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INTEGRATED GEOPHYSICAL METHODS AND TECHNIQUES FOR SITING PRODUCTIVE BOREHOLES IN BASEMENT COMPLEX TERRAIN OF SOUTHWESTERN NIGERIA

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ABSTRACT

Electrical resistivity survey involving 2D Dipole-Dipole subsurface imaging and 1D Vertical Electrical Sounding (VES) and an integrated magnetic and electrical resistivity survey involving magnetic profiling and 1D VES/2D electrical imaging techniques were carried out at two sites underlain by grey gneiss and pegmatised schist, respectively, within the Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria. The surveys were carried out with a view to delineating the subsurface layers and determining the geoelectrical characteristics; identify geological structures such as faults, fractured, jointed and sheared basement zones that are favourable to groundwater accumulation and transmission and estimate hydrogeologically significant borehole drill depth in an area with previous experience of failed borehole drilling attempts. At the two sites (A&B) investigated, the 2D resistivity images identified suspected fractured basement zones as low resistivity vertical discontinuities within high resistivity fresh basement host rock. The magnetic profiles at site B displayed typical magnetic anomaly of a thick dyke (two magnetic lows with central high in low magnetic latitude) over each vertical resistivity discontinuity. The follow-up VES delineated maximum of five subsurface layers which include the topsoil/laterite, weathered layer, partly weathered/fresh basement, fractured basement and the fresh basement. The weathered/fractured basement constitutes the main aquifer unit with thicknesses varying from 17.7 - 125 m. Two boreholes, one per site, were drilled to 80 m at site A and 70 m at site B. Both boreholes encountered the predicted fractured basement zones and the borehole logs correlated well with the interpretation models of the drilled VES locations. The boreholes were very productive (yields of about 1.5 l/s and 2.2 l/s at sites A & B respectively). The study demonstrated the effectiveness of integrated geophysical methods and techniques in providing information on the subsurface sequence and the structural disposition required for a successful groundwater development through borehole drilling, in a borehole-failure-prone basement complex terrain.

Keywords: Integrated Geophysical Methods, Geophysical Techniques, Productive Borehole, Basement Complex Terrain.

INTRODUCTION

Groundwater occurs in the weathered basement and in jointed/fractured/sheared/faulted basement columns. The weathered basement aquifer is porous but usually of low permeability because of its clayey nature while the storage capacity could be significantly high due to relatively high porosity.The groundwater yielding capacity is limited with consequently low-moderate level groundwater potential rating (Olorunfemi and Fasuyi, 1993). The secondary porosities arising from joints/fractures/faults create significantly large storage capacity in fractured basement aquifers. The connectivity of these geological features enhances the groundwater yielding capacity of the fractured basement aquifers. Where both the weathered and fractured basement aquifers exist, the groundwater yield is high (Olorunfemi and Fasuyi, 1993).

Aquifers (weathered and fractured basement) in the basement complex environment are discontinuous and most times limited in lateral and depth extent. Abortive and productive boreholes could be drilled within the same premises as observed in Olorunfemi *et al*. (2005), when such abortive boreholes are not properly cited to exploit existing aquifers.

The electrical resistivity method involving 1D Vertical Electrical Sounding (VES) is commonly used to identify aquifers in basement complex environment (Ako and Olorunfemi, 1989; Olorunfemi and Okhue, 1992; Olayinka and Olorunfemi, 1992; Olorunfemi and Fasuyi, 1993; Ademilua and Olorunfemi, 2000; Bayode *et al*., 2006 and Bayowa *et al*., 2014). At times, the VES techniques is preceded by horizontal profiling or electromagnetic profiling as a reconnaissance technique to map areas with thick weathered layer (overburden) and or discontinuities created by faults and fractured zones while the VES is adopted as a confirmatory technique (Olorunniwo and Olorunfemi, 1987; Hazell *et al*., 1988; Hazell *et al*., 1992; Olorunfemi *et al*., 1995; Afolayan *et al*., 2004; Oloruunfemi *et al*., 2005 and Sharma and Baranwal, 2005 and Okafor and Mamah, 2012). The VES and the horizontal profiling techniques are 1D data gathering for measurement of variations in resistivity or electromagnetic response along vertical and horizontal directions respectively. The interpretation of such data gives 1D image of the subsurface. However, the weathered basement and the fractured basement columns have 2D/3D geometries which make 1D investigation inadequate to properly define the aquifer systems.

Recently, 2D resistivity data gathering involving Dipole-Dipole or Wenner or Pole-Dipole or combination of some arrays (Wenner-Schlumberger) has been introduced as reconnaissance technique in groundwater investigation in basement complex terrain (Chirindja *et al*., 2017; Gao *et al*., 2018 and Oyeyemi *et al*., 2018). 2D resistivity subsurface imaging or resistivity tomography measures resistivity variationsalong both lateral and vertical directions. Such 2D data can be inverted into real 2D subsurface images. Such images are subsequently used to constrain the location of VES stations to either probe a significantly thick weathered basement column or a suspected fractured/faulted zone which presents itself as a zone of discontinuity on the 2D images. When two of such 2D images are combined, a 3D image could emerge.

One of the most important requirements for the location of a productive borehole is that it must be sited at a place where groundwater flow is assisted by fractures or faults, that is, in areas where the basement is fractured or faulted or sheared. The magnetic method is effective in the delineation of such geological features when the fractured/faulted/sheared zone has contrast in magnetic susceptibility with respect to the host rock. This may explain the recent introduction of the magnetic method as a reconnaissance tool in groundwater investigation in the basement complex environment (e.g. Hasan *et al*., 2018).

In an attempt to reduce the risk of abortive boreholes in borehole-failure-prone basement complex environment, the electrical resistivity method involving 1D and 2D (resistivity) subsurface imaging is now being integrated with the magnetic method (Hasan *et al*., 2018).

The Obafemi Awolowo University in Ile-Ife, Osun State, Southwestern Nigeria, was established in 1962. The university with a population of 500 students in 1967 currently has staff and students population of over 30,000. The university is served by a mini dam - Opa Dam, whose optimum production capacity of 1-1.2 million gallons of treated water per day, is grossly inadequate to meet the current water requirements of the university community. This makes groundwater development an inevitable back up and alternative water supply scheme, for the university community. Several boreholes had been drilled, some of which were abortive. This paper presents results of integrated geophysical survey methods and techniques employed in siting productive boreholes within different geological units within the university campus.

DESCRIPTION OF THE STUDY ENVIRONMENT

Geographic Location, Geomorphology, Geology and Hydrogeology

The Obafemi Awolowo University (OAU) campus is located in Ile-Ife, Osun State, Southwestern Nigeria. It is situated within geographic co-ordinates of Northings 829000 – 836000 mN and Eastings 667000 –673000 mE (Minna Zone 31) (Fig. 1). The topography varies in height from about 200 m a.s.l. along the river valleys to a maximum of about 430 m a.s.l. on Hill 3. The campus is drained by the OpaRiver and its tributaries and the drainage pattern is dendritic (Fig.1).

The Precambrian Basement Complex rocks of Southwestern Nigeria underlie the OAU campus (Fig. 2). The major basement rocks include granite gneiss, grey gneiss and mica schist. The gneisses are intruded by dolerite dykes and veins of fine grained granite gneiss. Other minor rock types include quartz veins and pegmatite (Boesse, 1989). The basement rocks outcrop as granite gneiss hills in the northwestern part (Fig. 1) and low lying banded gneiss in the central south. In areas underlain by schist, the basement rock is generally concealed by variably thick overburden.

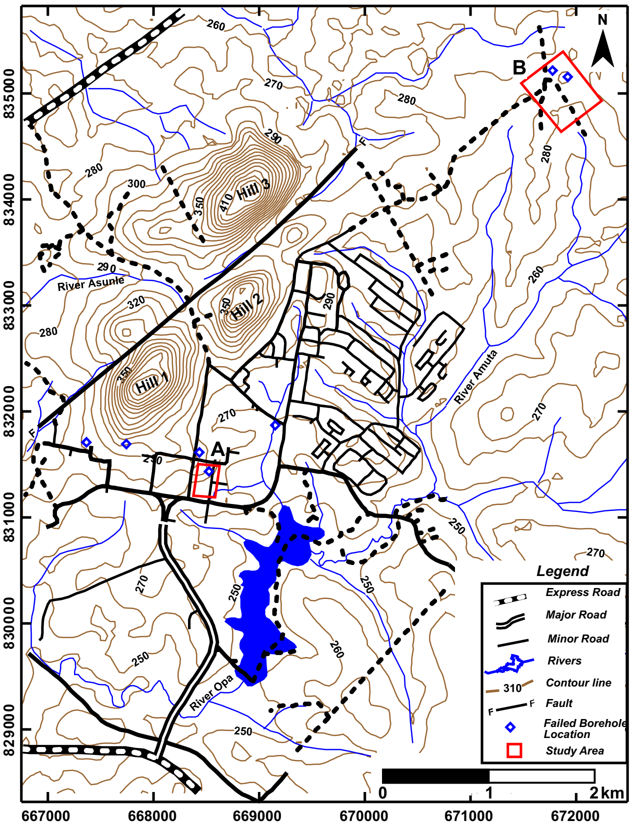

Fig. 1: Topographical Map of Obafemi Awolowo University Campus, Ile-Ife Showing the Study Areas

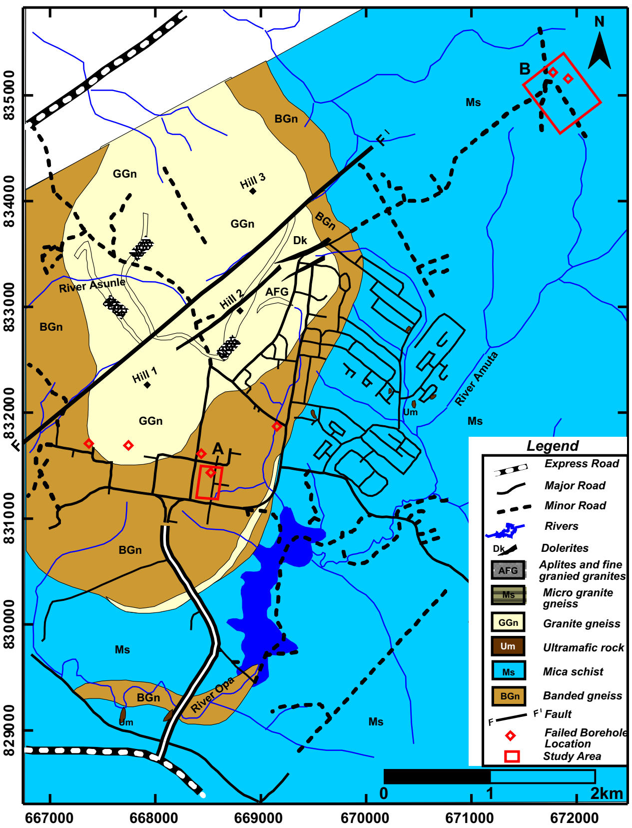

Fig. 2: Geological Map of Obafemi Awolowo University Campus, Ile-Ife Showing the Study Areas (modified after Boesse,1989)

The approximately NE-SW trending strike slip fault (F-F[1]) in the north constitutes the main geological structure (Fig. 2). Other structural elements include fractures, joints and folds.

Olorunfemi and Okhue (1992) delineated another strike slip fault F2 – F2[1] in the southern part of the campus (Fig. 3) suspected to have resulted from the geotectonic activity that created F – F[1]in the north. The study also identified networks of basement depressions and ridges in the lowland south (Fig. 3). The groundwater is contained in the weathered basement (weathered aquifer) and in faulted/fractured/jointed basement rock columns. Various combinations of the aquifer system exist within the OAU campus (Olorunfemi and Okhue, 1992 and Afolayan*et al.*, 2004).

METHODS OF STUDY

Two sites located within two of the three major geological units that underlain the OAU campus were investigated. The sites are designated A – Botany Department/Botanical Garden (grey gneiss underlain) and B - Agric Farm Centre (mica schist underlain) (see Fig. 2).

At site A, the geophysical investigation engaged the electrical resistivity method involving 2D Dipole-Dipole subsurface imaging as reconnaissance technique and 1D Vertical Electrical Sounding (VES) as a confirmatory technique. The 2D profiling utilized dipole length of 20 m and expansion factor, n, that was varied from 1 to 5. The VES Schlumberger half current electrode spacing was varied from 1 to a maximum of 325 m.

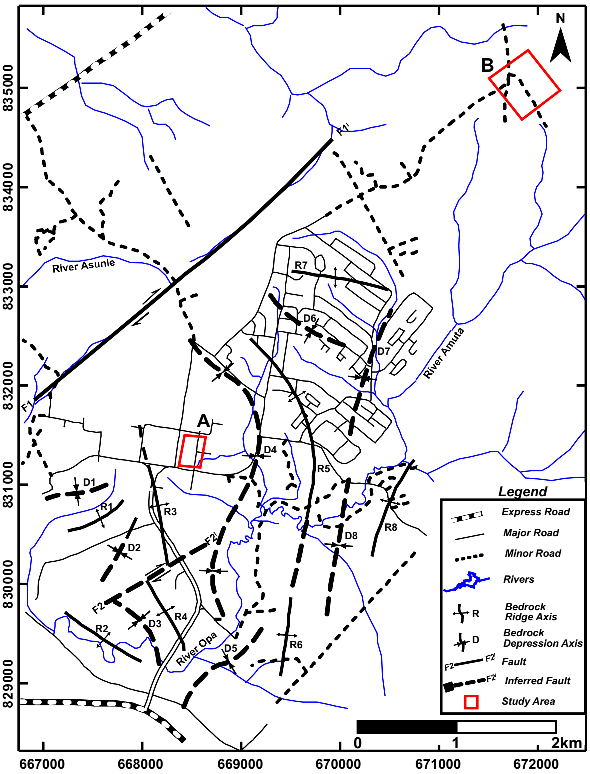

Fig. 3: Structural Map of Obafemi Awolowo University Campus, Ile-Ife (Olorunfemi and Okhue, 1992)

The Dipole-Dipole profiling was carried out along two traverses (TR 1&2) each 240 m long while two VES stations (one along each traverse) were occupied to further investigate identified suspected structures on the 2D resistivity images. The 2D resistivity data were inverted into 2D resistivity structures with DIPRO for window inversion software. The resulting images were used to constrain the VES locations. The interpretation of the 1D VES data involved partial curve matching and computer assisted 1D forward modeling with W-Geosoft/Winsev 5.1 software. The VES interpretation results (layer resistivities and thicknesses) were used to generate geoelectric section. One of the VES points (VES 2) was subsequently drilled, lithologically logged and pump tested.

The geophysical campaign at site A was aimed at identifying a site for productive borehole required to service a toiletry facility for the Biological Science Buildings. Few low lying basement outcrops, indicating shallow depth to basement bedrock, are characteristic of the survey area. An abortive borehole was previously drilled within this premise (see Fig. 4).

At site B, both resistivity and magnetic methods were engaged. The magnetic profiling and resistivity 2D imaging were adopted as reconnaissance techniques with the VES as a confirmatory tool. This site is underlain by mica schist with characteristically low fracture density (Olorunfemi and Fasuyi, 1993) and generally thick but clayey weathered basement columns (Olorunfemi and Okhue, 1992). Groundwater yields are generally low in schistunderlain areas because of the low yielding capacity of the clayey weathered basement. Groundwater yield in such environment could only be enhanced if fractured/faulted zones are delineated or intruded pegmatitic veins are identified. Both structural elements are amenable to delineation through magnetic profiling and 2D subsurface resistivity imaging. The aforementioned informed the adoption of this integrated survey approach.

The methodologies of the 2D and 1D resistivity surveys are as earlier discussed except that a dipole length of 25 m was used at this site. The magnetic profiling utilized 10 m station interval while standard field procedures were followed. The magnetic data were corrected for diurnal variation and offset. The residual magnetic data were presented as profiles and qualitatively interpreted by profiles inspection. Magnetic profiling was carried out along four traverses (TR 1-4) ranging in lengths from 400 – 510 m. Dipole-Dipole profiling was carried out along two of the traverses (TR 1 and 2). Fifteen (15) VES stations were occupied whose locations were constrained by the magnetic profiles/2D resistivity structures and were to principally investigate identified suspected structures and zones with suspected thick overburden. One of the VES stations (VES 6) was subsequently drilled, lithologically logged and pump tested.

The geophysical survey at site B was required to identify a site for a productive borehole that will service the Agric Farm Center. Two abortive boreholes were previously drilled within this premises. The data acquisition maps for the two sites investigated are contained in Figure 4.

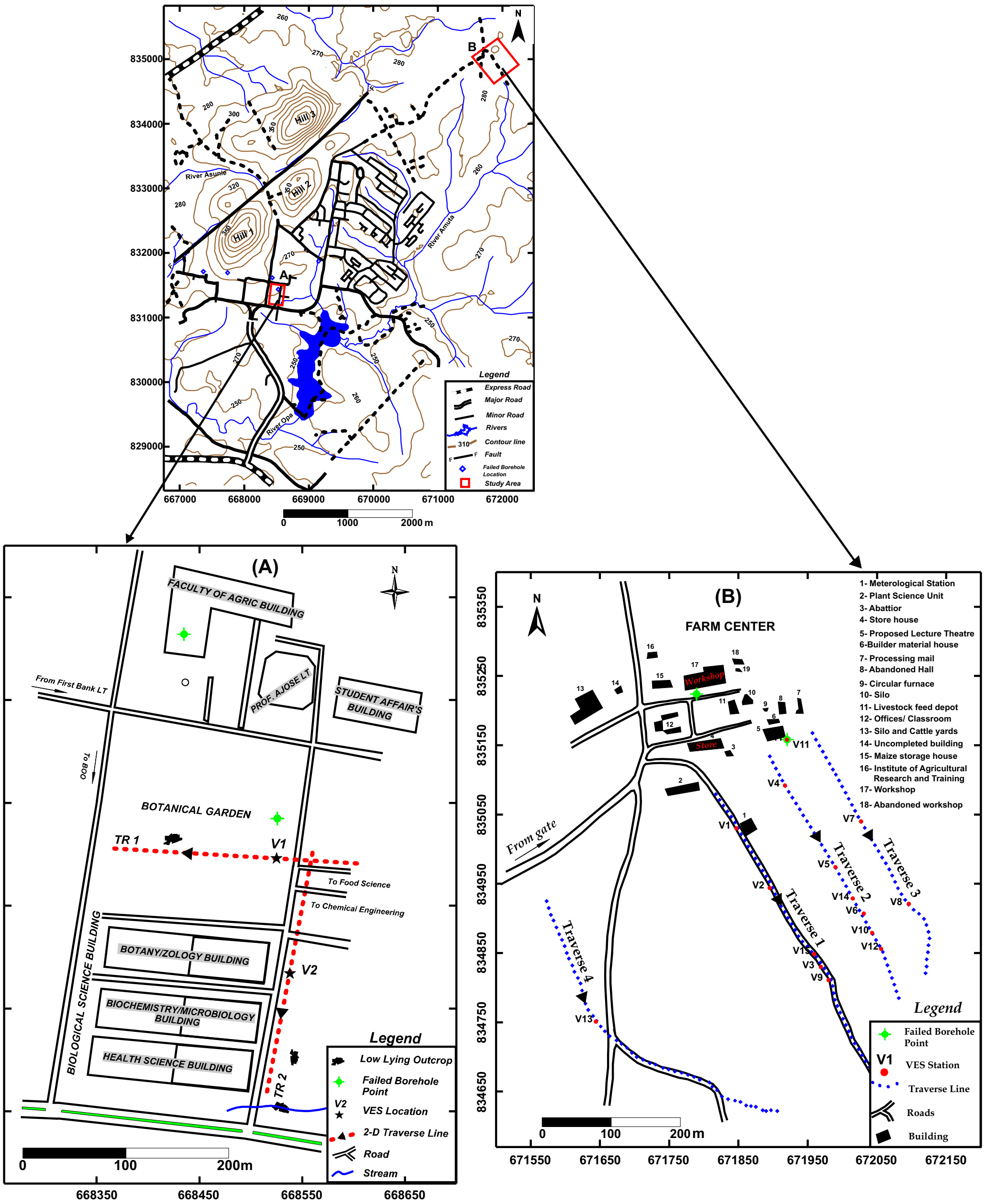

Fig. 4: Composite Data Acquisition Maps

RESULTS AND DISCUSSION

SITE A

The 2D resistivity structures obtained along traverses TR1 and TR2 are shown in Figure 5. The outcropping/near-surface basement bedrock was imaged as high resistivity zones with resistivities in the range of 700 Ωm – 20000 Ωm (in yellow/brown/purple colour band) at the western flank of traverse TR1 and 270 Ωm – 1000 Ωm (in yellow/brown colour band) at the northern and south central sections of traverse TR2. The overburden thickness varies from 0 m on outcropping basement rock along TR2 to less than 10 m on the western flank of TR1. The near surface basement bedrock is established by the existence of low lying outcrops in the vicinity of Traverses 1 and 2 (see Fig. 4). A marked low resistivity vertical discontinuity within the high resistivity basement bedrock, suspected to be fractured basement, was established between stations 5 and 4 along traverse TR1 and stations 5 and 6 along traverse TR2. The suspected fractured basement columns were depth sounded (VES 1 and 2).

The observed VES curves are the AKH and KHKA type (Fig. 6). Five geologic layers were delineated (Fig. 7). These include clay/sandy clay topsoil (layer resistivity: 67-264 Ωm; thickness: 0.4-2.0 m), weathered layer (79-149 Ωm; 6.2-7.0

m); partly weathered/fresh basement (280-1903 Ωm; 14.0-20.4 m); fractured/weathered basement (45-79 Ωm; 100-125.0 m) and the fresh grey gneiss basement bedrock (1903-∞ Ωm; depth to rock head: 6.6-9.0 m). The fractured basement constitutes the main aquifer unit. VES station 2 was subsequently drilled to maximum depth of 80 m and terminated within the fractured basement column. The borehole log correlated perfectly well with VES 2 interpretation model (Fig. 8). The borehole was self flushing throughout the drill works and gave a groundwater yield of about 1.5 l/s

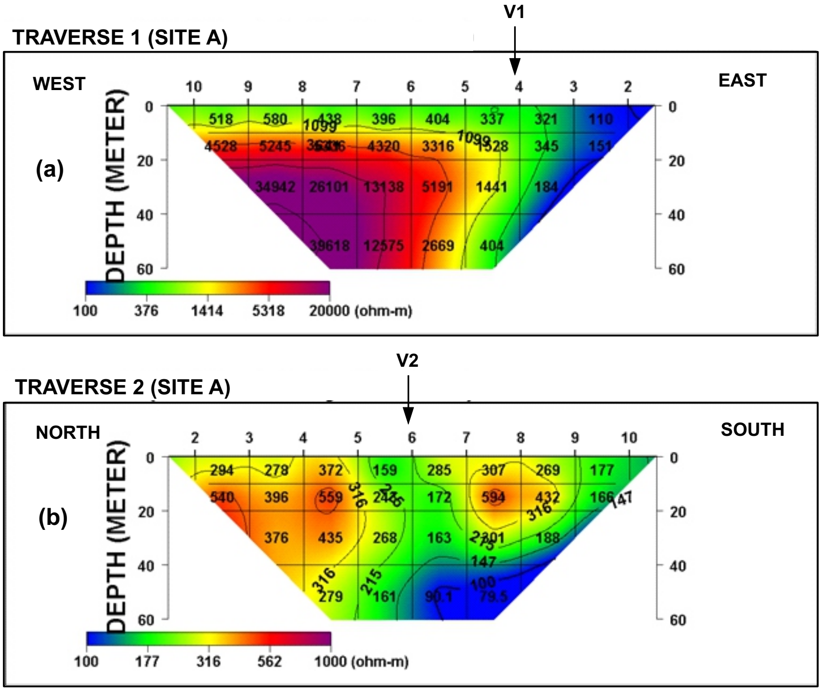

Fig. 5: 2D Resistivity Structures along (a) Traverse 1 and (b) Traverse 2

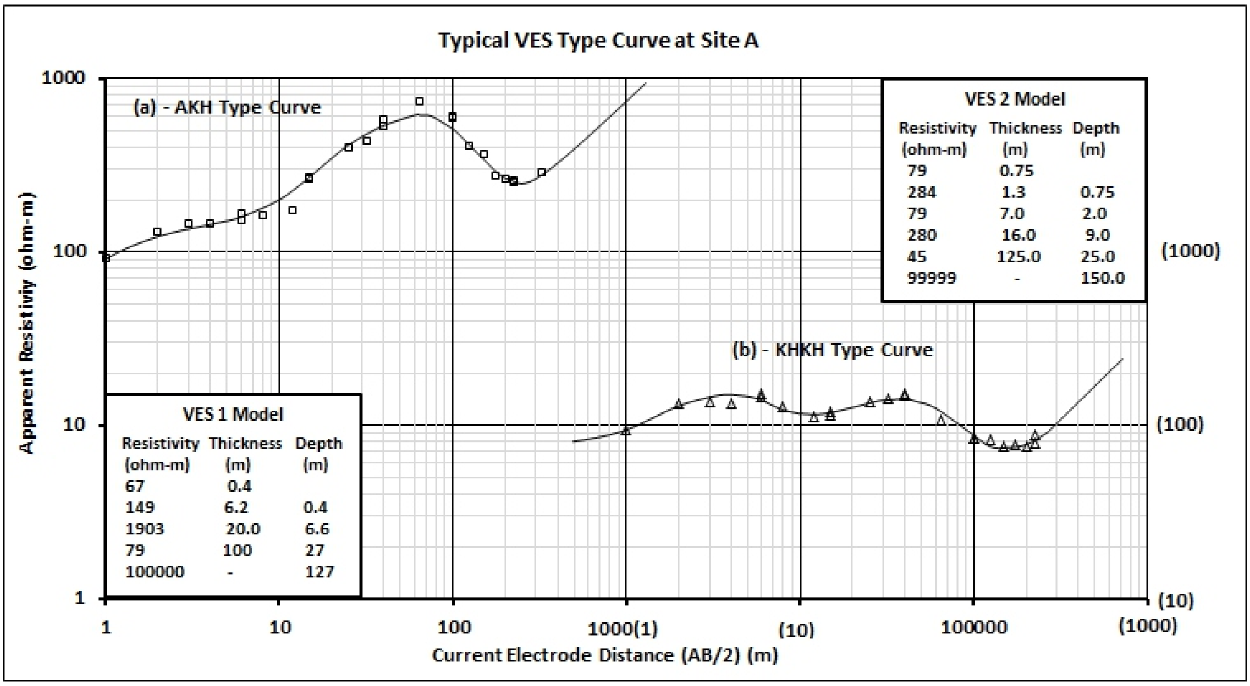

Fig. 6: Typical VES Type Curves Identified at Site A

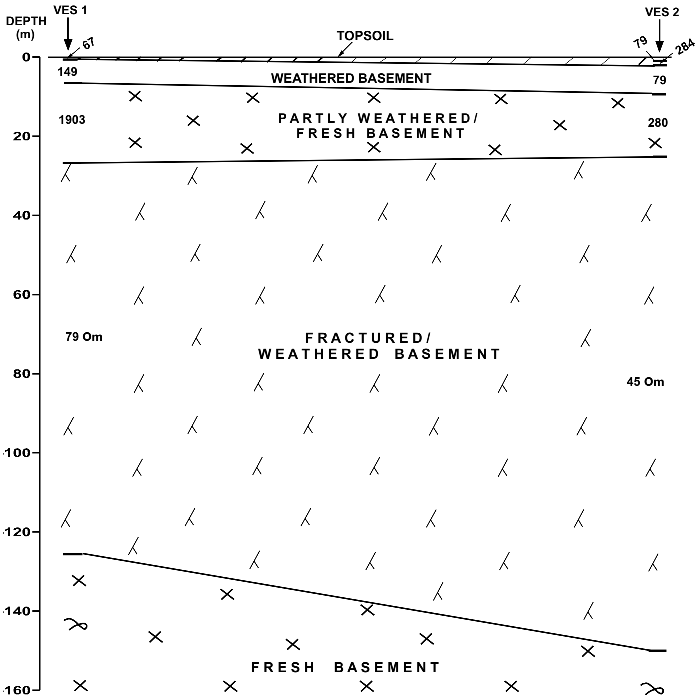

Fig. 7: Geoelectric Section Relating VES 1 and 2 along Traverse 2 at Site A

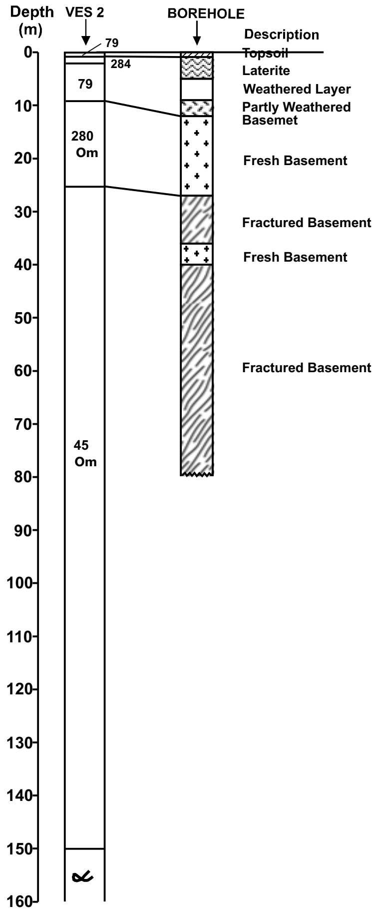

Fig. 8: Correlation of Borehole Log with VES 2 Interpretation Model

SITE B

Figure 9 shows the residual magnetic profiles along traverses TR1-4. The magnetic intensity varies from +22 to -92 nT. Only one magnetic anomaly typical of a thick dyke (two magnetic lows with central high in low magnetic latitude) was observed across the four traverses between stations 23 and 38 (TR1); 20-34 (TR2); 21 and 36 (TR3) and 14-29 (TR4). This magnetic anomalous zone correlated across the traverses in Figures 9 and 10 and is typical of a fault zone. The magnetic anomalies are asymmetrical and indicative of a southeasterly dipping structure. 2D Dipole-Dipole profiling was carried out along two of the magnetic profiles (TR1 and 2). The 2D resistivity structures obtained from the inverted data are shown in Figure 11. The two resistivity structures mapped a vertical discontinuity – typified by a low resistivity zone between high resistivity basement rocks which is characteristic of water saturated faulted zone. The surface manifestations of the faulted zones are between distances 225 and 325 m (stations 9-13) along traverse TR1 and between distances 200 and 300 m (stations 8-12) along traverse TR2. The 2D resistivity anomalous zone overlaps with the magnetic anomalous zone but is not as wide (Fig. 10). The magnetic anomalous zone appears spatially shifted southwards.

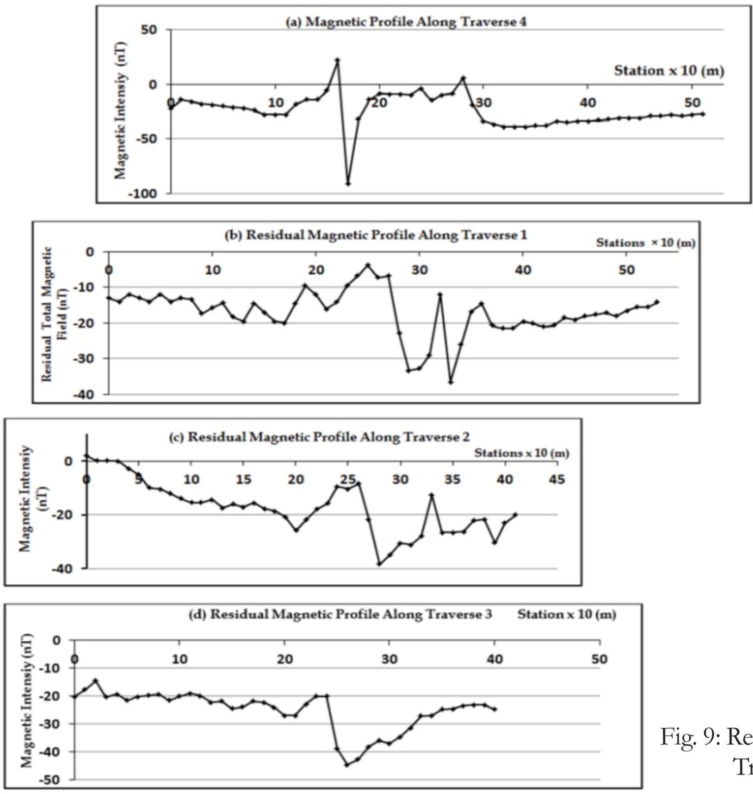

Fig. 9: Residual Magnetic Profiles along (a) Traverse 4, (b) Traverse 1, (c) Traverse 2 and (d) Traverse 3

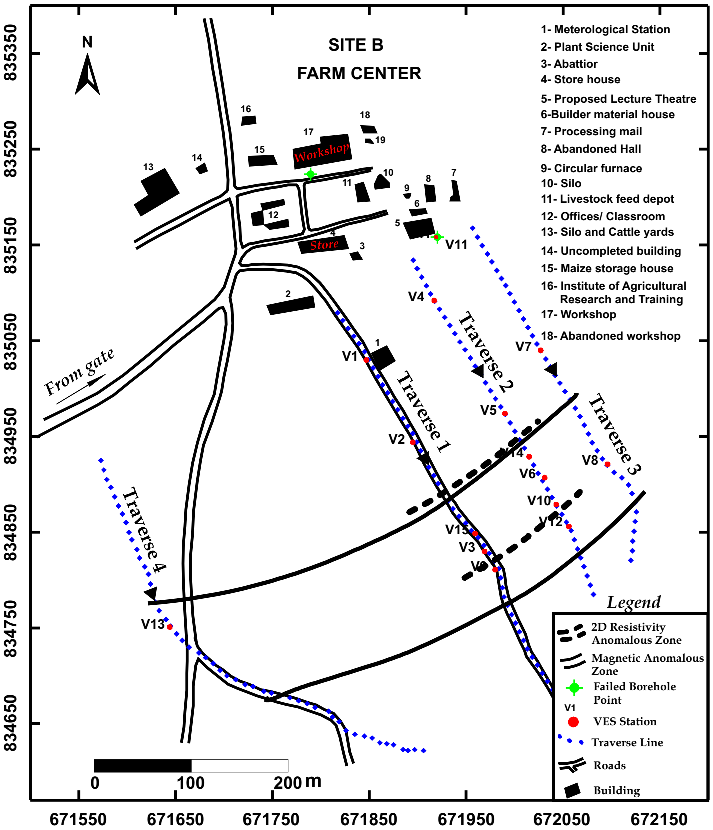

Fig. 10: Data Acquisition Map of the Study Area Showing Correlated Magnetic and Resistivity Anomalous Zones

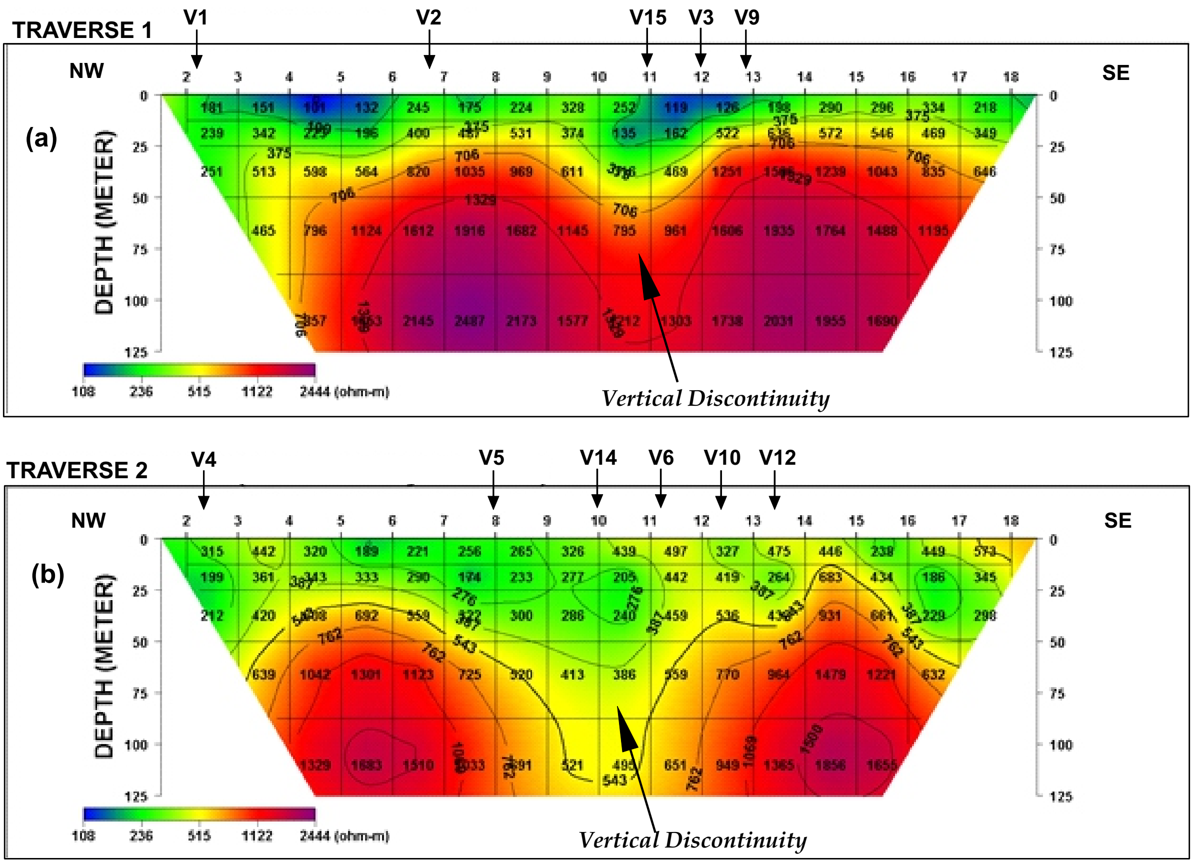

Fig. 11: 2D Resistivity Structures along (a) Traverse 1 and (b) Traverse 2

The VES stations were mostly concentrated within the zone of structure overlap as shown in Figure 10. Within the limit of the electrode spread, the observed VES type curves are the KH, HKH, KHKH and HKHKH type. Figure 12 shows the typical VES curves. The 2D geoelectric sections generated along the two traverses are shown in Figure 13. The geoelectric sections identify four geologic layers which include the sandy clay/clayey sand topsoil (layer resistivity: 119-455 Ωm; thickness: 0.6-3.1 m); laterite (430-1280 Ωm; 1.4-5.9 m); weathered/fractured basement (153-637 Ωm; 17.7-61 m) and fresh basement (852-∞ Ωm; depth to rock head: 3-70 m). The centers of the 2D resistivity structures, characterized by VES stations 6 and 15, display the thickest fractured basement column and hence deepest depth to the basal fresh basement along traverses TR 2 and 1 respectively. Fracturing and faulting enhances weathering, more so when the geologic structures are water saturated. It is therefore expected that overburden thicknesses should be relatively thicker within the suspected faulted zone. VES station 6 along traverse TR2 was eventually recommended for drilling having the thickest overburden and intermediate weathered/fractured layer resistivity (312 Ωm) with tendency for moderate degree of shaliness. The borehole gave a groundwater yield of about 2.2 l/s. Figure 14 compares the borehole log with the VES interpretation model. Both sections correlated very well, with the borehole establishing fractures within the suspected faults zone while the depth to the basal fresh basement was predicted to 96% accuracy (64 m from VES model and 67m from drilling).

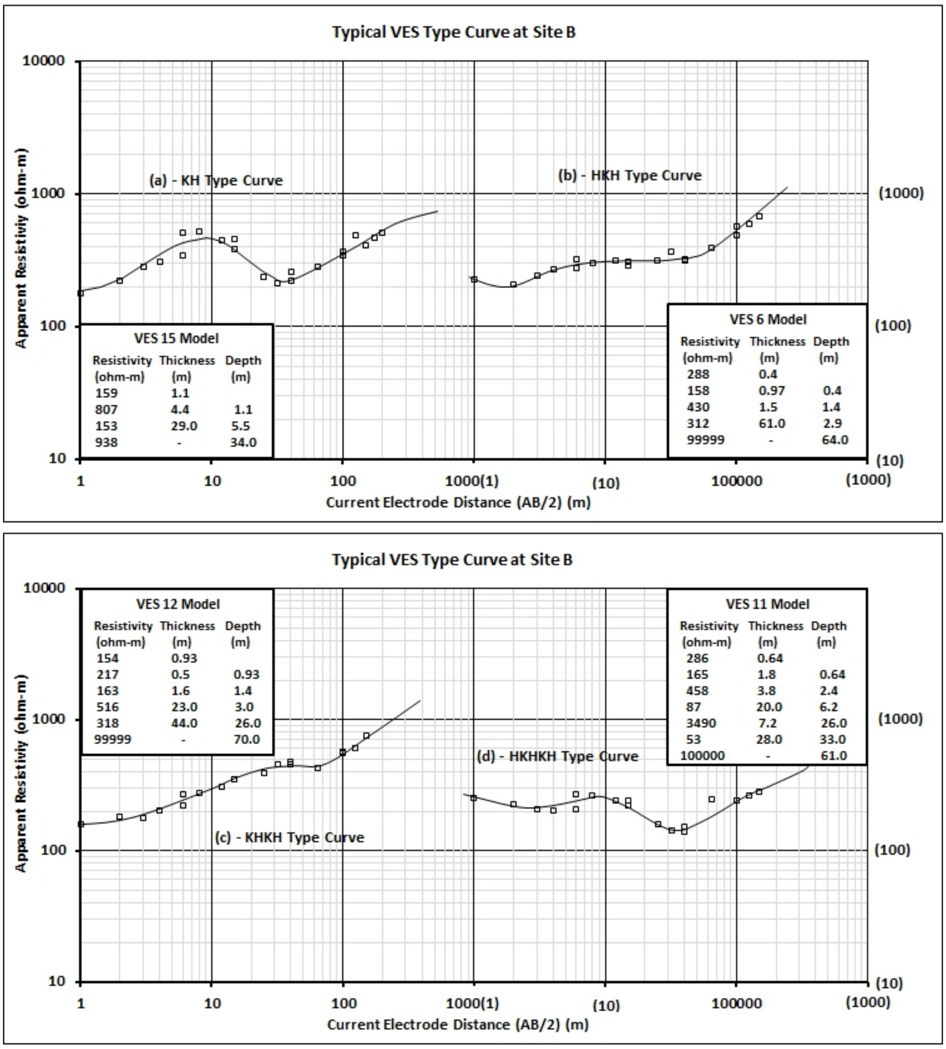

Fig. 12: Typical VES Curves (a) KH (b) HKH (c) KHKH and (d) HKHKH Identified at Site B

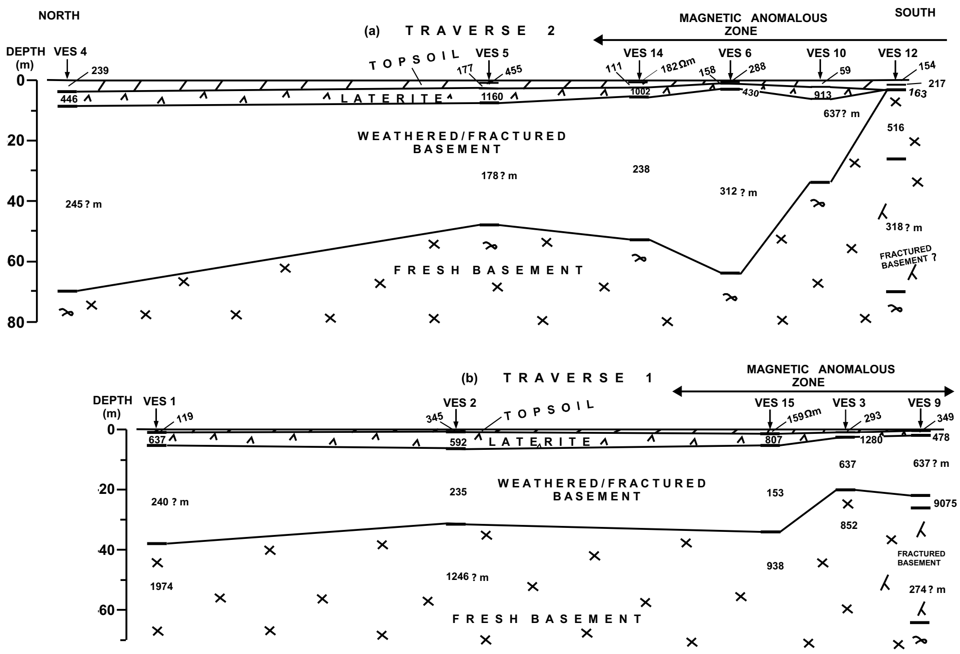

Fig. 13: Geoelectric Sections Relating (a) VES 4, 5, 14, 6, 10 and 12 along Traverse 2 and (b) VES 1, 2, 15, 3 and 9 along Traverse 1 at Site B

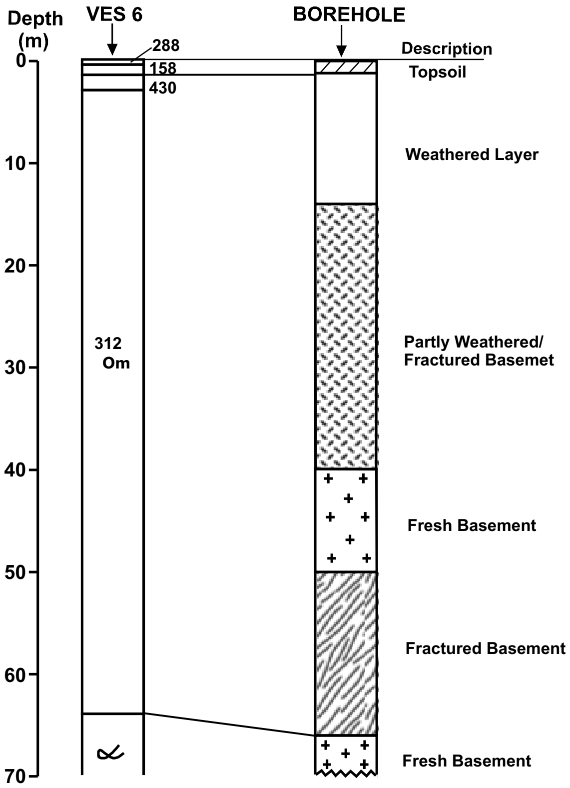

Fig. 14: Correlation of Borehole Log with VES 6 Interpretation Model

CONCLUSION

The electrical resistivity survey involving 2D Dipole-Dipole subsurface imaging and 1D Vertical Electrical Sounding (VES) and an integrated magnetic and electrical resistivity survey involving magnetic profiling and 1D/2D electrical imaging techniques were carried out at two sites underlain by grey gneiss and pegmatised schist, respectively, within the Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria. The two sites had previously experienced failed borehole drilling attempts. The surveys were carried out with a view to identifying suitable sites for productive boreholes. The magnetic profiling and the 2D resistivity imaging were adopted as reconnaissance techniques for the identification of geological structures such as faults, fractured, jointed and sheared basement zones that are favourable to groundwater accumulation and transmission. The 1D VES was used as a confirmatory technique to delineate the subsurface sequence and determine the geoelectrical characteristics, map unconfined/confined fractured basement columns and estimate hydrogeologically significant borehole drill depth.

At site A – the premises of Botany Department/Biological Garden, the 2D resistivity structures identify low resistivity vertical discontinuity suspected to be fractured basement within high resistivity outcropping/near-surface fresh basement (at 0 – 10 m depth) beneath the two traverses investigated. The follow-up VES delineated five subsurface layers including the topsoil, weathered layer, partly weathered/fresh basement, fractured basement and the fresh basement. The confined fractured basement constitutes the main aquifer unit with thicknesses of 100 – 125 m. The weathered layer aquifer is thin (6.2 – 7.0 m) and clayey (resistivity of 79 – 149 ohm-m). One of the VES points (VES 2) was drilled to 80 m, whose lithological log correlates perfectly well with the VES interpretation model. The fractured basement was encountered as predicted, but not completely penetrated (Fig. 8). The borehole was pump tested and it gave a groundwater yield of about 1.5 l/s.

At site B – the premises of Agric Farm Centre, the magnetic profiles display one major anomaly that is typical of a thick dyke and correlates across all profiles. The magnetic anomalous zone is suspected to be a fractured zone within the pegmatised schist. The follow-up 2D resistivity images identify same anomalous zone as low resistivity vertical discontinuity typical of a water saturated faulted zone within high resistivity fresh basement host rock. The 2D resistivity image-delineated suspected fractured zone overlaps significantly with the magnetic anomalous zone with the latter being much wider. The confirmatory VES delineate four subsurface geologic layers which include the topsoil, laterite, weathered/fractured basement and the fresh basement. The depth to the basement rock head varies from 3 – 70 m, with a maximum of 64 m within the delineated fractured zone, and beneath VES 6. The weathered/fractured basement constitutes the aquifer unit with thicknesses varying from 17.7 – 61 m. VES 6, located within the suspected fractured zone,was subsequently drilled. The borehole lithological log correlates very well with the VES interpretation model (Fig. 14). The lithological log establishes fractures within the suspected faulted zone up to a depth of 67 m as against the predicted 64 m (96% accuracy). The borehole was pump tested and it gave a groundwater yield of about 2.2 l/s.

This study demonstrated the effectiveness of integrated geophysical methods and techniques in providing information on the subsurface sequence and its structural disposition required for a successful groundwater development through borehole drilling in borehole-failure-prone basement complex terrain.

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