

Multi-Array Hydro-Geoelectric Characterization of a Crystalline Basement Complex environment

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AUTHORS' CONTRIBUTIONS

This work was carried out by the three authors. The lead author conceived the idea and designed the field parameters. The second author put the original manuscript in a research format and forwarded same to the publisher. The third author undertook the field data acquisition, interpreted the data, generated the diagrams and wrote the initial manuscript. The three authors have reviewed the analyses of the study results and approved the final manuscript.

ABSTRACT

The efficiency of integrated geoelectric arrays study was undertaken on a ubiquitous shallow Precambrian Crystalline Basement Complex rocks terrain of School of Earth and Mineral Sciences (SEMS) of The Federal University of Technology, Akure, southwestern Nigeria. Geophysical data acquisition was undertaken on fifteen (15) traverses in the area using Gradient, Dipole–Dipole and Schlumberger Vertical Electrical Sounding (VES) techniques. The field data were interpreted using both manual and computer iterations. The results are presented as map, sections and sounding curves. The results of the gradient array, dipole-dipole and Schlumberger VES enabled qualitative, semi-quantitative and quantitative hydrogeophysical evaluations respectively. Both gradient and dipole-dipole arrays indicate existence of fairly favourable hydro-geoelectric setting on the north central precinct of the area. The combined results of both arrays informed the location of 13 Schlumberger - VES points in the positive environment. The Schlumberger VES results show that clayey overburden materials (31 – 58 Ω m) with thickness varying between 8.7 and 16.9 m that can plausibly support abstraction of some quantity of groundwater underlie the fairly favourable northern flank. However, a fractured basement column delineated beneath VES 7 may sustain fairly adequate groundwater yield. Despite the high cost of implementing multiple geoelectrical arrays in groundwater projects, the outcome may justify the expenditure especially in cases where point of water abstraction is successfully identified particularly where properties have been developed in ubiquitous shallow bedrock environment similar to the terrain of study.

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Key words: Hydrogeoelectric, Hydrogeophysical, Resistivity, Aquifer and Basement rock

1. INTRODUCTION

Application of geophysical methods to hydrogeological problems is continuing to gain more ground in groundwater decision making process [1]. The established geophysical methods widely utilized in hydrogeophysics studies include seismic refraction [2], magnetic [3], electromagnetic (including the VLF-EM) [4], [5], [6], [7], seismic reflection [8] and the direct-current (*DC*) electrical resistivity method [9], [10]. Among these various methods the electrical resistivity method has been noted for its efficiency in solving hydrogeologic problems. The dominance of the electrical resistivity method in solving groundwater related problems is due to its non-invasive attribute, low cost, speed of data acquisition and ability to map both geological layers as well as determining the nature and composition of unseen subsurface formations [11],[12]. In the field of hydrogeophysics where characterization of aquifer properties results in optimal exploration of groundwater resources, the electrical resistivity method has therefore been widely utilized [15], [16], [17]). For effective utilization of electrical resistivity method in hydrogeophysics, some of the varieties of electrode configurations (especially Schlumberger, Dipole–Dipole and Gradient) should be integrated for field mapping. However, the choice of any of the electrode configurations depends largely on the objective of the survey, scope of study, local geology and the sensitivity of any or combination of the arrays to vertical and/or lateral variations in the subsurface resistivity distribution ([18], [19]. In many hydrogeological studies, each of these electrode configurations is often utilized individually or in combination to further enhance information on the hydrogeologic setting. The Schlumberger configuration which is best utilized in vertical electrical sounding (VES) enables 1-D geoelectric study of a point while combination of several soundings in an environment will enable 2-D or 3-D overview of the hydrogeologic setting. The Dipole-Dipole electrode configuration enables a 2-D evaluation of the hydrogeologic setting while multiple traverse combinations enable 3-D hydrogeologic evaluation. The gradient electrode configuration which is a non-conventional electrode configuration has been found more unique in resistivity survey for solving hydrogeologic problems (Aizebeokhai and Oyeyemi [17]). The output of gradient array subsurface resistivity images often present good resolution attributes which are essential for characterization of subsurface geologic features that can enhance hydrogeologic decision making process (Aizebeokhai and Oyeyemi [17]). The three electrode configurations have their peculiar attributes in hydrogeophysics ([18]; Loke and Barker [19]). Exploring their potential attributes in complimentary form can enhance hydrogeologic decision making output. Very few geoelectrical investigations for groundwater studies have considered exploring the use of both conventional and non-conventional arrays in a complementary form. This study has been conducted utilizing combination of rarely used gradient arrays with those of conventional Schlumberger and Dipole–Dipole arrays with a view of characterizing the subsurface features and delineating the underlying aquifer units. The study result is expected to enable the location of aquifer units and their lateral extent in the study area.

2. ELECTRODE ARRAYS AND THEIR UNIQUE ATTRIBUTES

In order to achieve the objectives of this study, three (3) array types viz: Schlumberger, Dipole–Dipole and Gradient were adopted. The arrays have different geometric factor equations which often determine their operational functionality for any specific resistivity survey task. Fig. 1 presents the layout of the electrode configurations and their geometric factors. Generally across the electrode configurations (Figure 1 a - c), the C_1 and C_2 are the injecting current electrodes while P_1 and P_2 are the measuring potential electrodes. The letters L, l and X of Figure 1c, implies that L = the distance from electrode C_2 to the middle of distance $C_1 - C_2$ and the "l" denotes the distance between P_1P_2 , whereas X represents the distance from the point of measurement to the middle of C_1-P_1 (P_2-C_2) electrodes to the spacing ("a"), respectively. The "n" and "a" in Figure 1 a & b are the minimum electrode spacing as well as the ratio of the distance between the C_1-P_1 (P_2-C_2) electrodes to the

spacing ("a") between the P₁-P₂ potential pair, respectively. The position and location of both the current and the potential electrodes and their separating factors often determine the probing depth and resolution of the delineated subsurface features in all the electrode configurations of choice. However, the gradient array has deeper probing depth compared to both Schlumberger and Dipole-Dipole. This is because of the field layout arrangement of gradient array which allows large current electrode separation.

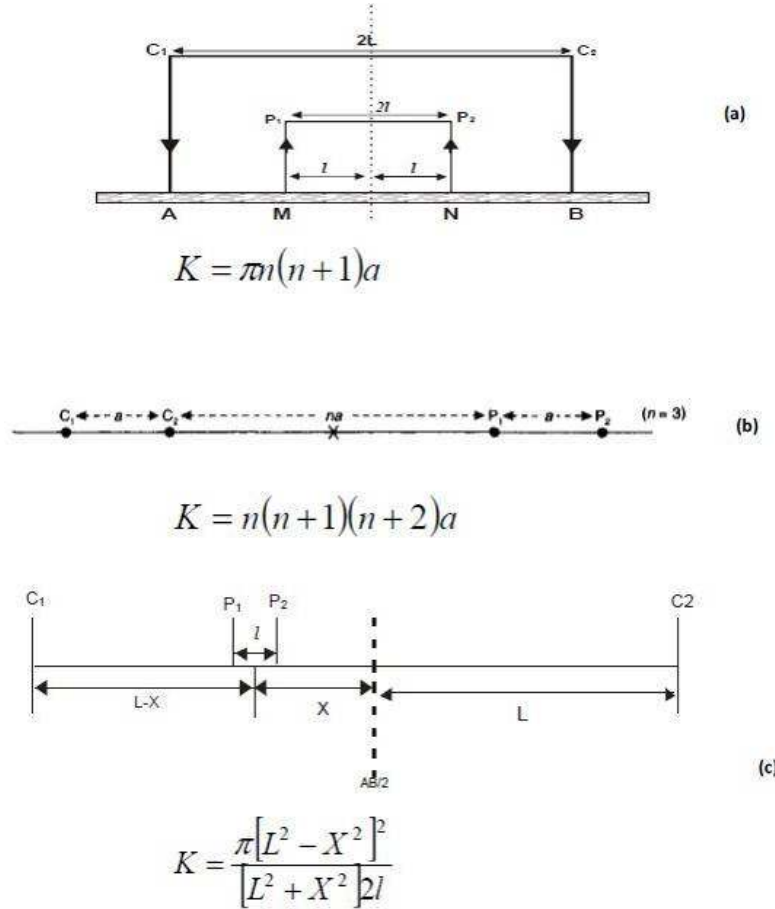


Fig. 1: The electrode configurations used for data measurement where (a): The Schlumberger, (b) The dipole-dipole, (c): The gradient and K: The geometric factor

3. GEOLOGICAL SETTINGS AND SITE DESCRIPTION

The study area (School of Earth and Mineral Sciences (SEMS)) is located within central area of the Federal University of Technology, Akure, southwestern Nigeria (Fig. 2). The University campus is situated on the northwestern flank of Akure metropolis and on the southern flank of Ibadan-Akure-Benin Federal Highway. The university which occupies an area of about 5 km² is situated within latitudes 7° 16'N and 7° 18'N and longitudes 5° 07' E and 5° 09'E. The university campus is situated on slightly rugged terrain with elevation between 350 m above mean sea level on the southeastern flank and 390 m at the northern flank of the campus. The area lies in the tropical rain forest with mean annual rainfall of about 1300 mm. Generally, the annual mean temperature in the area varies between 18°C and 33°C. The campus is well drained with the dendritic drainage pattern via three major streams that flow in the southern direction. Rocks of the Precambrian Crystalline Basement Complex of southwestern Nigeria [20] underlie the study area. The lithological units include granites, gneisses, quartzites and charnockite. Low-lying outcrops of granites, gneiss and quartzites occur in several locations, mostly in the northwestern and central parts of the study area (Fig. 3).

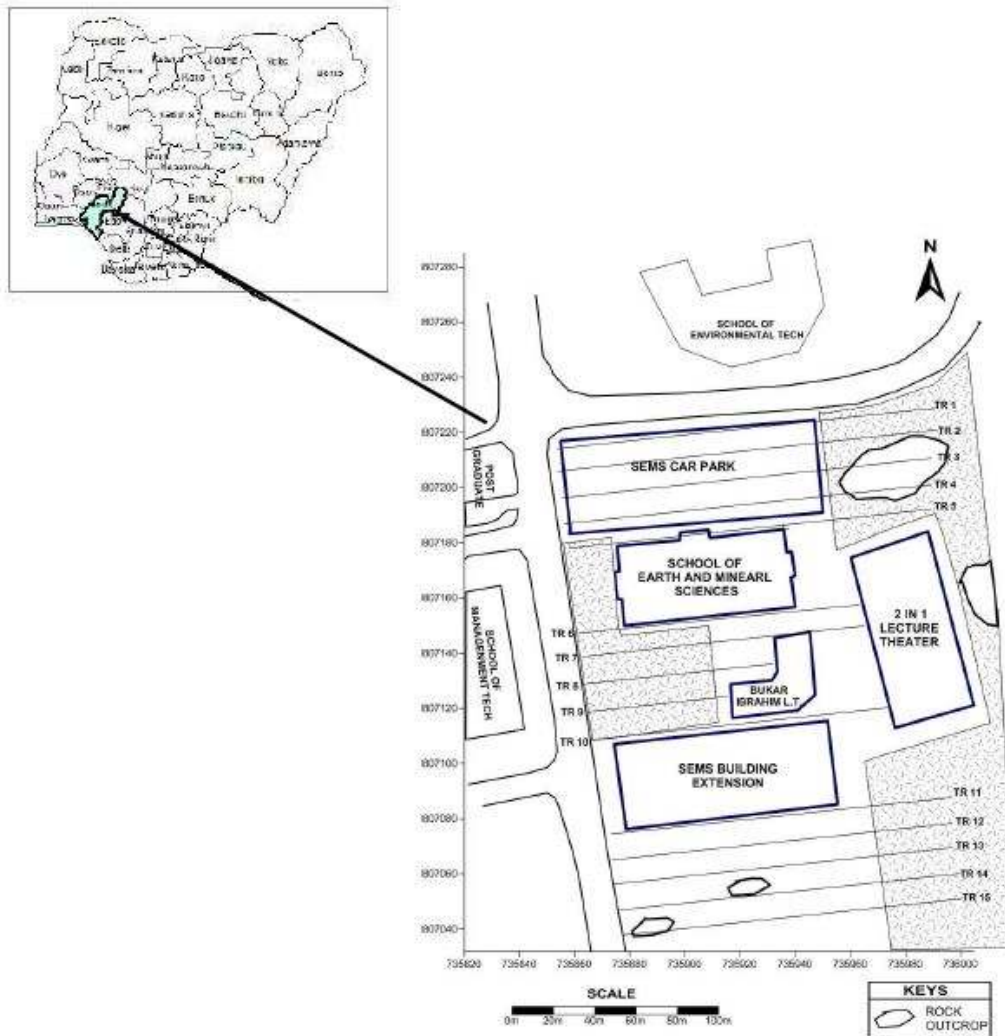


Fig. 2: Layout map of the area of study with the map of Nigeria as inset

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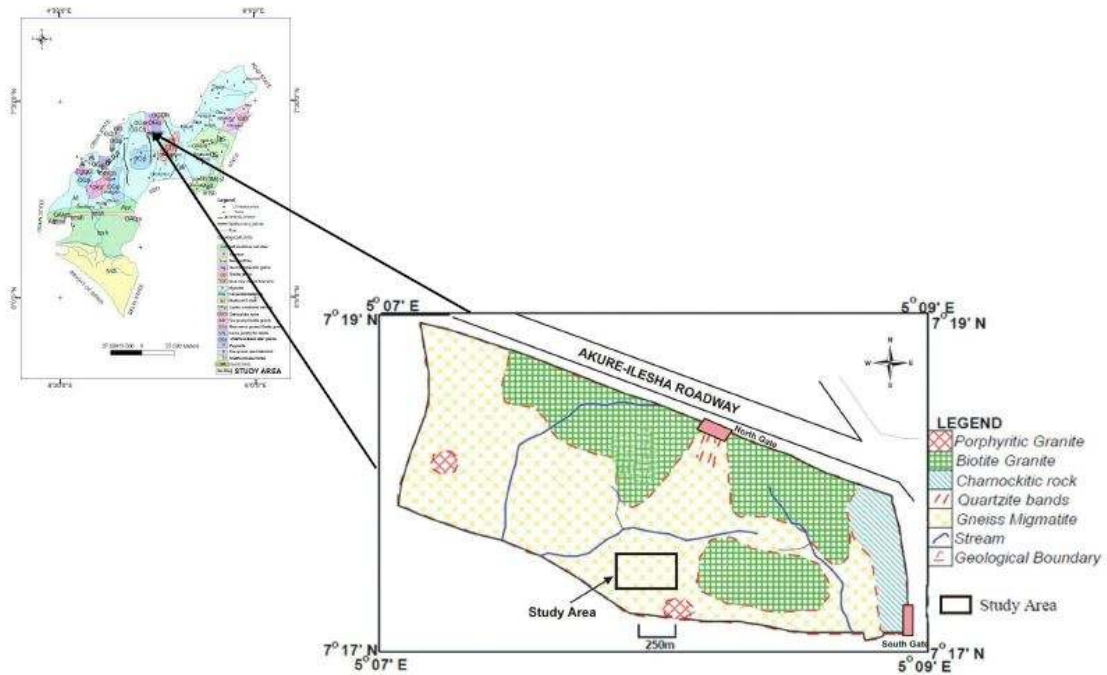


Fig.3: Geological map of the study area with the geological map of Ondo State as inset (After [21])

MATERIALS AND METHOD OF STUDY

Resistivity profiling measurements involved both the Gradient and Dipole-Dipole arrays (see Fig 4) while the Schlumberger array was adopted for vertical electrical soundings. The ABEM Terrameter (SAS 1000/4000 series) was utilized for the study. For data measurements with the gradient array, the current electrodes (C_1C_2) were fixed at a separation of 360 m while the potential measuring electrodes (P_1P_2) were moved within the current electrodes for each data measurement at constant electrode spacing of 10 m along each traverse. The data acquisition with dipole-dipole array involved constant electrode spacing of 5 m while the inter-dipole electrode expansion factor (n) was varied from 1 to 6. However, during the dipole-dipole array measurement, areas occupied by building structures were skipped. The Schlumberger array on the other hand, was adopted for VES data acquisition with maximum half-current electrode spread ($AB/2$) of 130.0 m.

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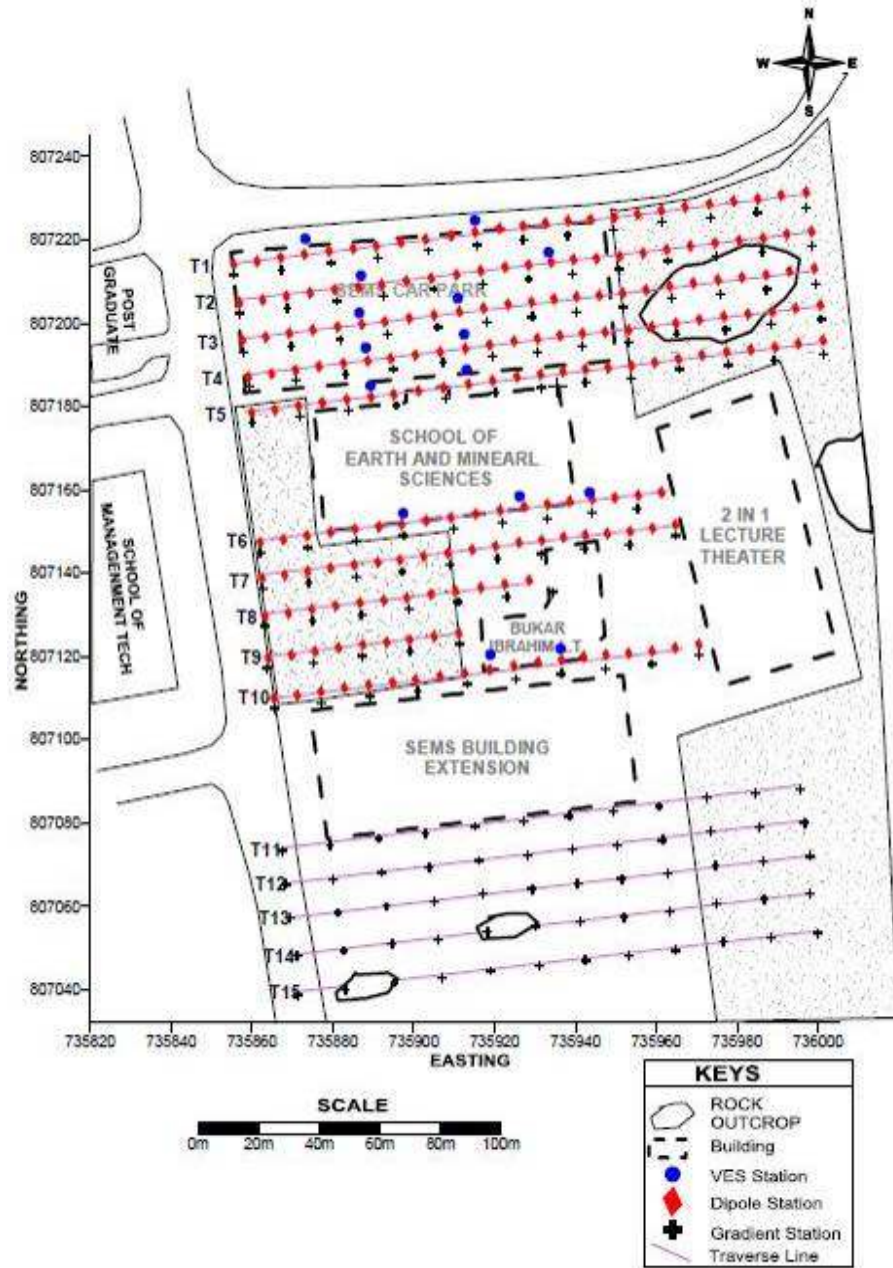


Fig. 4: Layout map of the study area showing geophysical data points

4.1. Data processing and inversion

The Gradient array data are presented as apparent resistivity map (Figure 5). The Dipole-Dipole data are presented as field and theoretical data pseudosections and 2-D resistivity structure sections using the DIPRO™ Software (Fig. 6). Typical Schlumberger vertical electrical sounding (VES) curves are presented in Figure 7. The field curves were curve-matched using Schlumberger master curves to determine geoelectric parameters (layer resistivity and thickness) of the delineated layers. The geoelectric parameters from the interpreted curves were then used as the initial models for computer iteration using Win Resist™ to obtain model geoelectric parameters for the delineated layers.

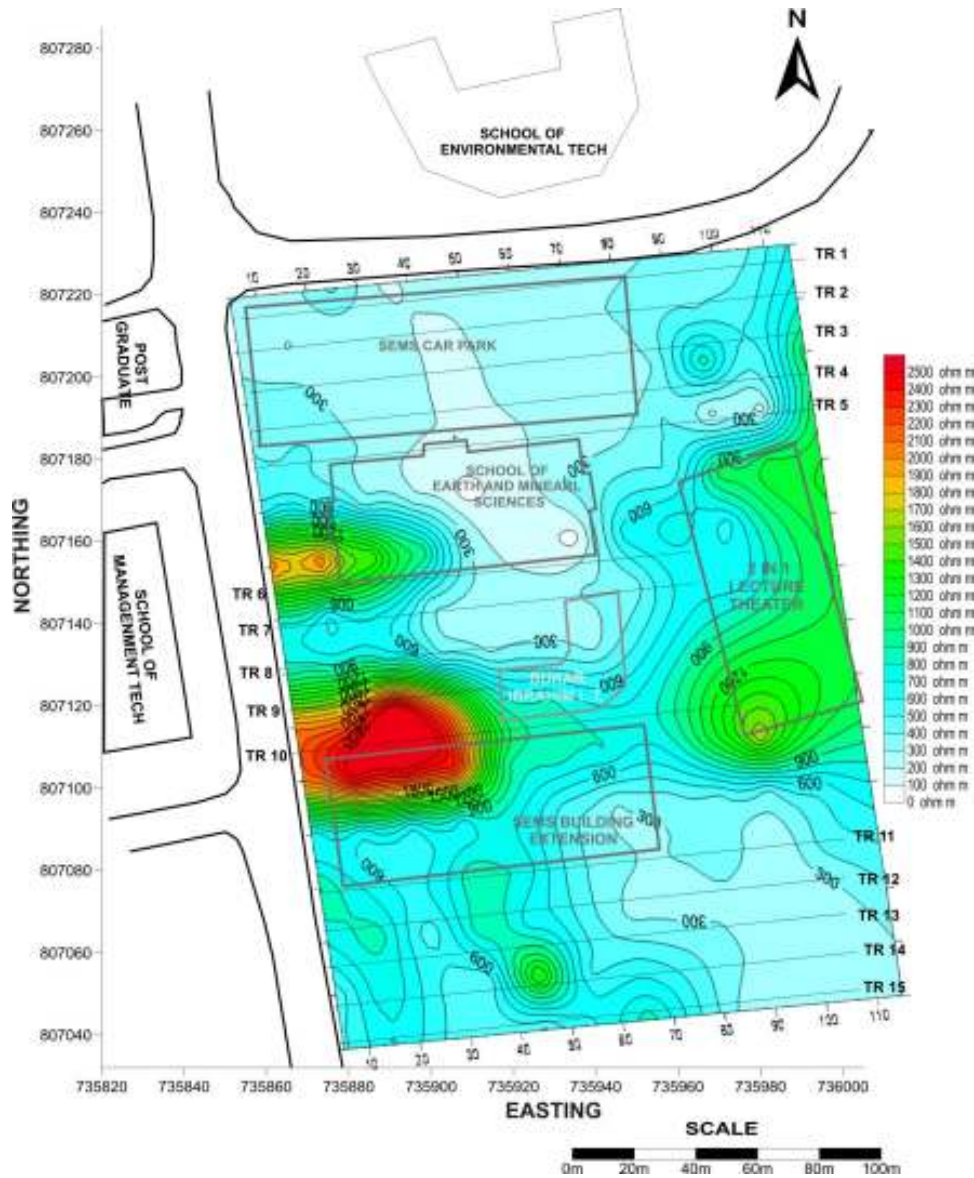


Fig. 5: The Gradient Array subsurface resistivity map of School of Earth and Mineral Science, Federal University of Technology, Akure Nigeria

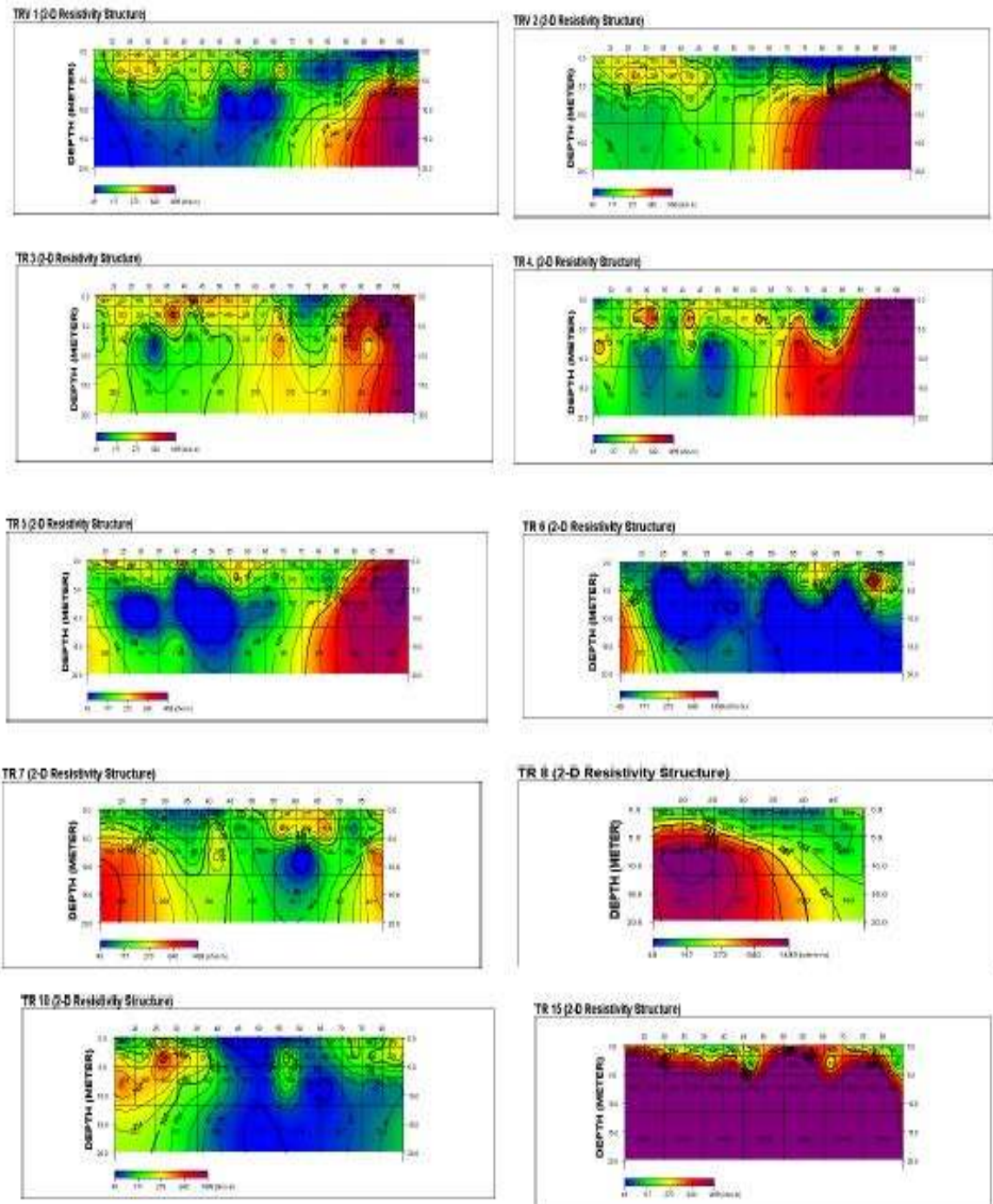


Fig. 6: The 2-D Resistivity structure sections obtained from the Dipole-Dipole data

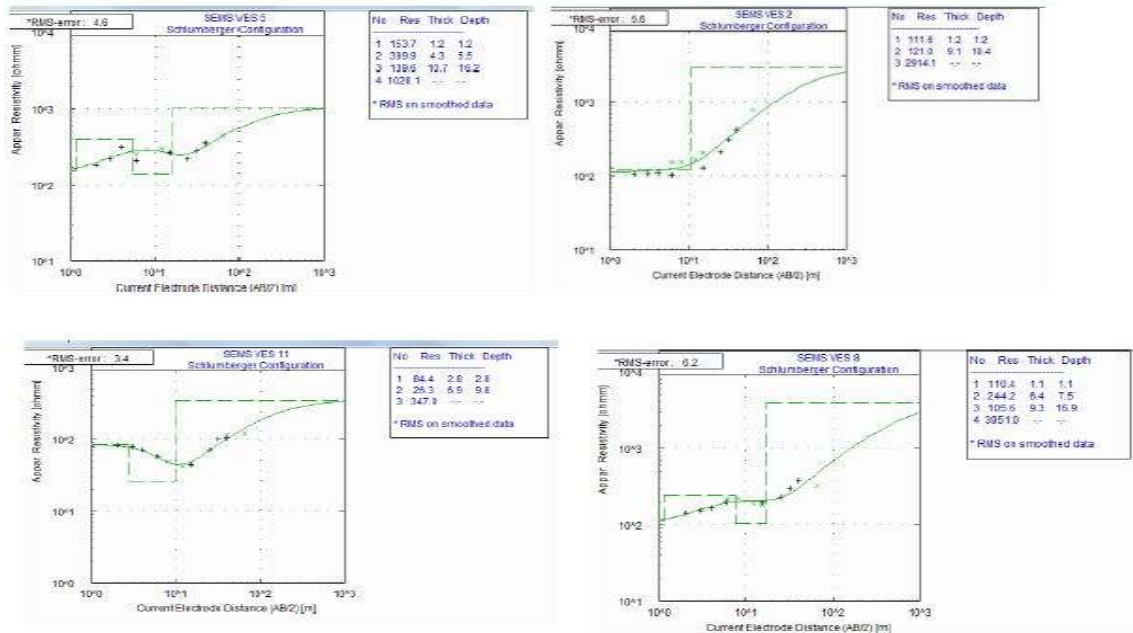


Fig. 7: Typical vertical electrical sounding curves generated along the Traverses

5. RESULTS AND DISCUSSION

5.1. Gradient Array

The subsurface lateral and vertical hydro-geoelectric characterization of the study area were facilitated using the results of the interpreted gradient and dipole-dipole arrays respectively. The gradient array measurements results output in form of terrain resistivity map is presented in Figure 5. The subsurface resistivity values obtained from the study vary widely across the traverses (100 – 2500 Ω -m) typifying subsurface structural complexity associated with the Basement Complex rocks environment. Low resistivity values (100 – 300 Ω -m) characterize the northern flank around traverses 1 – 4 (SEMS Car Park). Low resistivity values also characterize traverses 5 - 8 but with intrusion of some resistive features (diagnostic of shallow bedrock) on the eastern and western flanks. A significantly high resistivity features were obtained at the western flank around traverses 9 and 10 indicating the occurrence of shallow bedrock in the environment. There also exists a bedrock depression typified by low resistivity values at the central zone of the area. The southern flank is characterized by low resistivity values cutting across traverses 11 – 15. The low resistivity zones may be of some hydrogeologic significance.

A 3-dimensional model of gradient array resistivity vector is presented in Figure 6. The resistivity vector diagram presents pseudo bedrock relief within the environment. The map presumably indicates that the northern flank of the area presents a fairly favorable hydrogeologic setting.

The dipole-dipole array results present low resistivity values at shallow depth (5 m) on the northwestern fringe of the area of study around Traverses 1 (see Fig. 6). The northern flank presents resistivity distribution contrast suggesting some lithologic contrasts. The mapped lithological features could possibly be a fault zone filled with some conductive materials such as clay or weathered materials. Some features characterized by low resistivity values were delineated on traverses 2, 3 and 4. However, high resistivity features characterizing same traverses suggest the presence of shallow

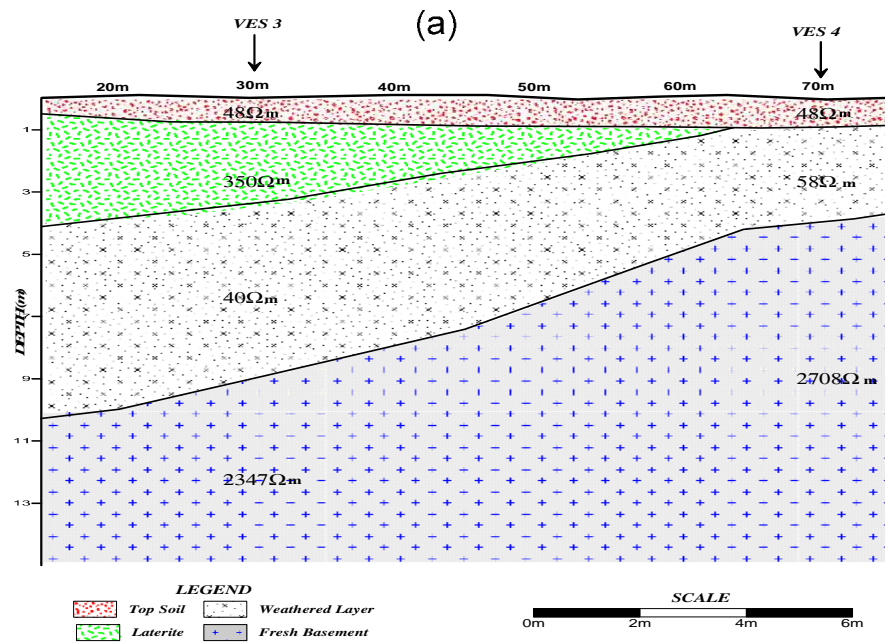
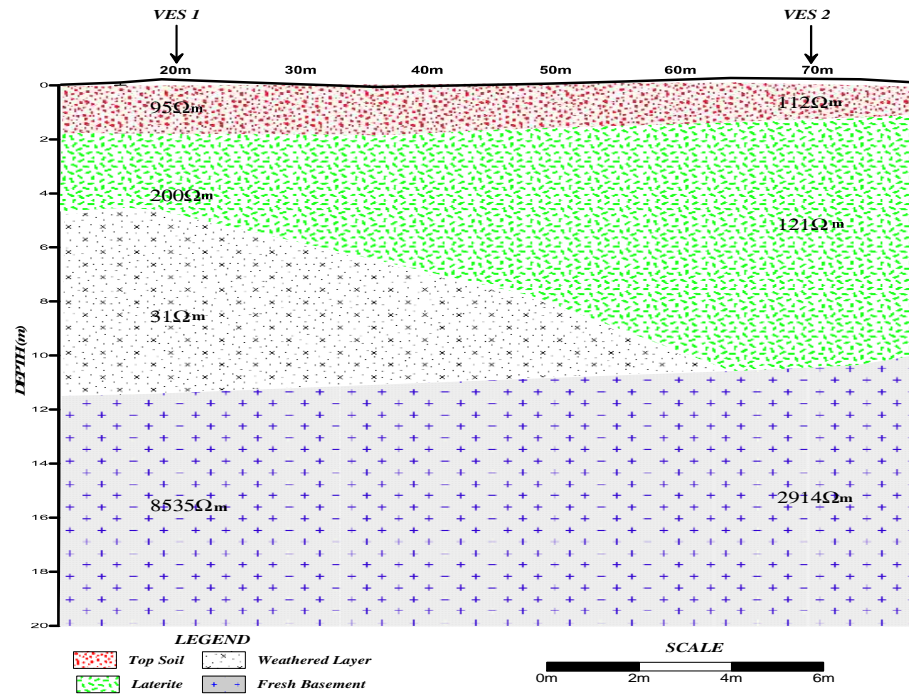
fresh crystalline rock. Low resistivity features to depth of 15 m were also delineated on traverses 6 and 7 with increase in thickness westwards. Such fairly thick feature may be of hydrogeologic significance (see Fig. 6). However, high resistivity values characterized traverses 8 and 9 indicating the presence of shallow crystalline rock. A presumably saturated zone (low resistivity characteristics) was encountered on Traverse 10. Lateral resistivity imaging of the study area was attained via gradient array whereas lateral and vertical imaging of subsurface features was attained by dipole-dipole array. While the results of the gradient array has enabled qualitative hydrogeophysical evaluation of the area the results of dipole-dipole has enabled semi-quantitative hydrogeophysical evaluation of the area. Both gradient and dipole-dipole arrays indicate existence of fairly favourable hydro-geoelectric setting on the north central precinct of the study area. The combined results of both arrays informed the locations of the Schlumberger - Vertical Electrical Sounding points in the positive environment.

5.2. The Vertical Electrical Sounding results

Quantitative hydrogeophysical evaluation is achievable using the Schlumberger - Vertical Electrical Sounding technique. Using the results of both gradient and dipole-dipole arrays as guide, thirteen (13) VES points were occupied in the area. The VES field data are presented as field curves (see Fig. 7). Geoelectric parameters (layer resistivity and thickness values) were derived from the interpreted field curves and the summary is presented in Table 1. The curve types obtained from the area varies from 3-layer A and H to predominant 4-layer KH. With the determined geoelectric parameter results, the geoelectric sections imaging the lithological sequence in the form of the delineated geoelectric layers were generated (see Fig. 8 a - c).

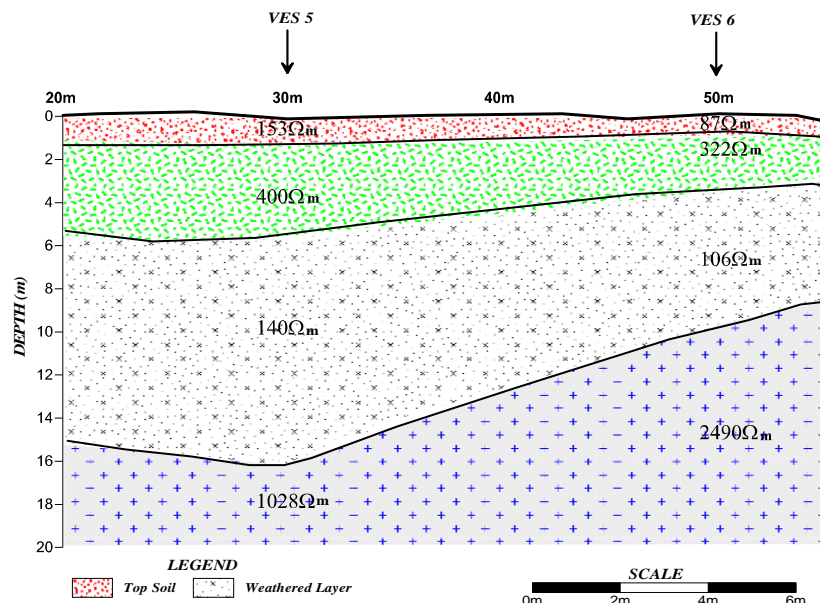
Table 1. Summary of geoelectric parameters obtained from VES data interpretation

VES No.	Resistivity ($\Omega\text{-m}$) $\rho_1/\rho_2/...../\rho_n$	Depths (m) $d_1/d_2/.../d_{n-1}$	Curve Type
1	95/200/31/8535	1.8/4.8/11.4	KH
2	112/121/2914	1.2/10.4	A
3	48/350/40/2347	0.6/4.0/10.0	K H
4	48/58/2708	0.9/4.0	A
5	153/400/140/1028	1.2/5.5/16.2	KH
6	87/322/106/2490	0.8/3.4/9.7	KH
7	76/592/109/296	0.6/1.6/6.7	KH
8	110/244/106/3951	1.1/7.5/16.9	KH
9	65/373/19/300	0.6/1.9/5.4	KH
10	91/197/35/671	0.8/3.7/10.2	KH
11	84/26/347	2.8/9.8	H
12	53/35/1199	2.2/8.7	H
13	45/77/15/118	0.7/2.8/5.3	KH

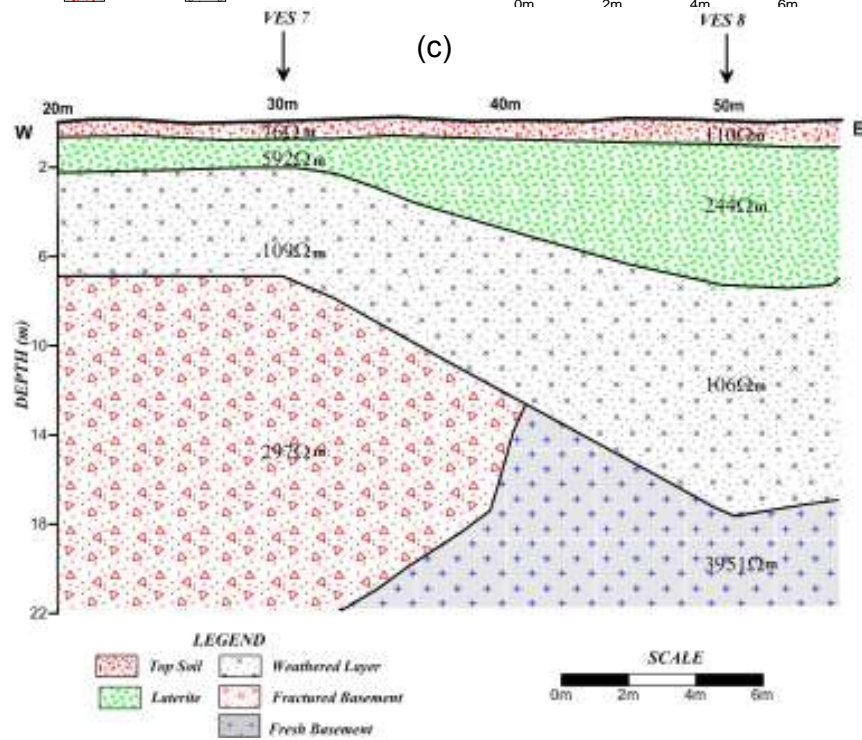


(b)

Fig. 8a: Geoelectric sections of (a) Traverse 1 and (b) Traverse 2

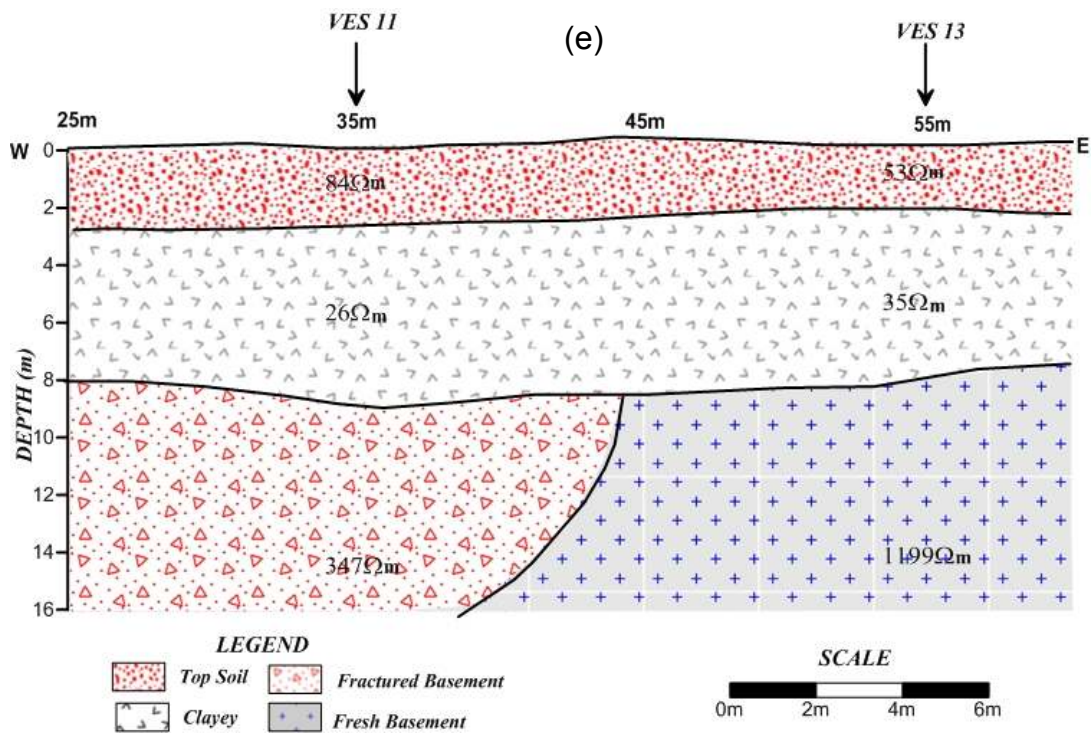
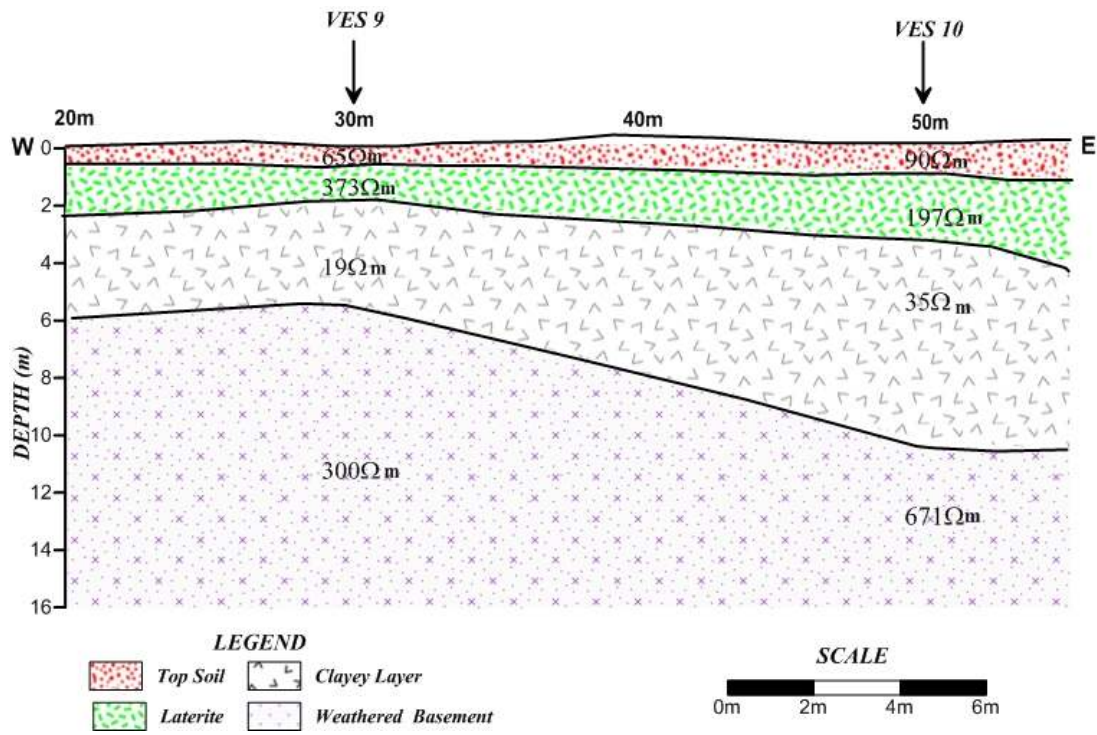


(c)



(d)

Fig. 8b: Geoelectric sections of (c) Traverse 3 and (d) Traverse 4



(f)

Fig. 8c: Geoelectric sections of (e) Traverse 5 and (f) Traverse 6

5.3. Groundwater Potential Evaluation

In order to enhance hydro-geoelectric characterization of the area, the results of the gradient, dipole-dipole and Schlumberger soundings are integrated. However, the Schlumberger-VES results were utilized for the generation of geoelectric sections that enabled easy identification of the subsurface lithological sequence boundaries. The concept for the use of the Schlumberger - VES output has been established in the study of [26]. The underlying subsurface lithological layers delineated in the area include the topsoil, lateritic substratum, weathered layer, fractured basement and fresh basement. These geoelectric layers are laterally continuous within the limit of the traverses though with varying thickness values. It is worth mentioning that the most appropriate approach of calibrating as well as establishing accurate interpretation of the delineated geoelectric layers is via exploring borehole lithological information (Lenky et al.[27], Utom et al.[28]; Oborie and Udom [29] 2014, Aizebeokhai and Oyeyemi [17]). The boreholes information often provides control on the lithologic contact delineation and consequently the subsurface stratigraphy. However, due to non-availability of borehole information in the study area, the lithological sequence underlying each VES location were interpreted adopting guides from previous works (Omosuyi et al.[30]; Omosuyi et al.[31]; Ofomola et al.[32]) for the generation of Figures 8a – c.

Interpretation of the geoelectric sounding curves shows that overburden column thicknesses within the SEMS area of the university campus vary between 5.6 m and 10.4 m. The overburden materials are therefore very thin and essentially constitute shallow aquifer units at all the VES locations. Arising from the geoelectric characteristics presented by the results of this survey, groundwater potential is of poor ranking at VES 4, VES 9 and VES 13 while it is of low ranking at VES 1, VES 2, VES 3, VES 5, VES 6, VES 8, VES 10, VES 11 and VES 12. The delineated topsoil (vegetative matters) presents thickness and resistivity values in the range of 0.6 to 1.8 m and 48 to 112 Ω m respectively. For the lateritic substratum, the resistivity values vary from 121 to 350 Ω m with higher thickness values on the eastern flank. The weathered layer that is presumably water bearing is clayey due to its low resistivity characteristics (31 – 58 Ω m). Marginally thick weathered materials (8.7 – 16.9 m) delineated beneath VES 1, VES 2, VES 3, VES 5, VES 6, VES 8, VES 10, VES 11 and VES 12 can plausibly support hand-dug well or shallow motorized borehole for abstracting some quantity of groundwater. However, fractured bedrock was delineated beneath VES 7 on Traverse 4 (northern car park area) that can apparently sustain fairly deep water abstraction motorized borehole with fairly adequate groundwater yield.

6. CONCLUSION

A hydrogeophysical characterization of a typical Crystalline Basement Complex environment has been carried out via combined use of different geoelectrical arrays. The study has established the disappointing hydrogeologic characteristics prevalent within the vicinity of the School of Earth and Mineral Science of Federal University of Technology, Akure, Nigeria. However shallow aquifer units have been identified in the area which can be developed for some groundwater exploitation with the fairly favourable hydrogeological point identified at VES 7 providing some relief. Despite the high cost of implementing integrated multiple geoelectrical arrays in hydrogeophysical investigation the outcome may serve as compensation especially in cases where properties have been developed in a similar ubiquitous shallow bedrock terrain.

ACKNOWLEDGEMENTS

The authors greatly acknowledge the assistance provided by the undergraduate students of 2012/2013 academic session and technologists of the Department of Applied Geophysics, Federal University of Technology, Akure during the fieldwork.

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