Combined use of different geoelectrical arrays for hydrogeophysical characterization of a Crystalline Basement Complex environment

ABSTRACT

The effectiveness of using multiple geoelectrical arrays for subsurface hydrogeophysical imaging has been evaluated in this study. The integrated geoelectrical arrays survey was staged on a typical hard rock terrain located in FUTA campus, south western, Nigeria. Geophysical data were acquired on the established fifteen (15) traverses in the area using three (3) electrode configurations namely: the gradient, the dipole – dipole and the Schlumberger. With the application of Surfer, Win – resist and DIPRO-Win geophysical software, the acquired geophysical data were processed to determine geoelectrical parameters (resistivity and thickness). Lateral resistivity distribution map and 2D resistivity structure pseudo – sections results produced from the gradient - dipole – dipole array aerial profiling survey imaged the existence of potential aquifers zones in the area. The mapped potential aquifers zones were further evaluated with Schlumberger – vertical electrical sounding array technique to produce geoelectrical sections which imaged the area subsurface lithological sequence and their hydrological implications. Based on the produced geoelectric sections imaging results, typical weathered layer and fractured basement characterized with resistivity values in the range of 31 Ωm to 300 Ωm and 297 Ωm to 347 Ωm, respectively across the traverses for feasible groundwater resources development in the study area were delineated. Results from the study has established a new approach of maximizing the relevance of geoelectrical resistivity imaging technique in hydrological study.

Key words: hydrogeophysical, electrode configurations, resistivity, lithological, geoelectrical and hard rock

1. INTRODUCTION

Application of geophysical methods to hydrogeological problems has gained more ground in environmental decision making studies such as hydrogeophysics, geotechnical etc Rubin and and Hubbard [1]. To mention few, the established geophysical methods widely explored in environmental studies include seismic refraction (Sundadararajian et al. [2]), magnetic method Sultan and Santos([3]) , very low frequency electromagnetic (VLF) (Sharma and Barawal[3]), electromagnetic method ([4]; Ehinola et al.[5]; Amadi and Nurudeen [6]), seismic reflection (Gruber and Rieger [7]), transient electromagnetic sounding (Barsukov et al.[8] ; Meju et al. [9]) and the direct-current (*DC*) electrical resistivity method(geoelectrical) (Rubin and Hubbard [9]; [10]; Jupp and Vozoff [11]). Among these various methods of geophysics, geoelectrical method has been noted for its efficiency in solving hidden layers problems in numbers of areas including hydrological, environmental, engineering and mineral prospecting. The attractiveness of geoelectrical prospecting technique in these aforementioned domains was because of its non-invasive nature, cost effectiveness, fast data acquisition and ability to map both geological layers as well as determining the nature and composition of unseen subsurface formation (Fitterman et al.[12]; Hinnell et al.[13]). Moreover, in the field of hydrogeophysics where characterization of aquifer properties for the purpose of optimal exploration of groundwater resources, the geoelectrical prospecting technique has been widely explored(Loke et al.[14] 2013;[15]; Margiotta et al.[16]). However, it should be noted that for efficient deploying of this geoelectrical method in environmental studies, various numbers of electrode configurations including Wenner, Schlumberger, dipole–dipole, pole–dipole and pole–pole arrays are commonly use. The gradient electrode configuration on the other hand which is a non-conventional electrode configuration has been found more unique in resistivity survey for solving environmental problems Aizebeokhai and Oyeyemi [17]. The choice of any of these electrode configurations depends largely on the objective of the survey, depth of investigation, horizontal data coverage, signal strength, the targets of interest, the local geology, and the sensitivity of the array to vertical and/or lateral variations in the subsurface resistivity surveys ([18]; Loke and Barker [19]). In most hydrological studies, each of these electrode configurations are often being used individually not minding their limitations in terms of time consuming and labour intensive during data acquisition which are expected to be looked into at the designed stage for any environmental field work survey.

In brief, considering the non-conventional array (the gradient), its output of subsurface resistivity images having attributes of good resolution which is essential for accuracy in interpretation and characterization of subsurface geologic features has enhanced environmental decision making process (Aizebeokhai and Oyeyemi [17]). This was because, the gradient array field layout often gives room for acquiring appropriate data density required for quality and good subsurface resistivity image resolution when the inverse models of the manually collected resistivity data is processed. The other conventional arrays equally have differs uniqueness associated with them in terms of data acquisition and image resolution output. It can be inferred from the above that these aforementioned electrode configurations have differs unique attributes peculiar to their uses in environmental studies ([18]; Loke and Barker [19]). Exploring their potential attributes in complimentary form can enhance their environmental decision output imaging. Very few geoelectrical investigation for environmental studies have considered exploring the use of both conventional and non-conventional arrays in complementary studies.

The present study is working on the hydrogeophysical characterization in a Crystalline Basement Complex environment via a combined use of Schlumberger, dipole–dipole and gradient arrays to conduct resistivity survey. The resistivity investigation was conducted with a view of combining the results of a rarely used gradient arrays with the results of those of conventional Schlumberger and dipole–dipole arrays with the view of characterizing the subsurface features and delineation of an area underlying aquifer units. The approach is illustrated using a case study in a typical Crystalline Basement Complex terrain southwestern, Nigeria. The study results is expected to locate and prediction of prolific aquifer units in the study area.

2. THE ARRAYS AND THE UNIQUE ATTRIBUTES

In order to achieve the objectives of this study, three (3) array types including Schlumberger, dipole–dipole and gradient were studied. The arrays have different geometric factors which often determined their operational functionality for a specific resistivity survey task. Fig. 1 presents the layout of these 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" denoted the distance between P_1P_2 , whereas X represented 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. Moreover, the "n "and "a" in Figure1 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 P_1-P_2 potential pair, respectively. The position and location of both the current and the potential electrodes and their separating factors often determined the probing depth and resolution of the delineated subsurface features in all the electrode configuration of choice. But then, the gradient array have higher probing depth compare to both Schlumberger and dipole–dipole. This is probably because the pattern of field layout arrangement of gradient array allows large current electrode separation compare to the minimum electrode spacing "a" peculiar to both Schlumberger and dipole–dipole arrays (Aizebeokhai and Oyeyemi, 2014).

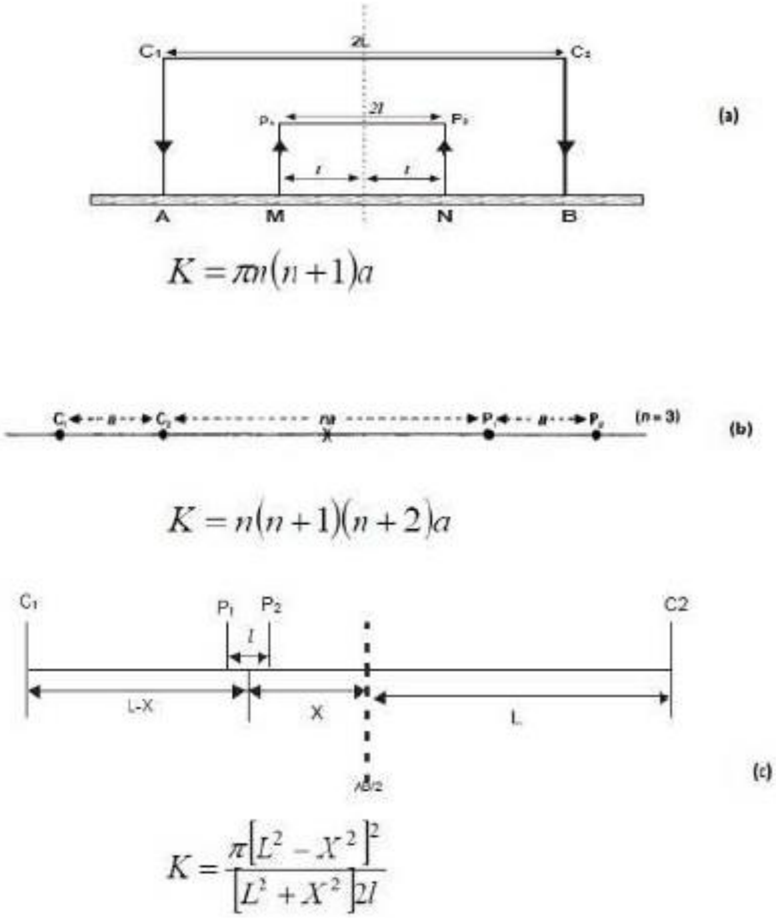


Fig. 1: The electrode configurations used for data measurement where (a): The Schlumberger, (b) The dipole–dipole, (c) : The gradient and K: The geometric factor

3. GEOLOGICAL SETTINGS AND SITE DESCRIPTION

The area investigated (School of Earth and Mineral Sciences (SEMS)) is located within the Federal University of Tech, Akure, in the north-western side of the Campus Southwestern Nigeria (Fig. 2). The University campus is situated on the northwestern flank of Akure town and on the southern flank of Ibadan-Akure-Benin Federal highway. The university which occupies an area of about 5 km^2 is situated within latitude 7° 16'N and 7° 18'N and longitude 5° 07'E and 5° 09'E. The area is situated on a gently undulating terrain with elevation between 350 m above mean sea level on the southeastern flank and 390 m at the north central area of the campus. The area lies in the tropical rain forest with mean annual rainfall of about 1300 mm. the area annual mean temperature is 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 basement complex of southwestern Nigeria [20] underlie the study area. The lithological units include granites, gneisses, quartzites and charnockite. Cardinally, pavement outcrops of granites, gneiss and quartzites occur in several locations, mostly in the northwestern and central parts of the study area. The area is cut in various places by quartzo feldsparthic veins and bands which give them their foliation ??? (Fig. 3).

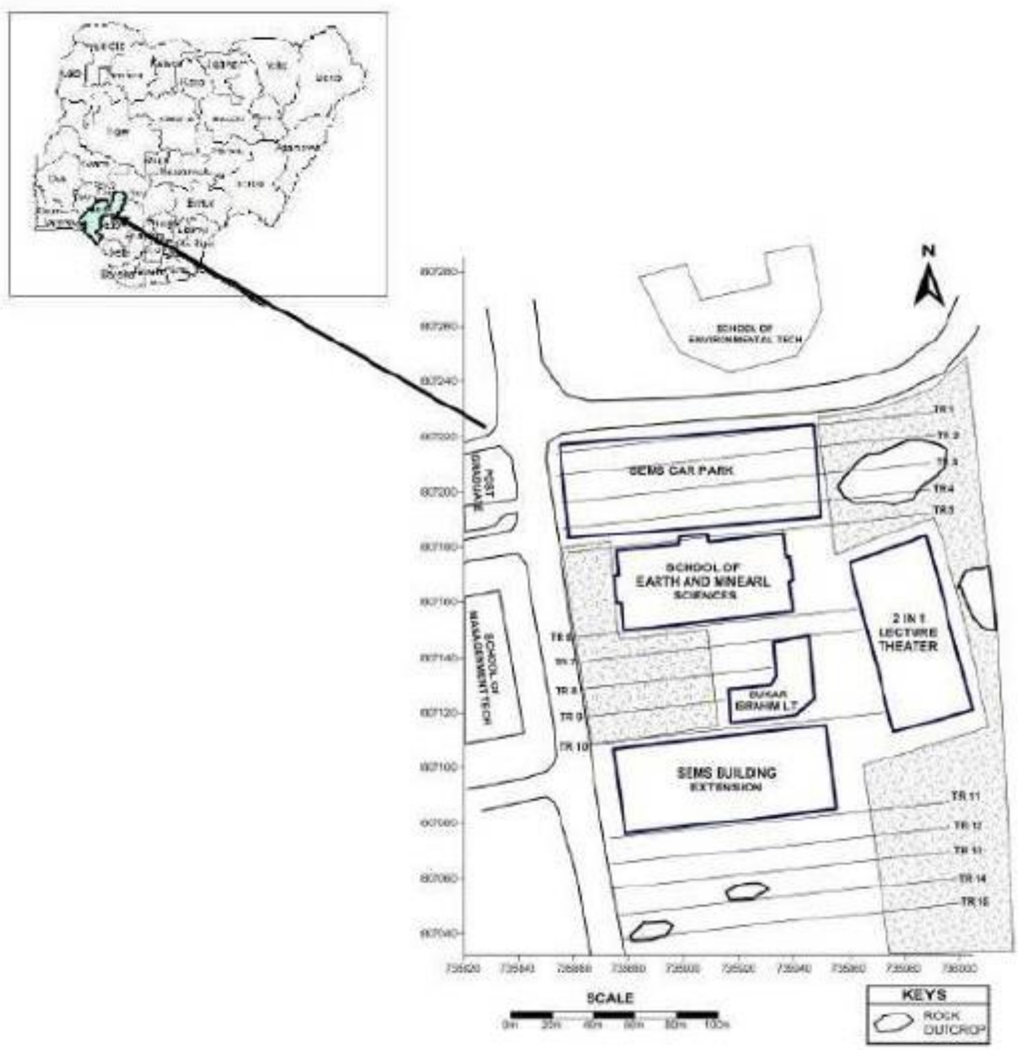


Fig. 2: The investigated area layout map with inset map of Nigeria

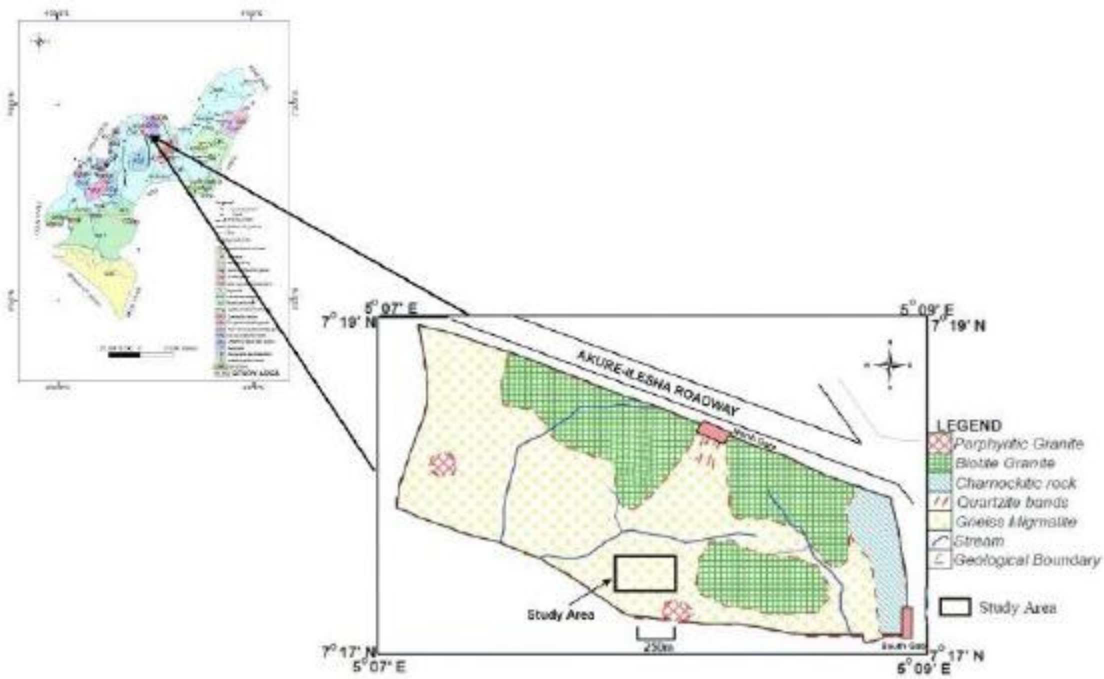


Fig.3: Geological map of the study area showing the inset geological map of Ondo state (After [21])

4. DATA ACQUISITION AND FIELD PROCEDURES

The geoelectrical resistivity surveys were conducted using Schlumberger, dipole–dipole and gradient arrays (electrode configurations). The data were manually collected along fifteen traverses using ABEM Terrameter (SAS 1000/4000 series). Apparent resistivity was measured during the survey. For resistivity profiling measurements both gradient and dipole-dipole arrays were used along the established traverses (see Fig 4). Whereas, the Schlumberger array was used for VESs data acquisition considering the interpreted results from the former arrays (gradient and dipole-dipole) measurement on the same traverses. 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) are progressively moved within the current electrodes for each data measurement at an interval of the minimum of 10 m electrode spacing along each of the traverses. The forward movement of the potential electrode was in a frog-jump type of movement. With this gradient array measurement on the traverses, there are some possible located distances from the point of measurement to the middle of C_1 and C_2 (X) such as 115m, 105, 95m, etc. The data acquisition with dipole-dipole array, entails the use of more than four electrodes with maximum electrode spacing of 5 m while the number of movement of electrode (n) is six (6). However, during the dipole-dipole array measurement, numbers of traverse (11 - 14) were skipped due to insufficient electrode spread. The Schlumberger array on the other hand, was used for conducting VESs along each of the traverses with maximum half-current electrode spread (AB/2) of 130.0 m. This electrode spread was considered sufficient for the effective depth of investigation anticipated.

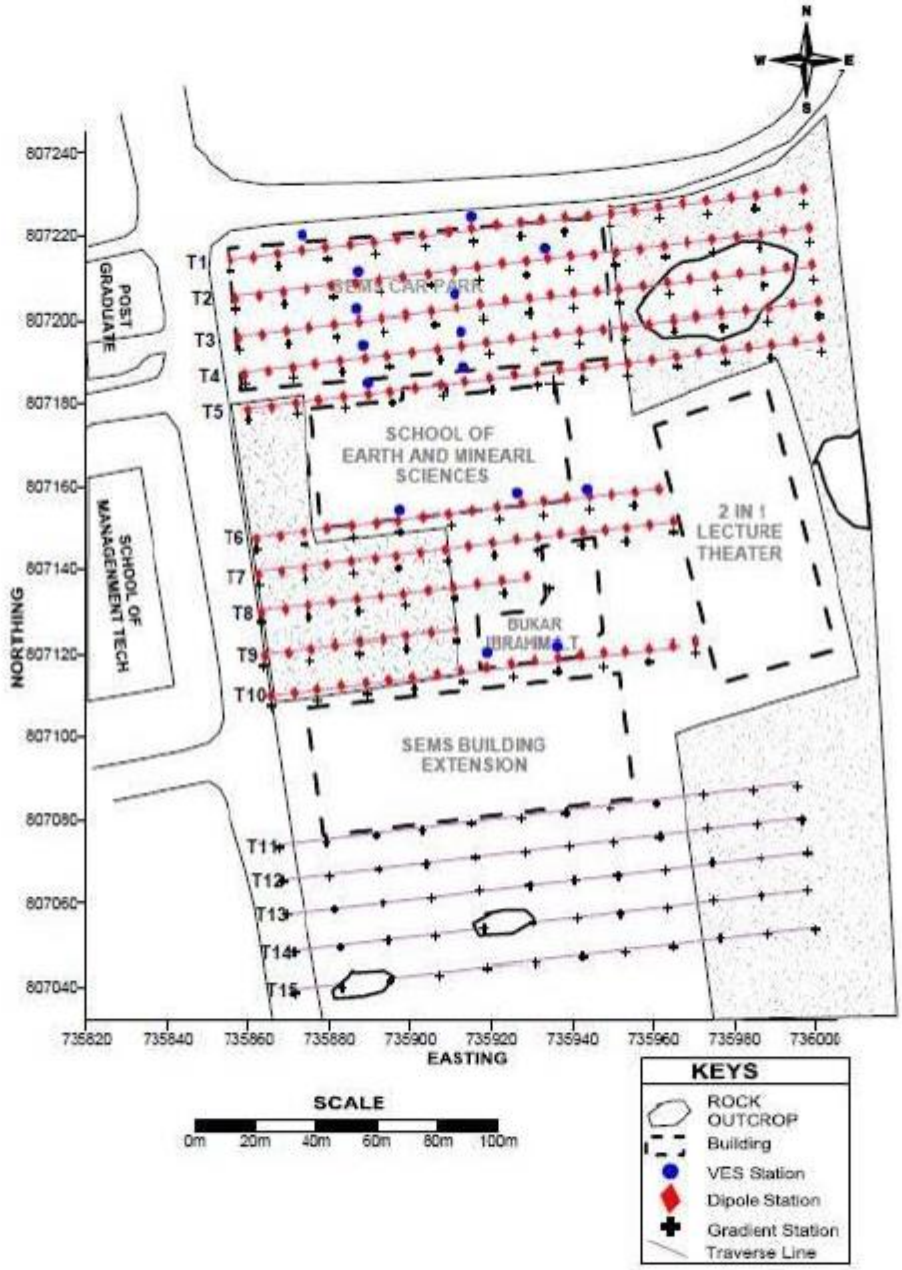


Fig. 4 : The investigated site map showing the traverse lines and the VES data point

4.1. Data processing and inversion

The data measured with the gradient array using the resistivity meter often display the apparent resistivity parameter which is varied across the traverses. The apparent resistivity data were processed with the used of Surfer 9.0 software to generate lateral resistivity distribution map considering the observed coordinated at each measurement data station along the established traverses (See Fig.5). For the dipole-dipole array measurement, the data acquired are multiplied with the geometric factor to give varying apparent resistivity values. Using the DIPRO Software, the acquired dipole-dipole array subsurface resistivity data are input, processed to generate the field and theoretical pseudo section together with the 2-D Resistivity structure pseudo section. The processed 2D resistivity structure pseudo sections inversion images are presented in Fig. 6. The acquire data with the Schlumberger-vertical electrical soundings (VESs) were processed by plotting the measured apparent resistivity values against half-current electrode spacing (AB/2) on bi-logarithmic graph sheets to generate VESs field curve (See Fig.7). The field curves were curve-matched with Schlumberger master curves to determine geoelectric parameters (layer resistivity and thickness) of the delineated layers. It should be noted that the authors' experience on the geology and hydrology of the studied area, were used to construct a preliminary model that would fairly fit the observed field resistivity curves for the purpose of meaningful subsurface aquifer delineation. The estimated geo-electric parameters from the interpreted curves were then used as the initial models for computer iteration on a Win-Resist program to obtain model geoelectric parameters for the delineated layers.

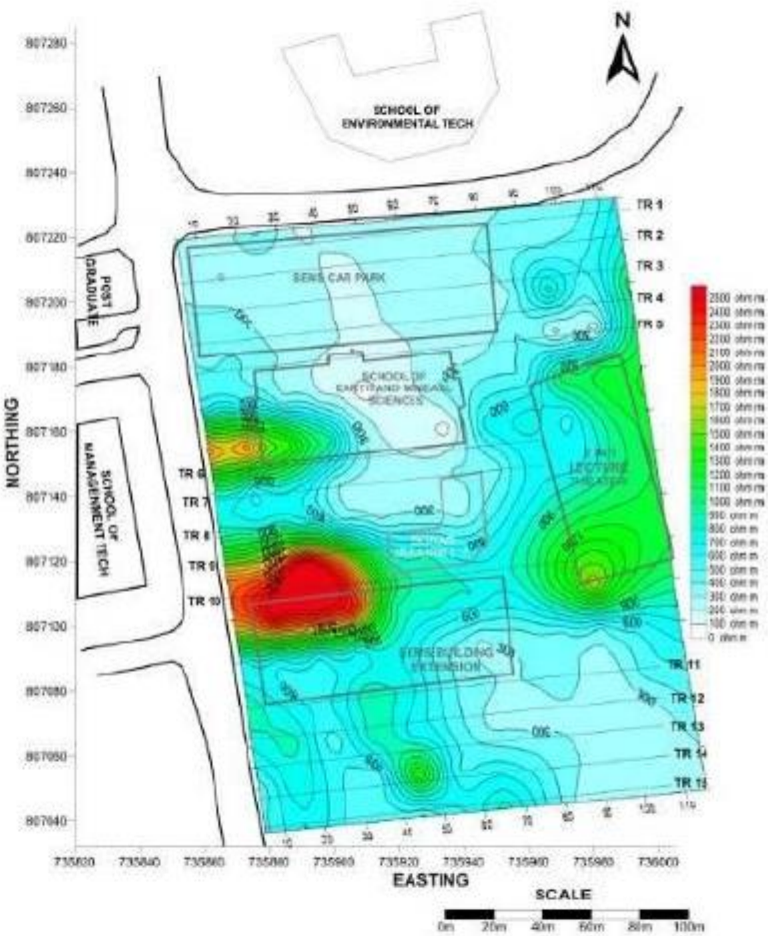


Fig. 5: The subsurface resistivity distribution map based on gradient array data

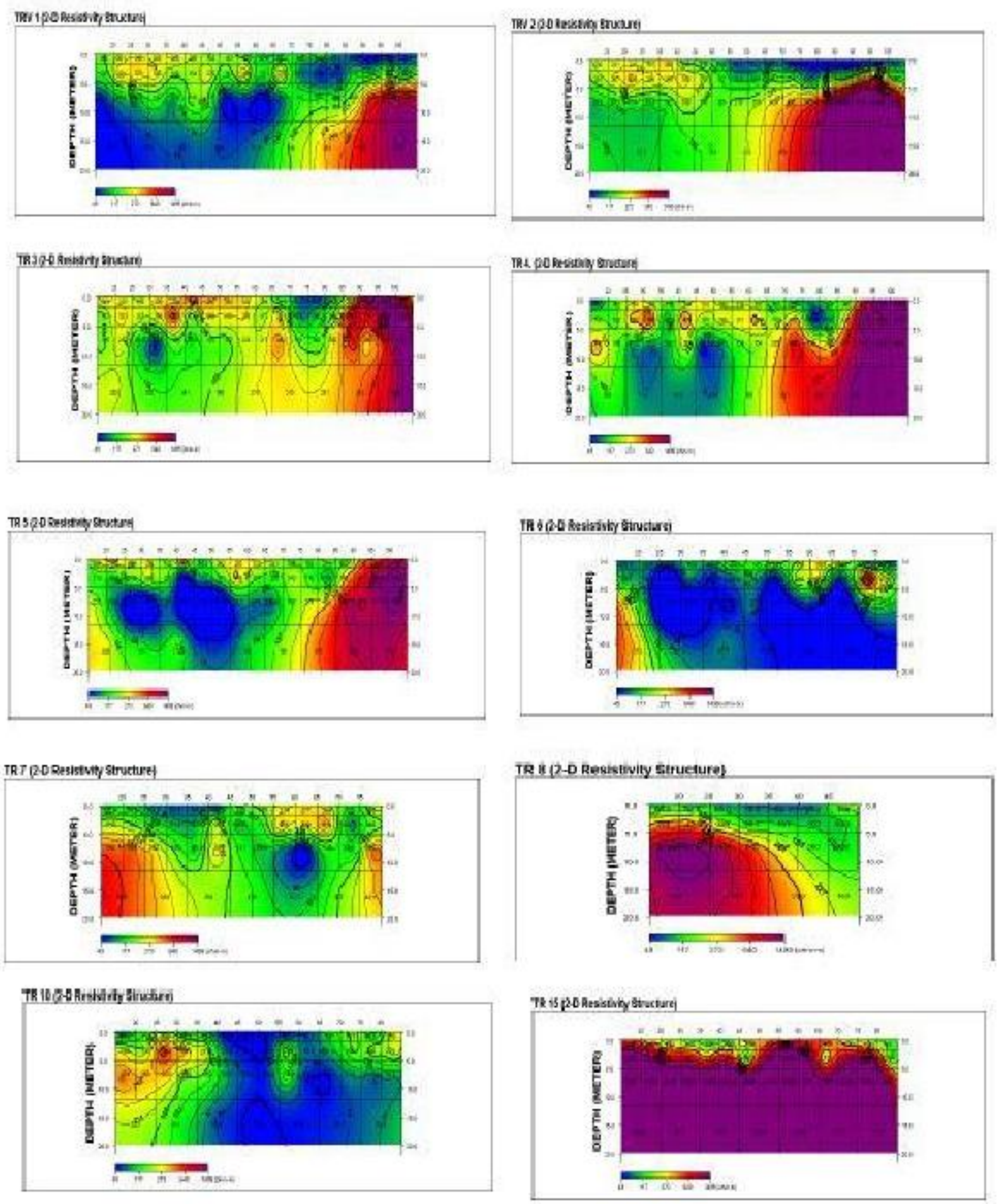
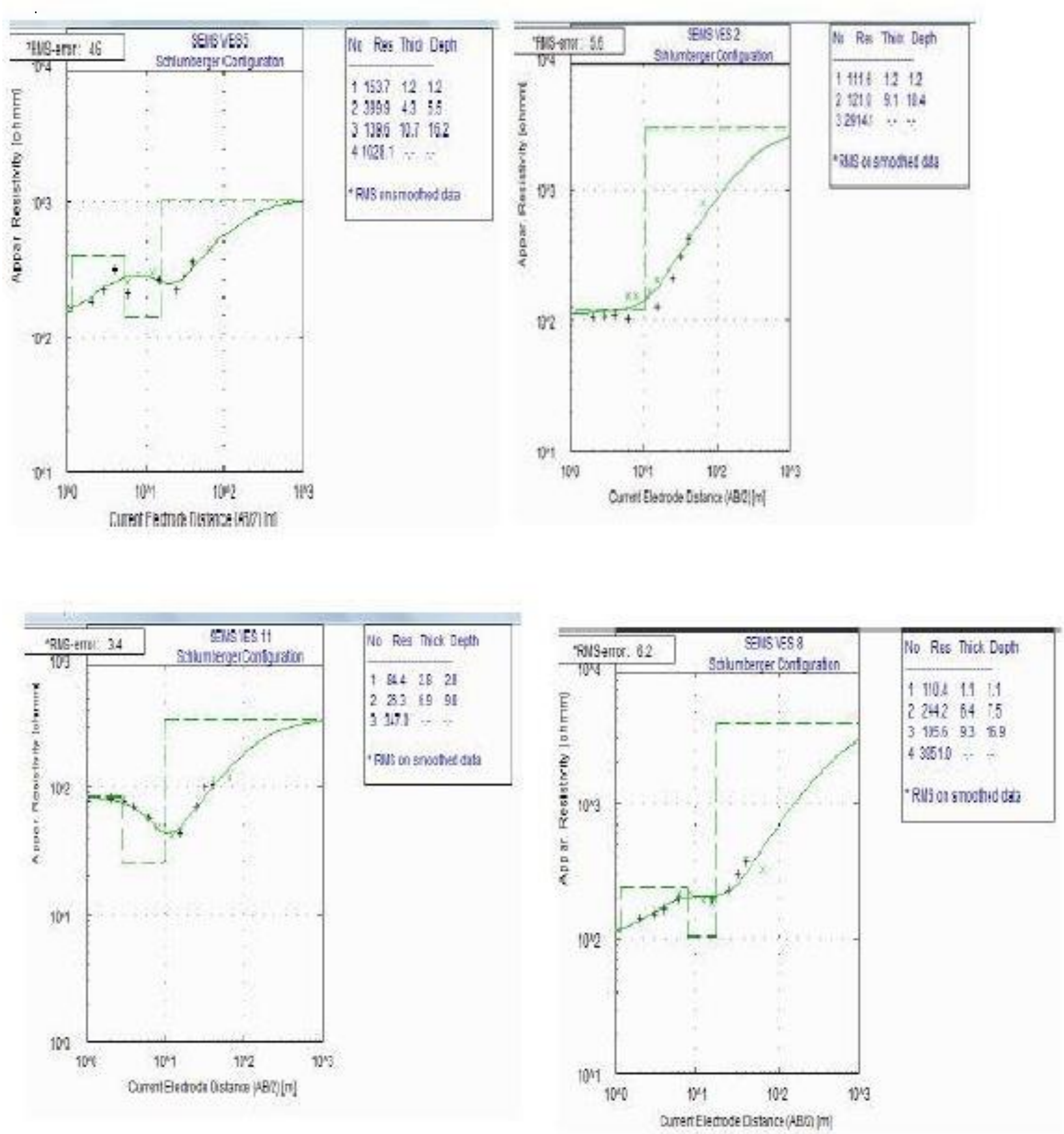


Fig. 6: The 2D Resistivity structure pseudo sections obtained from the Dipole-Dipole data

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



5. RESULTS AND DISCUSSION

5.1. The hydrological profiling imaging results

The 1^{st} and 2_{nd} dimensions mapping of the area subsurface characterization have been imaged from the results of the interpreted gradient and dipole-dipole array data. The results of the gradient array presented in Fig. 5, revealed the lateral resistivity distribution information about the area underlying subsurface formation to a probing depth of about 40 m. The area subsurface resistivity values are observed varied widely across the traverses typifying subsurface structural anomaly. The low resistivity subsurface features were seeing mostly associated with data measures across Traverses 1-4 (SEMS car park). The extension of low resistivity values also cut across Traverses 5 – 8 but with the evidence of some intercepted moderate resistivity structures both at the eastern and western flank of the area. A significant high resistivity anomaly features were noticed at the western edge of Traverses 9 – 10 indicating nearness of bedrock to the surface in the area. There also exist an evidence of depression zone characterized with moderate to low resistivity anomaly nearly at the center of the traverses. Considering the northern region, the suspected subsurface features delineated are also characterized with moderate to low resistivity values cutting across traverses 11 – 15. The mapped moderate to low resistivity anomaly zones are noted for possible hydrogeologic significance. For the dipole – dipole array imaging results, between the distances of 5 m – 20 m at a depth below 5 m in Traverses 1, a low subsurface resistivity formation is observed (see Fig. 6). Similarly, at distances between 50 m and 65 m, there appears a lithological features contrast in between separate bodies characterized with low resistivity values. The mapped lithological features could possibly be a fault zone filled with low conductive materials such as clay or weathered materials. Some notable locations that exhibit low resistivity values along Traverses 2, 3 and 4 were also mapped. Such notable locations occurred at different distances 10 m and 70 m on Traverse 3, but such similar zones were particularly more prominent in Traverse 4. Though, there are occurrence of a high resistivity values formation at some distances along these traverses could typified presence of fresh crystalline rock, a typical characteristic of the area geology. Traverse 6 also imaged low resistivity body to a depth of 15 m at distances between 23 m and 43 m, whereas there occur also such a low resistivity body but at a deeper depth at a distance between 49 m and 72 m which could be possibly be a water bearing formation of hydrogeologic significant (see Fig. 6). There observed in Traverse 7, a continuation of this low anomalous resistivity body (a typical saturated zone) visible in Traverse 6 at a distance between 67 m and 85 m. The observed evenly-distributed resistivity values subsurface features with high values imaged along Traverses 8 and 9 could also indicate the presence of crystalline rock which is the typical characteristics of the area geology. A possible saturated zone (low resistivity formation) at a greater depth located at distances between 40 m and 53 m along Traverse 10 was also imaged. Based on the above discussion, imaging the area subsurface features via gradient array resistivity profiling survey represent the 1st dimension approach, whereas the lateral and vertical imaging of those subsurface features giving by dipole – dipole array resistivity approach is the 2nd dimension approach. The results of the 1st dimension approach (see Fig. 5) establishing possible existence of aquifer units in the area were further confirmed with the 2nd dimension approach investigation. The combined results of both 1st dimension and 2$_{nd}$ dimension approaches informed the locations of the Schlumberger - Vertical Electrical Sounding investigation in the area.

5.2. The Schlumberger - vertical electrical sounding result

This research 3rd dimension of imaging the area subsurface characterization was via exploring the Schlumberger - vertical electrical sounding array technique. With the informed results of both 1st dimension and 2nd dimension approaches discussed above, the following points/locations along the established traverses as depicted in Fig. 4 were peaked. The located point distances along Traverse 1 are at 10 m and 50m. for Traverse 2, the locations are at 30m and 70m, Traverse 3: 30m and 50m, Traverse 4: 30m and 50m, Traverse 5: 30m and 50m, Traverse 6: 35m, 55m and 70m, Traverse 10, 50m and 65m. The obtained VESs data at these location points were processed and presented in the forms of field curve types (see Fig. 7). Determined from the interpreted field curves types are the geoelectrical parameters such as resistivity and thickness. Table 1, presented the summary of the estimated geo-electrical parameters and the curve types notations obtained in the area. Table 1 results revealed that the curve types that characterized the area varies from simple to complex curves types such as A, H and KH types, among which the KH is more prominent in the area. The A – type curve is characterized by an increase in resistivity from top soil to the bedrock while the intermediate layer in the H – type is commonly water saturated and is often characterized with low resistivity high porosity as well as high transmissivity/permeability i.e weathered layer (Olayinka and Olorunfemi, [22] and [23] cited in Ndatuwong and Yadav [24]). Whereas, for the KH – type, by qualitative interpretation, the possible weathered layer often occurs at greater depth and have impervious layer overlain it. Confined aquifer and high degree of possible secondary porosity formation development are often associated with the KH curve type (Mogaji et al. [25]). By the qualitative interpretation of the above – mentioned curve types, the excellent insight to map possible aquifer units for onward hydrogeological characterization of the area can be inferred. Hence, with the determined geoelectrical parameter results, the geoelectric sections imaging the lithological sequence in the form of the delineated geoelectric layers were established (see Fig. 8 a - c).

Table 1. Summary of geo-electrical parameters obtained from VESs data

Depths (m) $d_1/d_2/\ldots/d_{n-1}$	Resistivity (Ωm) $\rho_1/\rho_2/\ldots\rho_n$	Curve types
1.8/4.8/11.4	95/200/31/8535	KH
1.2/10.4	112/121/2914	A
0.6/4.0/10.0	48/350/40/2347	K H
0.9/4.0	48/58/2708	A
1.2/5.5/16.2	153/400/140/1028	KH
0.8/3.4/9.7	87/322/106/2490	KH
0.6/1.6/6.7	76/592/109/296	KH
1.1/7.5/16.9	110/244/106/3951	KH
0.6/1.9/5.4	65/373/19/300	KH
0.8/3.7/10.2	91/197/35/671	KH
2.8/9.8	84/26/347	H
2.2/8.7	53/35/1199	H
-	-	
-	-	
0.7/2.8/5.3	45/77/15/118	KH

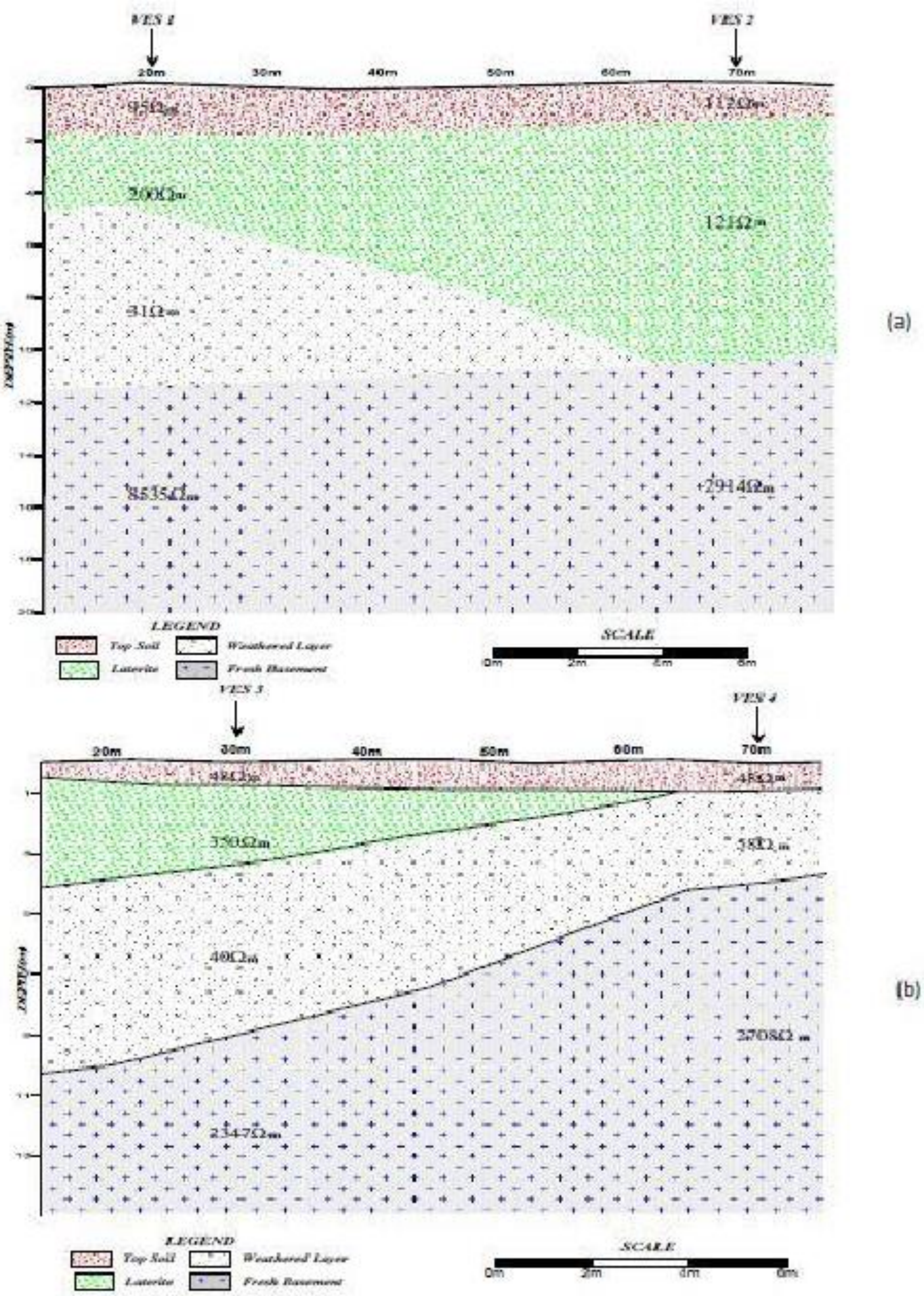


Fig. 8a: Geoelectric sections constructed from the processed VESs data:

(a) along Traverse 1 and (b) Traverse 2

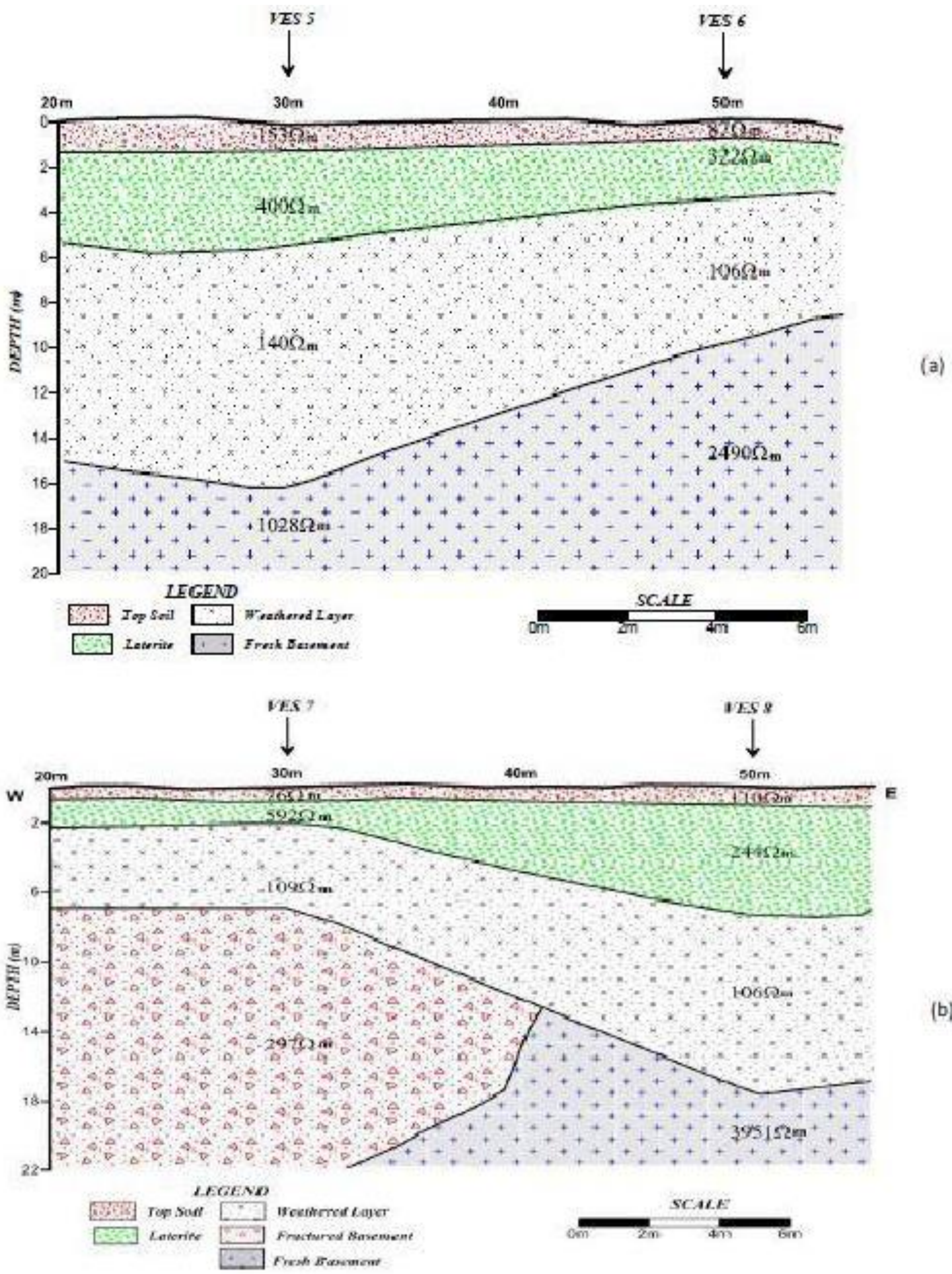


Fig. 8b: Geoelectric sections constructed from the processed VESs data:

(a) along Traverse 3 and (b) Traverse 4

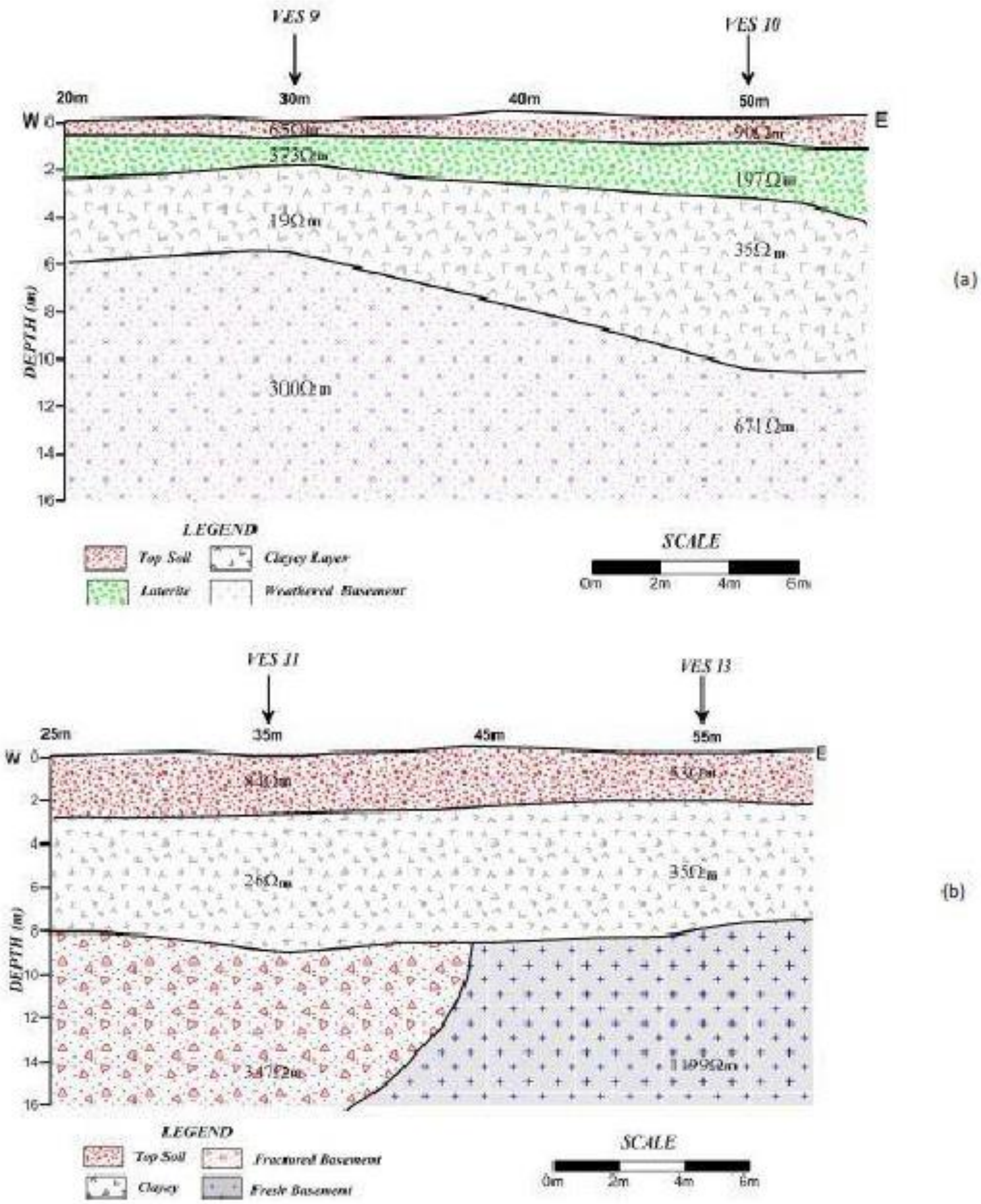


Fig. 8c: Geoelectric sections constructed from the processed VESs data:

(a) along Traverse 5 and (b) Traverse 6

5.3. The subsurface characterization and the hydrogeological implication

In order to effectively characterize the area subsurface hydrogeologic features, the results of the 1st, 2nd and 3rd dimensional approaches were integrated. However, for easier demarcation of the area subsurface lithological sequence boundary, the results of the Schlumberger - vertical electrical sounding images i.e the geoelectric sections output produced based was explored in the area. The concept for the use of the Schlumberger - vertical electrical sounding output has been established in the study of [26]. Referring to the produced geoelectric sections across the established traverses as shown in Fig. 8a - c, the underlain subsurface lithological layers delineated in the area includes top soil, laterite, weathered layer, fractured basement and fresh basement. These geoelectric layers are laterally continuous within the limit of the traverses though with varying thickness. 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]). According to these researchers, the boreholes information often provide control on the boundary demarcation of an area subsurface stratigraphy. However, due to unavailability of such borehole information, the lithological sequence underlying each VESs location were precisely interpreted considering the established information available on the previously published about the area (Omosuyi et al.[30]; Omosuyi et al.[31]; Ofomola et al.[32]). Besides, the authors' experience on the local geology and hydrology of the studied area were also considered in the VESs data interpretation. These information greatly served a guide in the construction of those geoelectric sections for the investigated subsurface sequence (Figs. 8a - c). Moreover, the accuracy of the model geoelectrical parameters (layer thicknesses and resistivity) were also established considering the root mean square error (RMS error) values which are generally < 10 % across all the model field curves (see Fig. 7). For the geoelectric sections along Traverses 1 and 2 (Fig. 8 a), VESs Nos 1 to 4 were connected where VESs 1 & 2 and VESs 3&4 fell along, respectively. The delineated top soil layers (unconsolidated formation) for the traverses is having thickness and resistivity values in the range of 0.6 m to 1.8 m and 48 Ωm to 112 Ωm, respectively. Though the top soil thickness in Traverse 2 is thinner and more saturated in contrast to Traverse 1 underlain top soil layer. For the lateritic layer mapped along the aforementioned traverses, the resistivity values is varied from 121 Ωm to 350 Ωm, however, this lateritic layer is thicker toward VES – 2 in the eastern direction (see Traverse 1), whereas the thickness is more to the VES – 3 in the western direction (see Traverse 2). On these traverses, the mapped weathered layer i.e water bearing formation, is clayey in nature as characterized by their resistivity values in the range 31 Ωm to 58 Ωm. Moreover, a depression weathered layer formation with 6 m thickness mapped delineated beneath VES – 3 can reliably support hand dug well for exploring groundwater resources in the area in Travers 2 compared to the weathered layer underlain VES -1 in Traverse 1 which is on the water divergent zone (the ridge). In the case of the subsurface imaging sections produced along Traverses 3 & 4, the VESs Nos 5 to 8 were located (see Fig. 8b). The subsurface lithological characterization imaged in Traverses 3 & 4 is similar to the lithological sequences discussed in Traverses 1 and 2 with exception of the evidence of fractured basement delineated beneath VES – 7 in Traverse 4. The delineated weathered layer underlain VESs 5 & 7 as well as the mapped fractured basement probed to a depth of 22 m at VES – 7 are characterized with resistivities values of 140 Ωm, 106 Ωm and 297 Ωm, respectively. With these ranges of resistivities values, the delineated weathered layers and the fractured basement are typical water bearing saturated formation (possible aquifer units). The weathered layer and the fractured basement delineated are good clue of existence of water bearing formation units that are essential for groundwater potential evaluation in the area. Along Traverses 5 & 6, there occur also are prospective water bearing formations (aquifer units) such as the depression zone weathered layer and the fractured basement underlain VESs Nos 10 &11. The evidence of relative thick column formation of resistivity values in the range 19 Ωm, to 36 Ωm typifying clayey formation overlaying the delineated aquifer units across Traverses 5 & 6 confined the aquifer units delineated (Mogaji et al.[25; Bala and Ike [33]; Olorunfemi and Fasuyi [34]). For feasible groundwater resources development in the area, those mapped water bearing units (the aquifer units) underlain VESs 10 & 11 can be explored.

6. CONCLUSION

A hydrogeophysical characterization of a typical Crystalline Basement Complex environment has been carried out via combined use of different geoelectrical arrays. Among the used arrays is the gradient array, a non-conventional array, others includes the dipole – dipole and the Schlumberger arrays are the conventional arrays. With the geoelectrical method, a three dimensional approaches (1st, 2nd and 3rd) of evaluating the area underlying hydrogeologic features was experimented. Both gradient and the dipole – dipole arrays were engaged for the areal/lateral profiling survey which were complemented with the Schlumberger – vertical electrical sounding array investigation. From the acquired gradient and the dipole – dipole arrays data, the area subsurface imaging was evaluated based on the produced lateral resistivity distribution map and 2D – resistivity structure pseudo-sections from these arrays, respectively. The subsurface imaging results from both gradient and the dipole – dipole arrays survey were further evaluated via Schlumberger-vertical electrical sounding array technique. Geoelectric parameters (layer resistivity and thickness) were obtained from the

Schlumberger-vertical electrical sounding conducted along the established traverses in the area. The results from vertical electrical sounding (VES) are presented in the forms of field curve types and geoelectrical cross sections, which gives the information about the area lithological changes and subsurface aquifer units characterization. It was established from the above results that there exist numbers of aquifer units underlain the study area which can be developed for groundwater resources exploitation. Hence, the study has established the efficacy of integrating multiple geoelectrical arrays in hydrogeophysical investigation compared to one array survey.

REFERENCES

1. Rubin, Y., Hubbard, S. S. eds Hydrogeophysics, water science and technology library, v. 50: Dordrecht, The Netherlands, Springer, 2006:523 p.
2. Sundararajan, N., Srinivas, Y., Chary, M. N., Nandakunmar, G., Chary, A .H. Delineation of structures favourable to groundwater occurrence employing seismic refraction method. A case study from Tiruvuru, Krishna district, Andhra Pradesh. Proceedings of Indian Academic Science (Earth Planet. Sci.), 113, (3), 2004:259-267.
3. Sharma, S. P., Barawal, V.C. Delineation of groundwater –bearingfracures zone in hardrock area integrating very low frequency electromagnetic and resistivity data. Journal of Applied Geophysics2005: 57, 155-166.
4. Meju, M.A., Denton, P., Fenning, P. Surface NMR sounding and inversion to detect groundwater in key aquifers in England; comparison with VES-TEM methods. Journal of Applied Geophysics 2002: 50, 95-111.
5. Ehinola, O.A., Opoola, A.O., Adesokan, H.A. Emperical analysis of electromagnetic profiles for groundwater prospecting in rural areas of Ibadan Sounthwestern Nigeria. Hydrogeology Journal, 2006: 14, 613-624. doi:10.1007/s10040-005-0468-z.
6. Amadi, U.M.P., Nuruden, S.I.. Electromagnetic survey and the search for groundwater in the crystalline basement complex of Nigeria. Journal of Mining and Geology.1990: 26, 45-53.
7. Gruba, W., Rieger, R. High resolution seismic reflection –constraints and pitfall in groundwater exploration. RMZ-Materials Geoenvironment. 2003: 50, (1), 133-136.
8. Barsukov, P.O., Fainberg, E.B., Khabensky, E.O. Joint inversion of TEM and DC soundings Paper presented at the 10th European Meeting of Environmental and Engineering Geophysics, Utrecht, the Netherlands. 2004.
9. Rubin, Y., Hubbard, S. Hydrogeophysics.Springer, Dordrecht, the Netherlands.2005: 523 pp.
10. Koefoed. O. Geosounding principles 1: resistivity sounding measurements. Elsevier Science Publishing Co, Amsterdam. 1979.
11. Jupp, D.L.B., Vozoff., K. Joint inversion of geophysical data. Geophys J Roy Astron Soc.1975: 42, 977–991.
12. Fitterman, D.V., Deszcz-Pan, M., Prinos, S.T. Helicopter electromagnetic survey of the Model Land Area, Southeastern Miami-Dade County, Florida: *U.S. Geological Survey Open-File Report* 2012: 1176, 77 p.
13. Hinnell, A.C., Ferre, T.P.A., Vrugt, J.A., Huisman, J.A., Moysey, S., Rings, J., Kowalsky, M.B. Improved extraction of hydrologic information from geophysical data through coupled hydrogeophysical inversion. *Water Resources Research,* 2010: *doi*:10.1029/2008WR007060.
14. Loke, M.H., Chambers, J.E., Rucker, D.F., Kuras, O., Wilkinson, P.B.Recent developments in the direct-current geoelectrical imaging method, *Journal of Applied Geophysics* doi: 10.1016/j.jappgeo.2013.02.017.
15. Slater, L. Near surface electrical characterization of hydraulic conductivity: from petrophysical properties to aquifer geometries - a review. *Surveys in Geophysics'*2007:*28,* 169-197.
16. Margiotta, S., Mazzone, F., Negri, S., Calora, M. The role of integrated high resolution stratigraphic and geophysic surveys for groundwater modelingLaboratorio di modellistica idrogeofisica e stratigrafica per i rischi naturali, Dipartimento di Scienza dei Materiali, Universit `a del Salento, via per Monteroni, Lecce 73100, Italy. 2008.
17. Aizebeokhai, A.P., Oyeyemi, K.D. The use of the multiple-gradient array for geoelectrical resistivity and induced polarization imaging. Journal of Applied Geophysics.2014: 364–376.
18. Aizebeokhai, A.P. 2D and 3D geoelectrical resistivity imaging: theory and field design.Sci. Res. Essays.2010: 5 (23), 3592–3605.

19. Loke, M.H., Barker, R.D. Practical techniques for 3D resistivity surveys and data inversion.Geophys. Prospect.1996b :44, 499–524.
20. Rahaman, M.A. Recent advances in the study of the Basement complex of Nigeria Precambrian Geology of Nigeria. A Publ. of Geological survey of Nigeria.1988. Pp.
21. Kareem, A.W., Ojo, J.S. A geophysical investigation of basement structure in Federal University of Technology Akure campus, A thesis submitted to Applied Geophysics department. SEMS. 1997.

22. Olayinka, A.I., Olorunfemi, M.O. Determination of geoelectric characteristics of Okene area and implication for a borehole sitting J.Min, Geo.1992: Pp: 403 – 414.
23. Jones, M.T. The weathered zone aquifers of the basement complex area of Africa. Q J Eng Geol. 1985: 27(2):63–69.
24. Ndatuwong, L.G., Yadav, G.S. Application of geo-electrical data to evaluate groundwater potential zone and assessment of overburden protective protective capacity in part of Sonebhadra district, Uttar Pradesh. Environ Earth Sci. 2014: DOI: 10.1007/s12665-014-3649-z most squares criterion, Geophysical prospecting, 53, (4), 463-480.
25. Mogaji, K.A., Olayanju, G.M.,Oladapo, M.I. Geophysical evaluation of rock type impact on aquifer characterization in the basement complex areas of Ondo State, Southwestern Nigeria: Geo-electric assessment and Geographic Information Systems (GIS) approach. International Journal of Water Resources and Environmental Engineering. 2011a: Vol. 3(4), pp. 77-86.
26. Shaaban, F.F. Vertical electrical soundings for groundwater investigation in northwestern Egypt: a case study in a coastal area. African Earth Sciences.2001: 33 (2001) 673–686 Publishing Co, Amsterdam.
27. Lenky, L,. Hamori, Z., Mihalffy, PInvestigating the hydrogeology of water – supply area using direct – current vertical electrical soundings. GEOPHYSICS. . 2005: VOL. 70, No 4.
28. Utom, A.U., Benard, I.O., Boniface, C.E.E., Nkechi, E. E., Harold, C.O. Estimation of subsurface hydrologicalparameters around Akwuke, Enugu, Nigeria using surface resistivity measurements. J. Geophys. Eng.2013: 10 (2013) 025016 (8pp).
29. Oborie, E., Udom, G.J. Determination of aquifer transmissivity using geoelectrical sounding and pumping test in pats of Bayelsa State, Nigeria. Journal of physical and Environmnetal Science Research. 2014:Vol. 2(2), pp. 32 – 40
30. Omosuyi, G.O., Ojo, J.S., Enikanselu, P.A. Geophysical investigation for groundwater around Obanla-Obakekere in Akure area within the Basement Complex of Southwestern Nigeria. *Journal of Mining and Geology.*2003.
31. Omosuyi, G.O., Adegoge, A.O., Adelusi, A.OInterpretation of Electromagnetic and Geoelectric Sounding Data for Groundwater Resources around Obanla-Obakekere, near Akure, Southwestern Nigeria. *The Pacific Journal of Science and Technology*. 2008: . Volume 9. Number 2. November 2008. Pp. 509 – 525.
32. Ofomola, M.O., Adiat, K. A .N., Olayanju, G.M., Ako, B.D. Integrated geophysical methods for post foundation studies, Obanla Staff Quarters of the University of Technology, Akure, Nigeria. Pac J Sci Technol. 2009: 10(2):93–111.

33. Bala, A.E., Ike, E.C. The aquifer of the crystalline basement rocks in Gusau area, northwestern Nigeria. J Min Geol. 2001 : 37(2):177–184.
34. Olorunfemi, M.O., Fasuyi, S.A. Aquifer types and the geoelectric/hydrogeologic characteristics of part of the central basement terrain of Nigeria (Niger State). *Journal of African Earth Sciences*.1993: *16*, 309-317. http://dx.doi.org/10.1016/0899-5362(93)90051-Q.