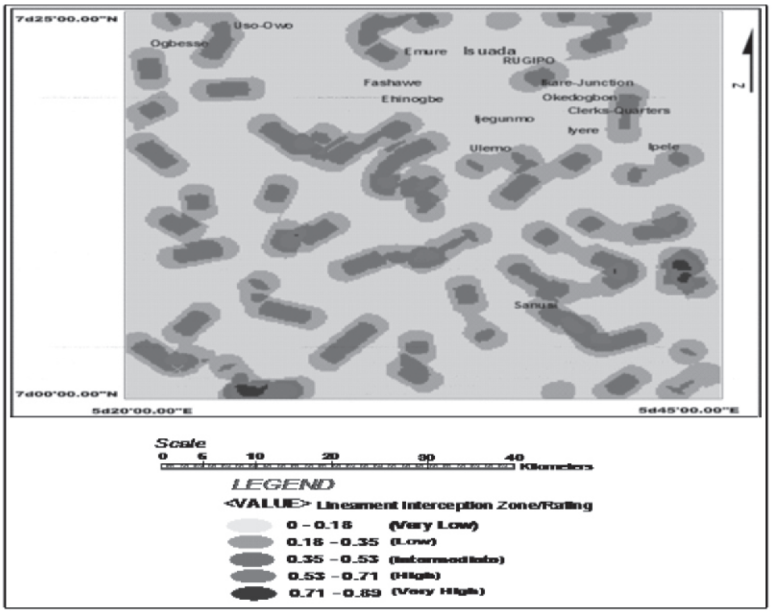


Fig. 10: Lineaments Interception Map around the Study Area

Table 1: Hydro-geological Field Data Obtained within the Study Area

Well No./ Location	Easting	Northing	Elevation (m)	Depth to Water Level (m)	Total Depth of well (m)	Water Column (m)	Static Water Level (m)
1 (SE)	0781976	0799863	325	8.1	11.2	3.1	316.9
2 (SE)	0783358	0799585	331	9.7	12.2	1.3	321.3
3 (NE)	0782782	0799244	341	10.5	15.3	4.8	330.5

Table 2: Information Obtained on the Existing Boreholes within the Study Area

Borehole No.	Easting	Northing	Depth (m)	Condition Since When Dug
1	0782558	0799383	20	Very Productive
2	0782763	0799463	45	Very Productive
3	0782811	0799139	30	Fairly Productive
4	0783066	0799503	30	Fairly Productive
5	0782782	0799378	45	Not working
6	0782407	0800466	45	Less Productive

Geophysical Results

Vertical Electrical Sounding

The 2-D geoelectric section (Fig. 11) along traverse 1 shows four distinct subsurface geoelectric layers; the topsoil/laterite, weathered layer, partly weathered layer/fractured basement and the fresh basement. The topsoil resistivity values vary from 97 – 118 Ω-m. The layer thickness varies from 0.6 m to 1.6 m. The topsoil is generally thin. The weathered layer has resistivity that varies between 149 – 460 Ω-m with thickness between 0.8 – 5.9 m. The partly weathered layer/fractured basement which is the main aquifer along this traverse has resistivity values between 41 and 108 Ω-m; and its thickness varies from 15.9 to 28.8 m.

Existing borehole 1 and 5 were drilled into the fractured basement to a depth of 20 m and 45 m respectively. While borehole 1 is still working and well productive; borehole 5 has failed. This could be due to the fact that it was drilled into the low fractured basement aquifer with resistivity above 100 Ω-m indicating a less fractured density zone with low porosity and permeability, unlike borehole 1 which has a resistivity values below 100 Ω-m. The basement rock has resistivity between 3527 and 10441 Ω-m

The geologic section along traverse 2 is shown in Figure 12. The sections composed mainly of topsoil, clay substratum, weathered layer, partly weathered layer/fractured basement and fresh basement. The topsoil has resistivity values between 120 and 441 Ω-m, indicating a clayey sand/sand material with thickness that ranges between 0.9 m to 1.2 m. It is directly underlain by a thin clayey formation with 20 Ω-m resistivity with thickness of 1.5 m. The partly weathered layer/fractured basemen is the main aquifer along this traverse has resistivity value of 52 Ω-m and thickness of 22.8 m.

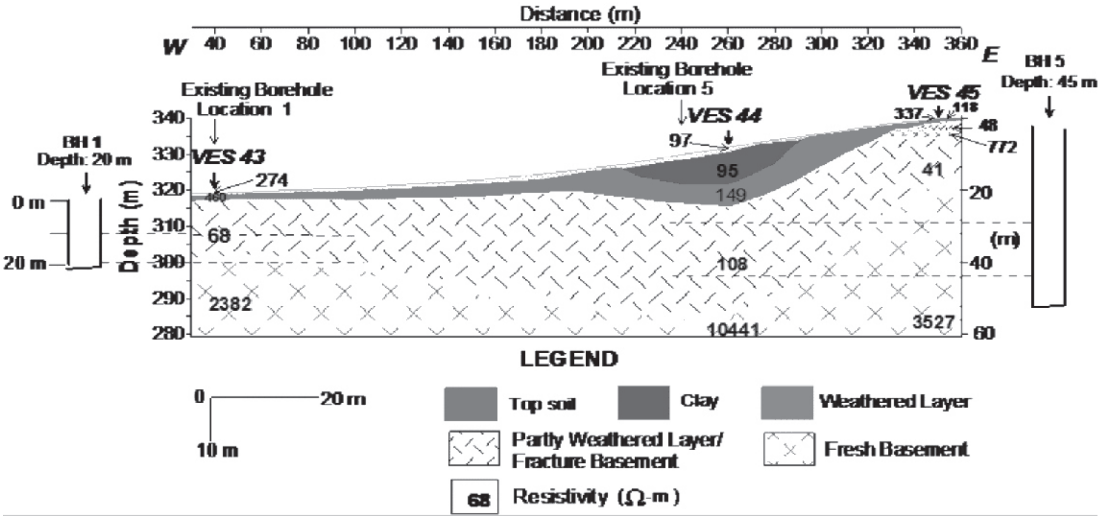


Fig. 11: Borehole Sections along Traverse 1

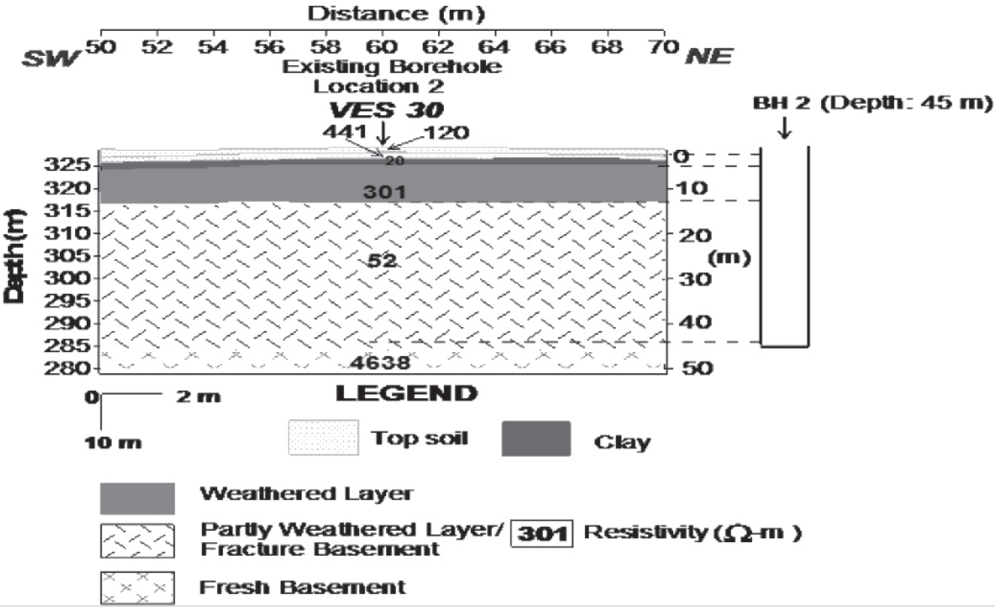


Fig. 12: Borehole Section along Traverse 2

The borehole along this traverse was drilled under VES 30 to a depth of 45 m and very productive. The fresh basement underlies the partly weathered basement/fractured basement with resistivity value of 4638 Ω-m.

The 2-D geoelectric section (Fig. 13) along traverse 3 shows four distinct subsurface geoelectric layers; the topsoil, weathered layer, partly weathered layer/fractured basement and the fresh basement. The topsoil has resistivity values that vary between 60 Ω-m and 1474 Ω-m indicating a clayey/sand/lateritic material. The thickness ranges from 0.4 m to 3.9 m.

The weathered layer resistivity values are in the range of 64 Ω-m – 562 Ω-m, with thickness between 3.0 m and 26.9 m. The weathered layer forms the main aquifer along this traverse.

Existing borehole 4 was drilled into the clayey weathered layer aquifer (with resistivity value less than 100 Ω-m) up to a depth of 30 m but less/fairly productive due to the fact that clayey aquifer has good reservoir quality but is generally poor in transmitting the water i.e. it has a good porosity but poor permeability. The partly weathered layer/fractured basement has resistivity in the range of 40 Ω-m – 522 Ω-m with thickness values between 8.3 m and 9.1 m.

The fresh basement has low resistivity values varying from 327 Ω-m to 376 Ω-m due to screening effect of the overlying low resistivity layer. However, it would have been better if the borehole was situated at VES 23 (which has good prospect) due to combination of relatively thick layers of sand/clayey sand weathered layer and highly fractured basement aquifers.

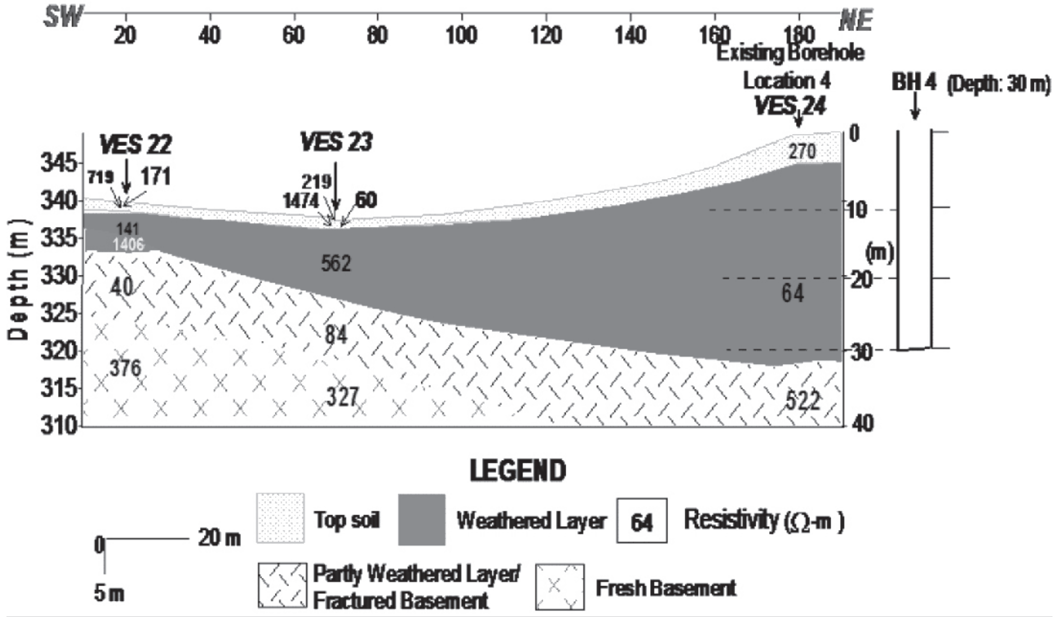


Fig. 13: Borehole Section along Traverse 3

The geologic section along traverse 4 is shown in Figure 14. The sections composed mainly of Topsoil/Laterite, weathered layer, partly weathered layer/Fractured basement and Fresh basement. The topsoil which is lateritic in nature has resistivity values between 304 and 790 Ω-m, with thickness that ranges between 0.9 m to 1.5 m. It is directly underlain by weathered layer (first intercepted aquifer) which is very thick under VES 46 and thin under VES 47. The resistivity values of the weathered layer vary from 165 to 336 Ω-m indicating clayey sand aquifer, with thickness between 6.5 m and 30.4 m. The partly weathered layer/fractured basement forms the second aquifer along this traverse has resistivity values ranging from 382 Ω-m to 535 Ω-m; with thickness generally greater than 20 m.

Existing borehole 6 along this traverse was drilled under VES 47 to a depth of 45 m and was less productive due to the fact that the density of the fracture/joint that characterized the fractured basement was low which was evidenced by its resistivity value of 336 Ω-m. It might have been a better venture if it was drilled under VES 46 to depth not more than 30 m. The fresh basement underlies the partly weathered basement/fractured basement with resistivity value of 4638 Ω-m.

The 2-D geoelectric section (Fig. 15) along traverse 5 shows four distinct subsurface geoelectric layers; the topsoil, clay substratum, weathered layer, partly weathered layer/fractured basement and the fresh basement. The topsoil has resistivity values that vary between 135 Ω-m and 262 Ω-m indicating a clayey sand material. The thickness ranges from 0.8 m to 0.9 m. Clay underlies the topsoil under VES 35The weathered layer resistivity values are in the range of 64 Ω-m – 562 Ω-m, with thickness between 3.0 m and 26.9 m. The weathered layer forms the main aquifer along this traverse. Existing borehole 4 was drilled into the clayey weathered layer aquifer (with resistivity

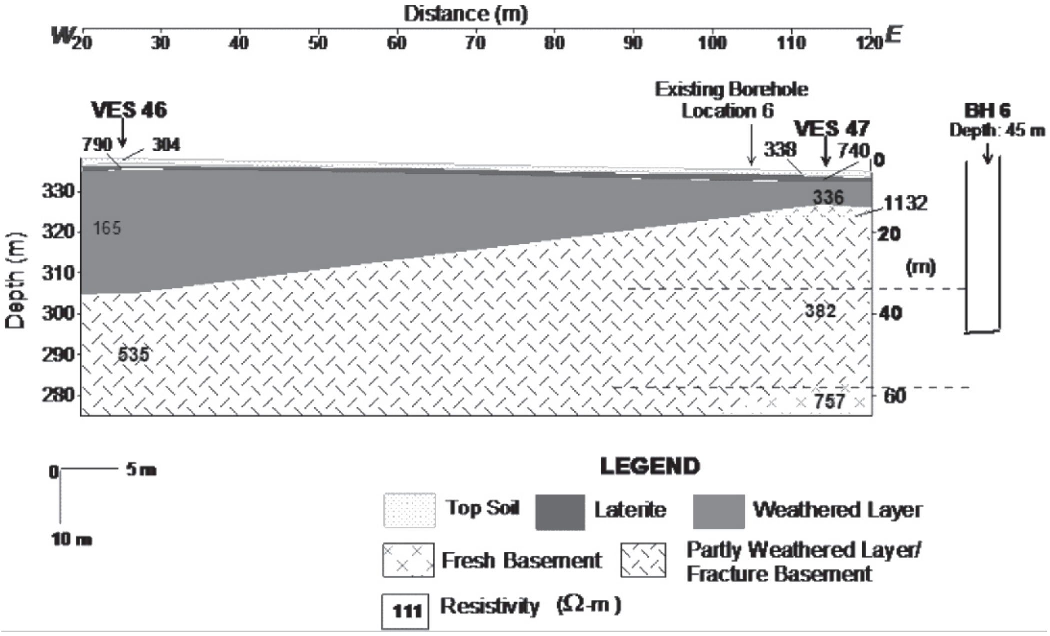


Fig. 14: Borehole Section along Traverse 4

Value less than 100 Ω-m) up to a depth of 30 m but fairly productive due to the fact that clayey aquifer has good reservoir quality but is generally poor in transmitting the water i.e. it has a good porosity but poor permeability.

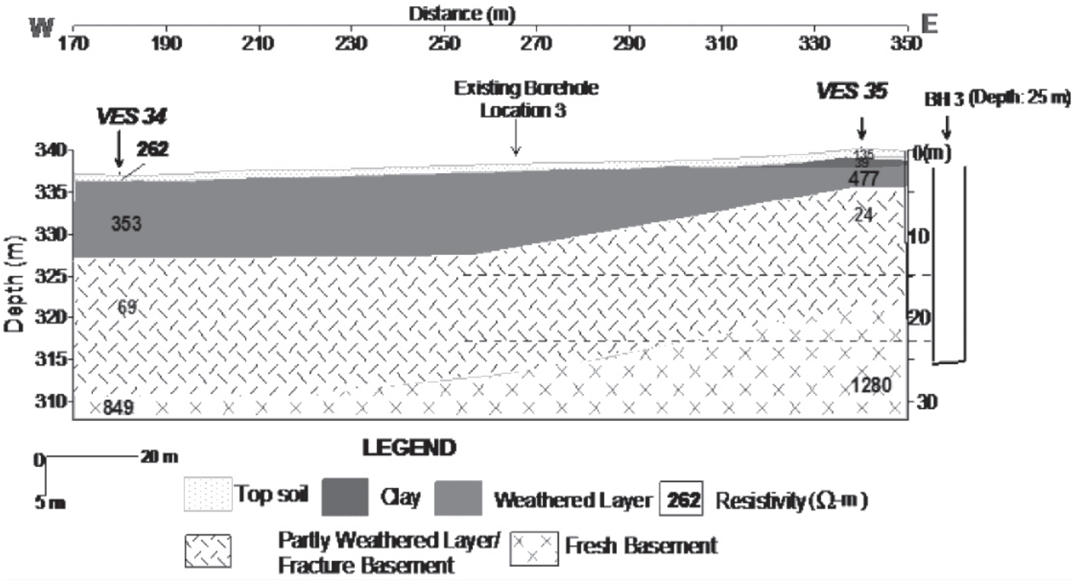


Fig. 15: Borehole Section along Traverse 5

The partly weathered layer/fractured basement has resistivity in the range of 40 Ω-m – 522 Ω-m with thickness values between 8.3 m and 9.1 m. The fresh basement has low resistivity values varying from 327 Ω-m to 376 Ω-m due to screening effect of the overlying low resistivity layer. However, it would have been better if the borehole was situated at VES 23 (which has good prospect) due to combination of relatively thick layers of sand/clayey sand weathered layer and highly fractured basement aquifers.

Conclusion

Integrated geophysical investigation and lineament mapping were conducted at Rufus Giwa Polytechnic, Owo, Southwestern, Nigeria with the aim of identifying the factor(s) responsible for borehole failures in the study area. Integrated lineament mapping and Vertical Electrical sounding were two methods utilized for the study. The result of the study revealed that most possible causes of failure of some of the boreholes can be attributed to (i) groundwater potential/hydrogeological inconsideration (ii) design and construction and (iii) operational and maintenance failures. It is possible for one factor to lead to the other. For example, a borehole poorly designed, constructed and completed could result in silt/sand/clay pumping and eventually affect the rubber seals in the hand pumps or the impellers in the case of submersible pumps.

Recommendation

Further pre-drilling geophysical investigations including borehole logging should be conducted in the area to enhance or facilitate well design and completion processes for optimization of resulting borehole yield. This will prevent the common occurrence of borehole failure and loss of money; Concentration should be on drilling new boreholes with a comprehensive pre-hydrogeophysical investigation instead of remediation of the failed boreholes; and water quality analysis and complete borehole documentation should be carried out. This should be in accordance with known professional practice.

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