The Use of 2D Resistivity Images to Constrain 1D Vertical Electrical Sounding (VES) Curve Interpretation for Suppression-Prone Confined Fractured Basement Column

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ABSTRACT

With the gradual depletion of shallow weathered layer aquifers in basement complex terrain due to over-abstraction of the groundwater, confined fractured basement aquifers are becoming increasingly important targets for groundwater development. However, for reasons of depth of burial, aquifer thickness, masking effect of resistive confining basement rocks and intermediate resistivity relative to that of the enclosing layers, confined fractured basement columns are sometime prone to being suppressed on Vertical Electrical Sounding (VES) curves. This paper demonstrates, with case studies, how 2D electrical resistivity images can provide alternative information to borehole in constraining VES data interpretation, for the identification of suppression-prone groundwater bearing confined fractured basement.

(Keywords: confined fractured basement, suppression, 2D resistivity images, ID VES, groundwater development)

INTRODUCTION

Wherever the subsurface sequence is stratified and layer resistivity values vary only in the vertical direction (with depth); that is, resistivity is laterally uniform (Irshad, 1976), the Vertical Electrical Sounding (VES) technique of the electrical resistivity method has found useful applications in subsurface layer delineation, layer thickness estimation and depth to subsurface layer determination. This has made the VES technique commonly applied in engineering and groundwater investigations, where subsurface layer definition and depth estimates to and thicknesses of subsurface layers are of paramount interest (Zohdy *et al.,* 1980; Olorunfemi and Fasuyi *et al.,* 1993; Aina *et al.,* 1996; Ajayi *et al.,* 2005; Mohamaden, 2016; Oyeyemi and Aizebeokhai, 2018; Olorunfemi *et al.,* 2020).

However, because the subsurface earth is far from homogeneous; layer resistivity values within subsurface layers vary in all directions. Ideal VES curves are rarely obtainable and interpretation results are subjected to varying degrees of error. In addition, interpretation results of VES data are never unique. The non-uniqueness is partly due to the principles of equivalence and suppression (Maillet, 1947; Zohdy *et al*., 1980; Sanuade *et al*., 2019).

Equivalence is a phenomenon whereby a multilayered VES curve corresponds to several geoelectric models (distributions of layer thicknesses and resistivities) provided the total longitudinal conductance (S) for the H type curve ($\rho_1 > \rho_2 < \rho_3$), where ρ_1, ρ_2, and ρ_3 are the layer resistivity values for layers 1, 2 and 3 or the total transverse resistance (T) for the K type curve ($\rho_1 < \rho_2 > \rho_3$) are the same; as defined by Zohdy *et al*. (1980) below:

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \dots\dots + \frac{h_n}{\rho_n} \quad (1)$$

$$T = \sum_{i=1}^{n} h_i\rho_i = h_1\rho_1 + h_2\rho_2 + h_3\rho_3 \dots\dots + h_n\rho_n \quad (2)$$

Where h is the layer thickness
ρ is the layer resistivity
i is the position of each layer, and
n is the number of layers.

For the electrically equivalent geoelectric models for the H and K type curves, the VES curves are the same.

A layer whose resistivity value is intermediate between the resistivities of the enclosing layers (i.e. $\rho_1 < \rho_2 < \rho_3$) may not have significant influence (could be suppressed) on the resulting VES curve, unless the layer is appreciably thick. Layer suppression is therefore relevant to an A type geoelectric model or one containing the model. This phenomenon is similar to the hidden layer problem in the seismic refraction method. A suppressed geoelectric layer cannot be delineated and depth estimate to the suppressed layer will be over-estimated (Olayinka, 1997). Ambiguities due to equivalence and suppression can be reduced when VES curve interpretation is constrained by information from boreholes, where such are available.

Where the topsoil or the near-surface subsoil is very resistive, the resistivities of the subsurface layers are over-estimated (Adeniran *et al*., 2009). Where such layer is very conductive, the underlying layer resistivity value is underestimated. A supposedly infinitely resistive fresh basement rock that is overlain by a very conductive (low resistivity) weathered layer will manifest as a low resistivity medium which is most time erroneously interpreted as fractured basement (Olorunfemi and Oni, 2019). This is a masking effect of an overlying layer.

In area underlain by basement complex rocks, a confined fractured basement column, sandwiched between fresh basement rocks, is prone to suppression (Ojo and Olorunfemi, 2013; Sanuade *et al.,* 2019). Ojo and Olorunfemi (2013) established that such confined fractured basement column is only detectable on the VES curve for thicknesses ranging from 10 - 50 m or more and depth of burial ranging from 31 - 201 m for resistivity reflection coefficients (K) between the overlying high resistivity basement and the underlying low resistivity confined fractured basement, ranging from -0.92 to -0.56. Within the above thresholds, confined fractured basement manifests as an inflection on the rising segment of the VES curve with the dislocated segments rising at a maximum angle of 45° to the horizontal. Outside the threshold, the layer is prone to suppression.

However, the confined fractured basement column is becoming increasingly important in groundwater development in basement terrain with the gradual depletion of the upper clayey and low permeability weathered basement aquifer, due to over abstraction of its groundwater. The fractured basement sometimes has large storage capacity and high transmissibility when the fracture density is high and connected and the effective (secondary) porosity is high. However, the overlying high resistivity fresh basement has a masking effect on the low resistivity confined fractured basement, as observed by Adeniran *et al*. (2009).

The interpretation error associated with the principles of equivalence and suppression, as earlier indicated, can be reduced where there are borehole information to constrain the VES data interpretation. In predrilling geophysical investigations for groundwater development in basement complex area, there are rare access to subsurface borehole information. This makes the delineation of a suppressed confined fractured basement column with VES technique difficult. This paper uses 2D resistivity images as alternative source of subsurface information needed to constrain 1D VES data interpretation for the resolution of suppressed confined fractured basement column, on VES curves.

METHODOLOGY

In recent time, integrated geophysical methods and techniques have been adopted in geophysical investigations for groundwater development in problematic basement complex terrain (Chirindja *et al.,* 2017; Hasan *et al.,* 2018; Gao *et al.,* 2018; Oyeyemi and Aizebeokhai, 2018; Olorunfemi and Oni, 2019; Olorunfemi *et al.,* 2020; Oni *et al.,* 2020). The evolving field practice is to integrate both 1D VES and 2D subsurface imaging (with dipole-dipole array) techniques with the latter applied as a reconnaissance technique. The essence is to use the resulting 2D resistivity image to constrain the location of the follow-up VES and its data interpretation (as an alternative to borehole information). This methodology was applied in the case studies described below some of which were used to highlight the usefulness of 2D resistivity images in resolving suppressed confined fractured basement columns.

CASE STUDIES

All the case studies presented here were carried out prior to drilling operations and for groundwater development at different locations within the basement complex terrain of Southwest Nigeria.

Case Study I

This case study was carried out within the estate of the Obafemi Awolowo University, Ile-Ife, in Ife Central Local Government Area of Osun State, Southwest Nigeria. The site is underlain by grey gneiss (Figure 1).

Figure 2 presents the 2D resistivity image (dipole - dipole) obtained along a N-S traverse. The 2D structure imaged a near surface high resisitivity fresh basement rock on the northern and southern flanks (low lying outcrops of the grey gneiss are found on the southern flank) with a low resistivity vertical discontinuity between stations 5 and 7 (about 40 m wide).

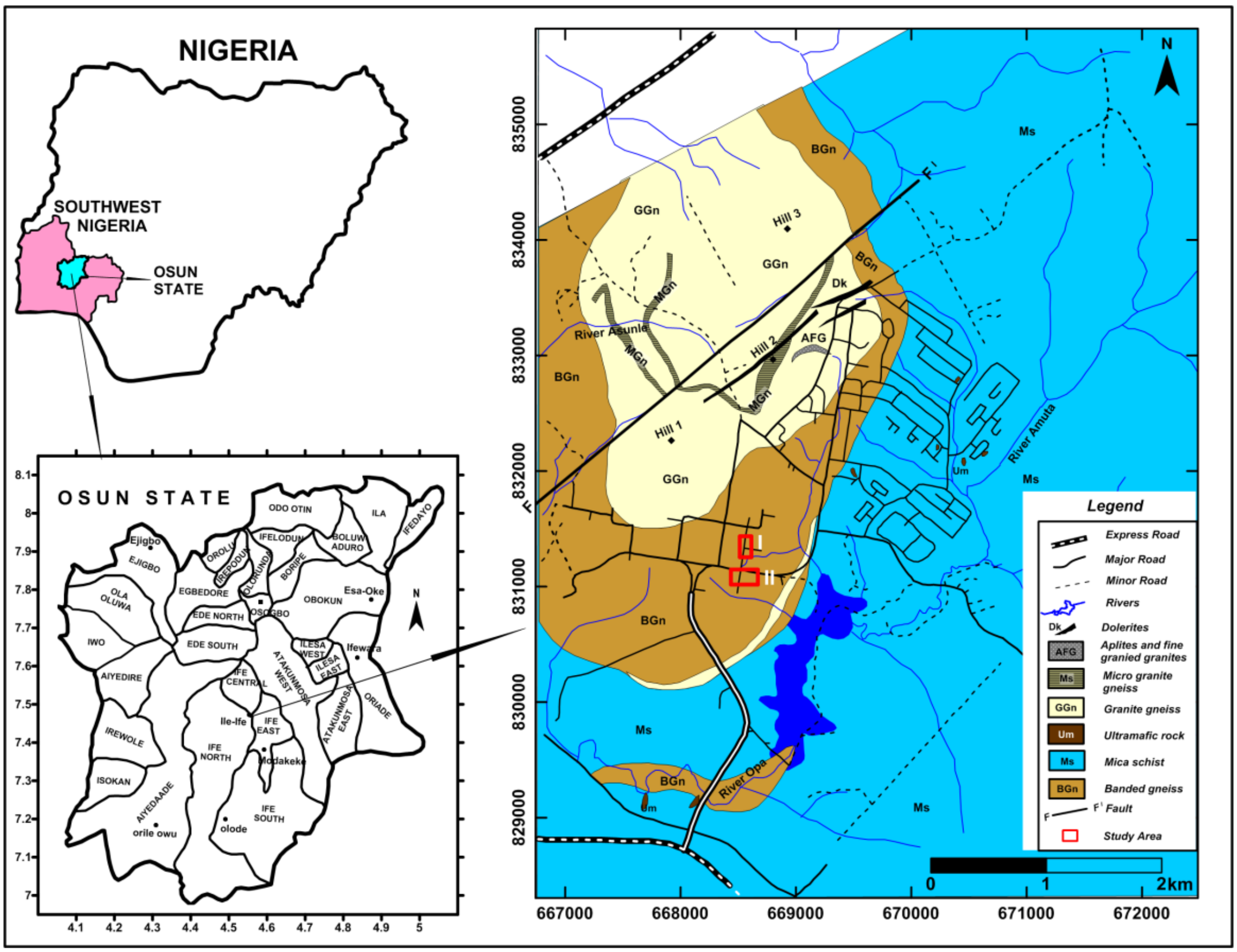

Figure1: Map of Obafemi Awolowo University, Ile-Ife, with Superimposed Geology, Showing the Study Areas.

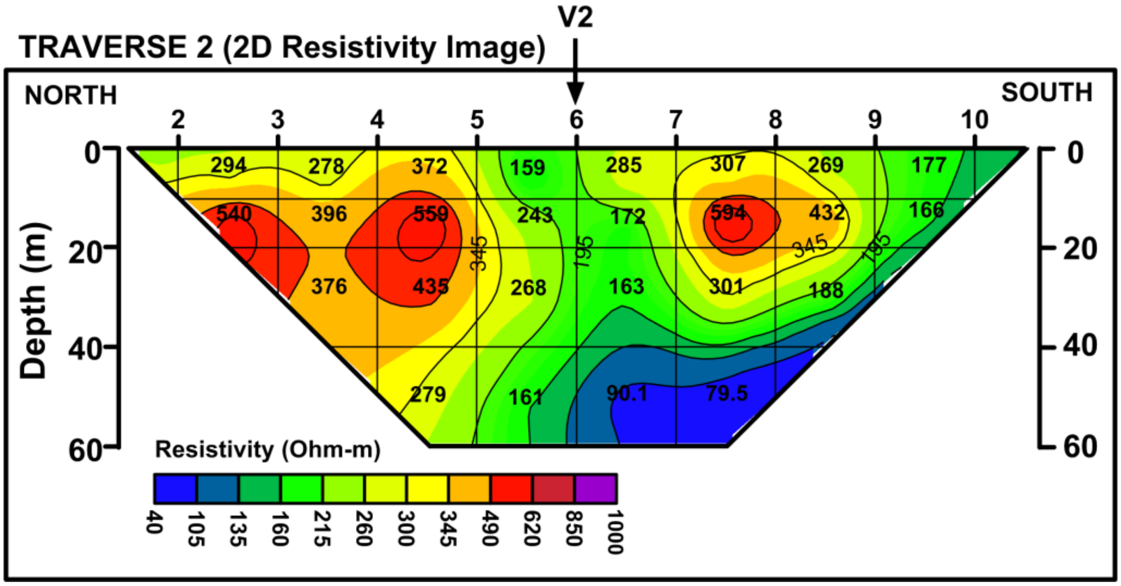

Figure 2: 2D Resistivity Structure beneath the Investigated Traverse Showing the VES Location (from Olorunfemi and Oni, 2019).

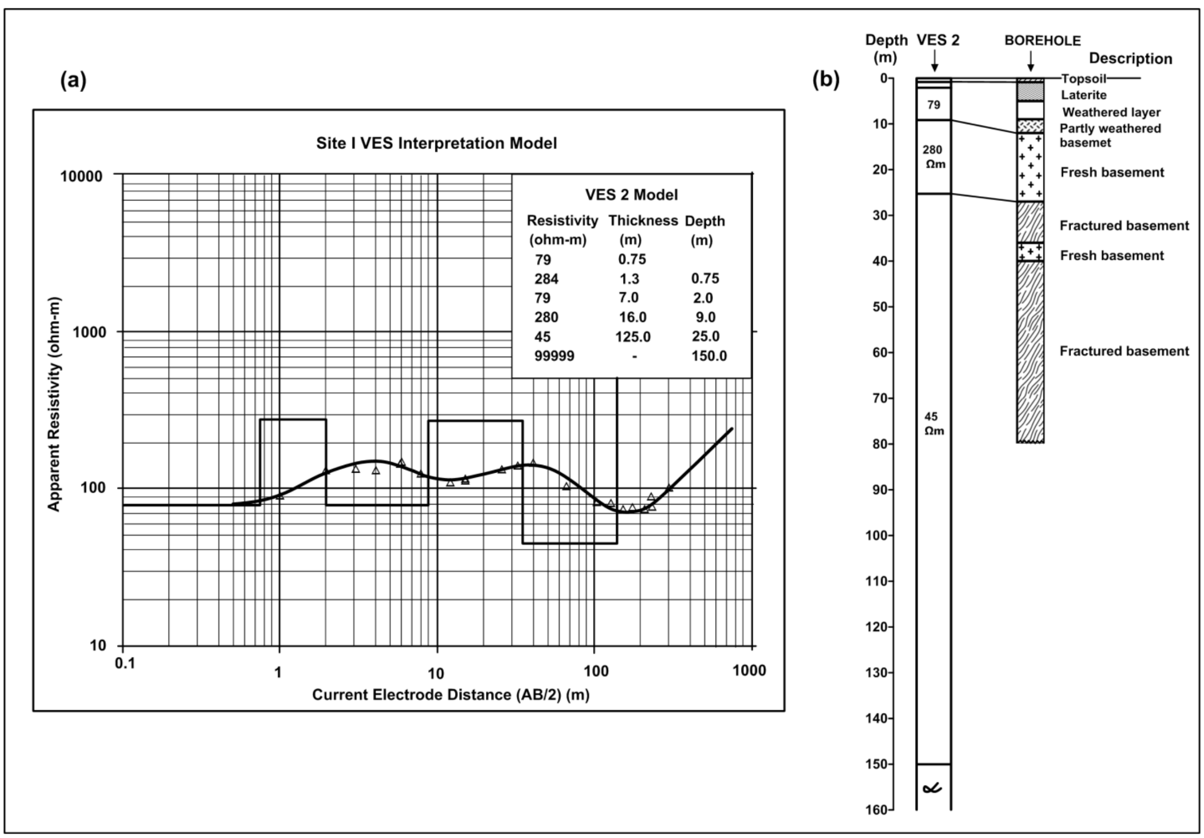

Figure 3: (a) VES Interpretation Model (KHKH Type) (b) Correlated VES and Borehole (BH) Lithological Logs with Description of Subsurface Layers (Culled from Olorunfemi and Oni, 2019).

The vertical discontinuity is typical of a fractured/faulted basement zone (Olorunfemi *et al.,* 2020). A confirmatory VES (V2) was carried out at station 6 to confirm the structure. The observed VES curve is the KHKH type (Figure 3a), typical of a multi-aquifer (weathered and fractured basement) system that include a confined basement fractured column, as corroborated by the drillers log (Figure 3b).
The confined fractured basement manifests as the second trough on the VES curve with layer resistivity of 45 Ωm. The upper fresh basement gives a layer resistivity of 280 Ωm due to the masking effect of the low resistivity (79 Ωm) overlying weathered layer, with a resistivity reflection coefficient (K) of -0.72.

The borehole lithological log correlates very well with the VES interpretation model. The confined fractured basement characteristics of 125 m thickness and very low resistivity of 45 Ωm, fall within Ojo and Olorunfemi (2013) thresholds hence it is not suppressed on the VES curve. The borehole was terminated at a depth of 80 m within the fractured basement with a yield of 1.5 l/s.

Case Study II

This case study was executed at a distance of about 200 m south of the site for Case Study I (Figure 1) with the same underlying lithological unit. Figure 4 displays the 2D resistivity image obtained along a W - E traverse. The image shows that the high resistivity basement rock is shallow at the eastern flank but delineates a low resistivity vertical discontinuity at the western edge. The center of this structure (at around station 4) falls at the middle of an access road hence the confirmatory VES was displaced towards the edge of the structure (close to station 5). The VES curve is the QHKH type (Figure 5a).

The VES curve is diagnostic of a confined fractured basement displaying an inflection on the rising segment of the VES curve (Olorunfemi and Fasuyi, 1993 and Ojo and Olorunfemi, 2013) with a layer resistivity of 49 Ωm and thickness of 65 m. The confining upper fresh basement rock displays a relatively low layer resistivity of 464 Ωm due to the very low resistivity (37 Ωm) of the overlying weathered basement, with a reflection coefficient (K) of -0.81. The borehole lithological log correlates very well with the VES interpretation model both in lithological differentiation and depth estimates (Figure 5b).

This high groundwater yielding borehole sustains a 2-horsepower submersible pump. The confined fractured basement is significantly thick while the layer resistivity is relatively low, hence it is not suppressed.

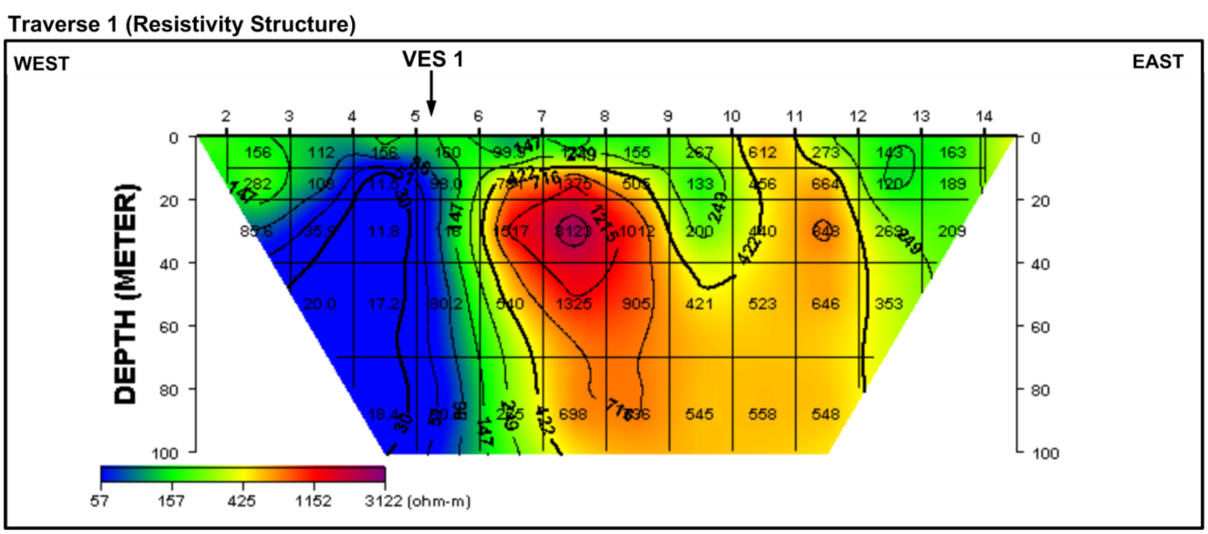

Figure 4: 2D Resistivity Structure beneath the Investigated Traverse Showing the VES Location.

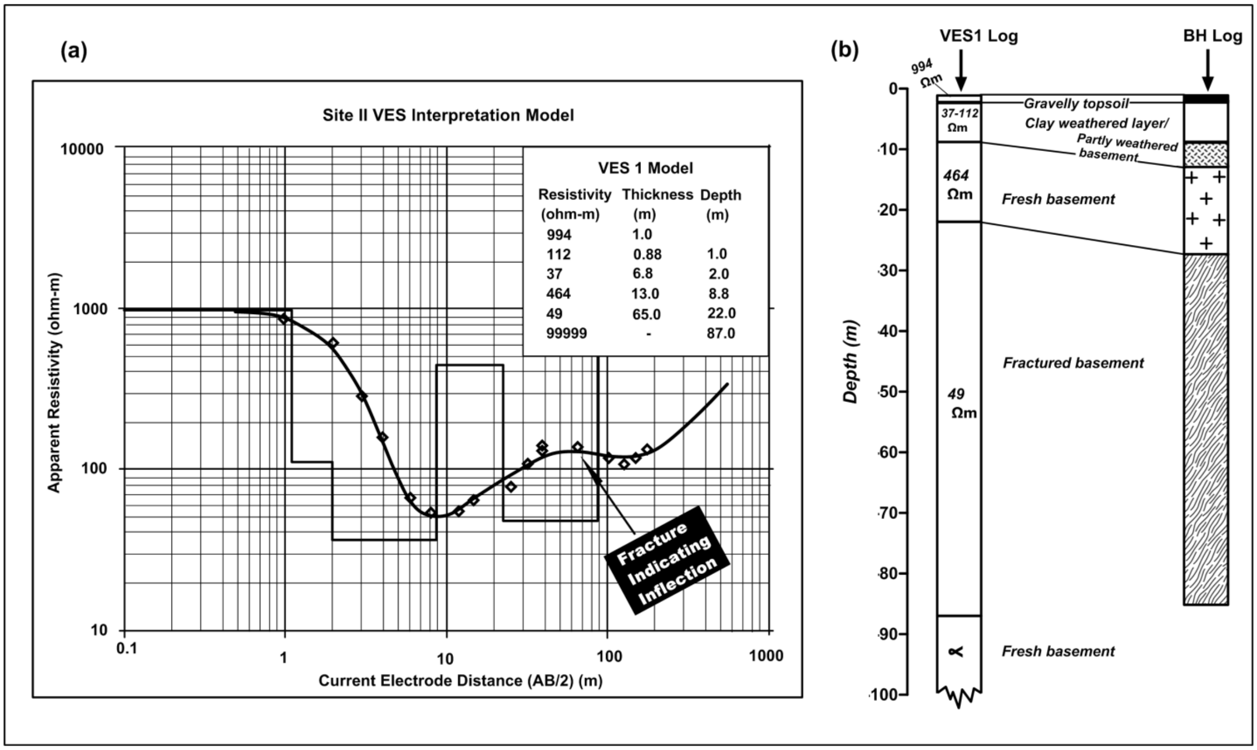

Figure 5: (a) VES Curve and Interpretation Model (b) Correlated VES and Borehole (BH) Lithological Logs with Description of Subsurface Layers.

Case Study III

This case study was carried out at Iyemero in Ikole Local Government Area of Ekiti State, Southwest Nigeria (Figures 6a & b). The site is underlain by granite gneiss (Figure 6a). Figure 7 shows a 2D resistivity image obtained along a NNW – SSE traverse. The image delineates a high resistivity near surface basement rock (a low lying outcrop occurs to the east (Figure 6b)) with a low resistivity vertical discontinuity typical of a fractured/faulted basement between stations 10 and 16 (about 120 m wide).

A near surface resistive layer overlies the suspected fractured/faulted basement. A confirmatory VES was located midway the structure (at station 13.5). On visual inspection, the VES curve is a typical H ($\rho_1 > \rho_2 < \rho_3$) or HA type curve ($\rho_1 > \rho_2 < \rho_3 < \rho_4$), which are at variance with the 2D resistivity structure beneath the VES location.

The interpretation models with the assumption of H and HA type are shown in Figures 8a & b. Both interpretations put the resistive basal fresh basement at 12 m and 8.7 m, respectively, with the HA type model delineating a partly weathered basement zone with layer resistivity of 600 Ωm. These two models are at variance with the 2D resistivity structure that puts the resistive basement at over 100 m. None of these two VES interpretation models identified the low resistivity confined fractured basement column at depth.

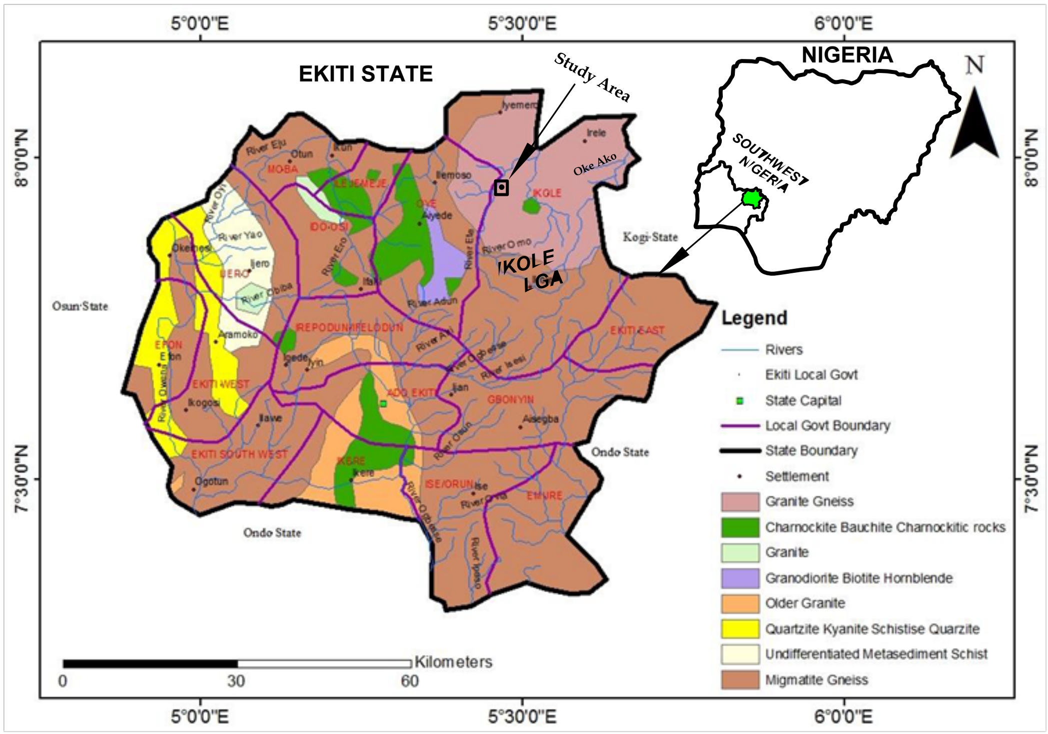

Figure 6a: Map of Ekiti State with Local Government Areas and Superimposed Geology, Showing the Study Area.

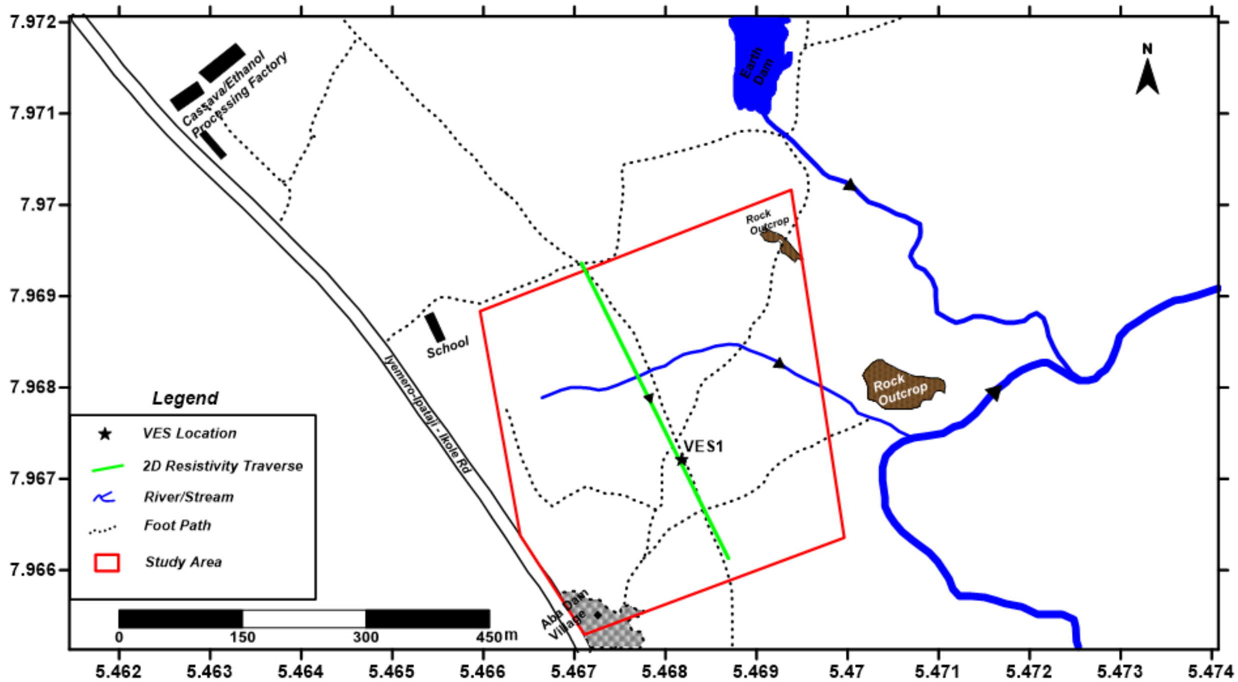

Figure 6b: Map of the Study Area Showing the 2D Resistivity Traverse and the Vertical Electrical Sounding (VES) Location.

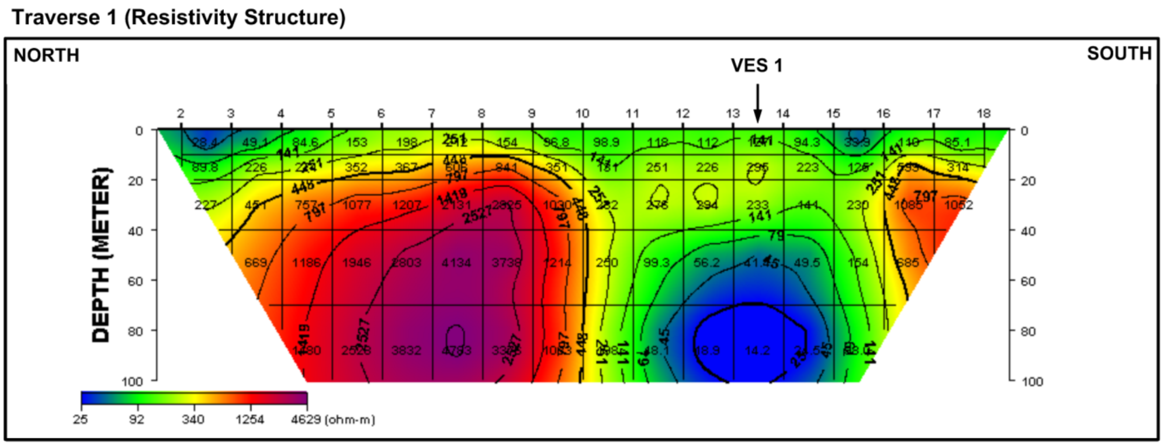

Figure 7: 2D Resistivity Structure along the Investigated Traverse.

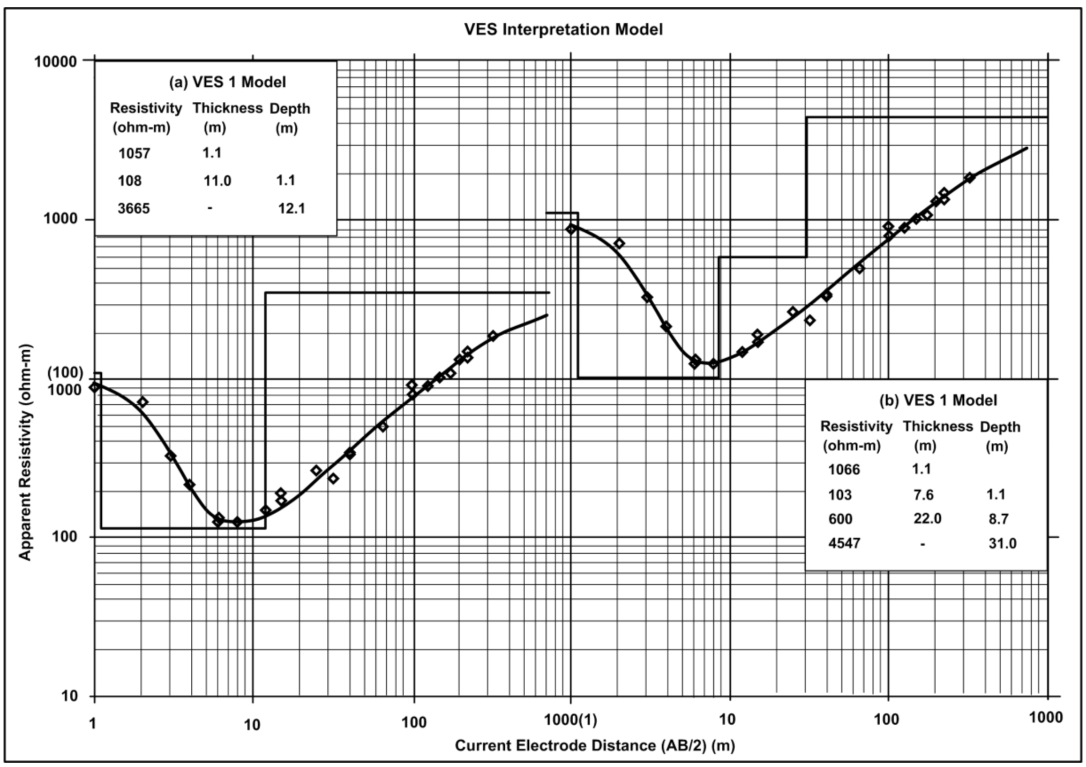

Figure 8: VES Interpretation Models (a) H Type (b) HA Type.

A re-interpretation of the VES that took cognizance of the virtually obscured inflection on the rising segment of the VES curve between electrode spacings (AB/2) of 100 and 200 m, identified a confined fractured basement column beneath a very resistive (42111 Ωm) fresh basement at depth of 39 m (Figure 9a). This interpretation was corroborated by the drillers log (Figure 9b) with a geoelectrical model of HAKH type ($\rho_1 > \rho_2 < \rho_3 < \rho_4 > \rho_5 < \rho_6$).

Apparently, the relatively low resistivity confined fractured basement was suppressed by the very resistive overlying basement rock, with a reflection coefficient (K) of -0.97. The basement rock turned out to be a dark and hard dolerite dyke intrusion. The groundwater encountered at the predicted depth of 39 m rose to less than half a meter from the surface, under a sub-artesian condition.

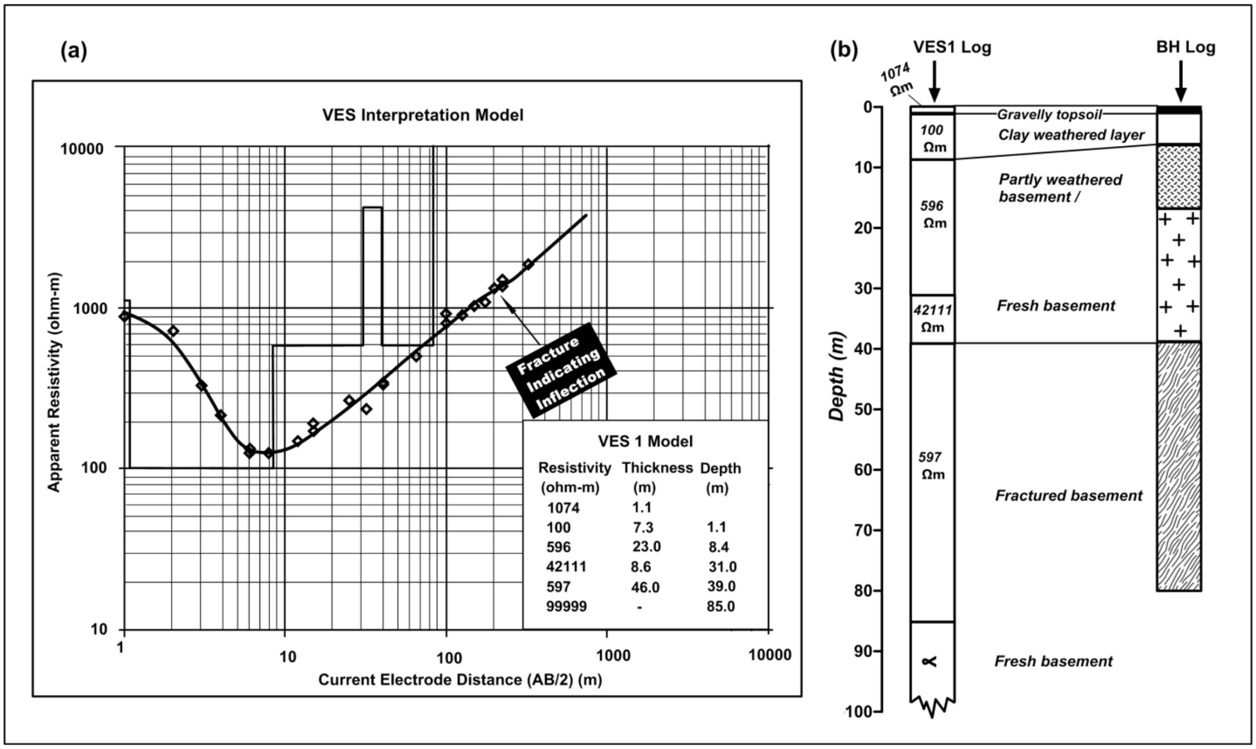

Figure 9: (a) VES Interpretation Model (HAKH Type) (b) Correlated VES and Borehole (BH) Lithological Logs with Description of Subsurface Layers.

The borehole was fitted with a 1.5-horsepower submersible pump with continuous discharge. It could sustain a higher capacity pump. But for the 2D resistivity image, the confined fractured basement could not have been delineated.

Case Study IV

This case study was implemented at Idi-Ahun, Ifepeju in Ife North Local Government Area of Osun State, Southwest Nigeria (Figure 10). The site is underlain by granite gneiss. Figure 11 displays the 2D resistivity image obtained along the investigated traverse. The northern flank indicates a high resistivity basement at depths of between 20 and 25 m with a low resistivity vertical discontinuity (whose southern edge is not fully defined) on the southern flank. A VES station was located within this low resistivity zone. This structure is typical of water saturated fractured/faulted zone, with the resistive fresh basement at depths that could be greater than 75 m.

On visual inspection, the VES curve defines a QH type geoelectric model and was so interpreted (Figure 12). The interpretation gave a depth to supposedly fresh basement at 20 m, about 19 m of which constitutes the weathered basement. This interpretation corroborates the subsurface sequence on the northern flank but is at variance with the subsurface image on the southern flank with supposedly resistive basal fresh basement at depths greater than 75 m.

Using the 2D image as constraint and taking cognizance of the virtually obscured inflection on the VES curve between electrode spacing (AB/2) 125 m and 250 m (measurement at AB/2 = 200 m could be anomalous), the VES curve was reinterpreted to delineate a 32 m thick relatively low resistivity (246 Ωm) confined fractured basement at depth of 41 m (Figure 13a). The low resistivity confined fractured basement is overlain by a resistive (8655 Ωm) confining fresh basement with a reflection coefficient (K) of -0.94. The borehole log correlates very well with the VES interpretation model; and the confined fractured basement was delineated (Figure 13b). The borehole sustains continuous groundwater discharge with a 1-horsepower submersible pump.

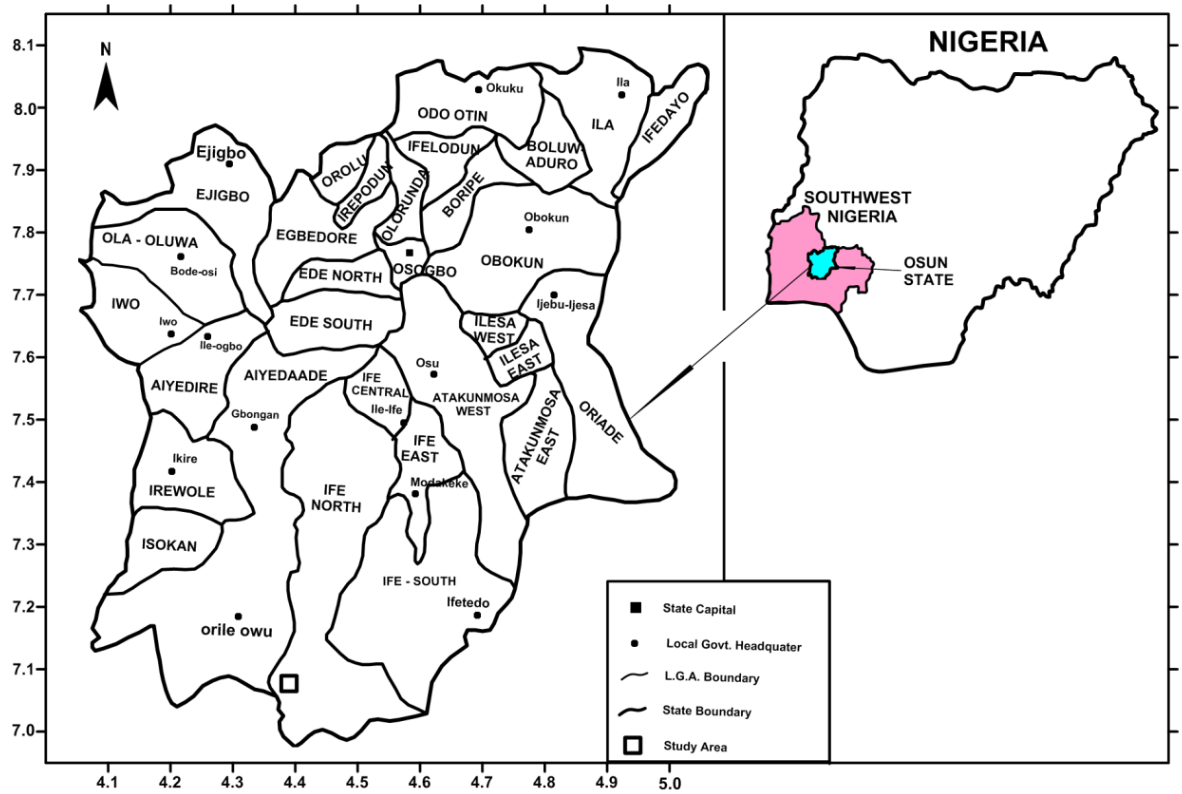

Figure 10: Map of Osun State Showing the Local Government Areas and the Locality.

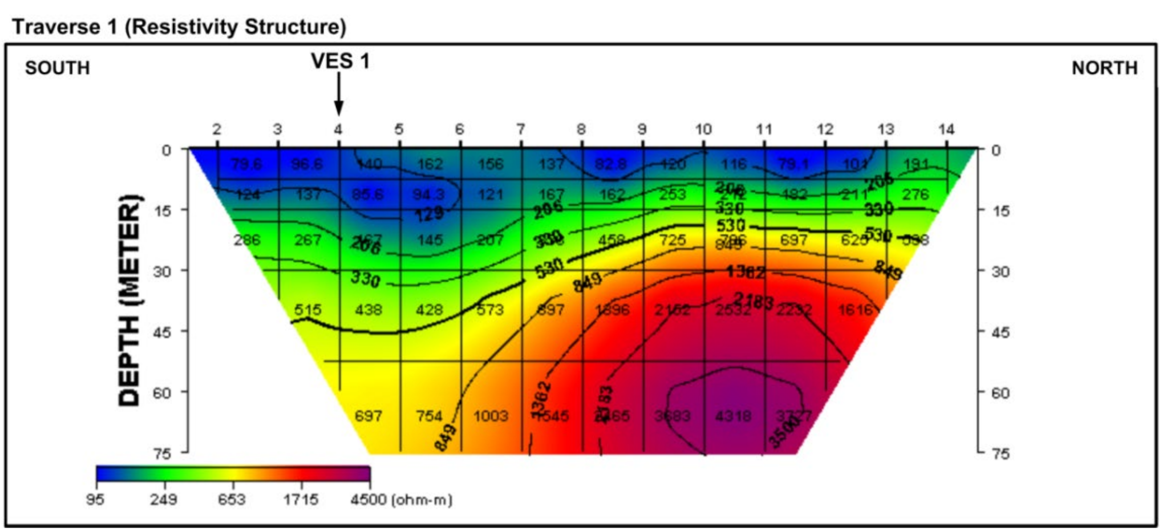

Figure 11: 2D Resistivity Structure beneath the Investigated Traverse.

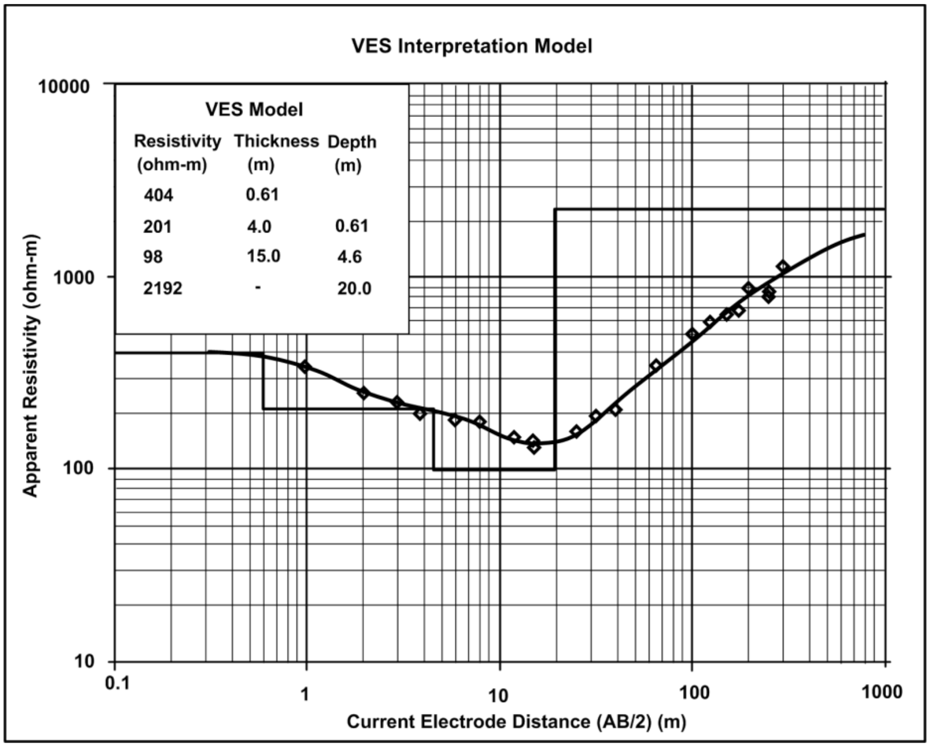

Figure 12: VES Interpretation Model (QH Type).

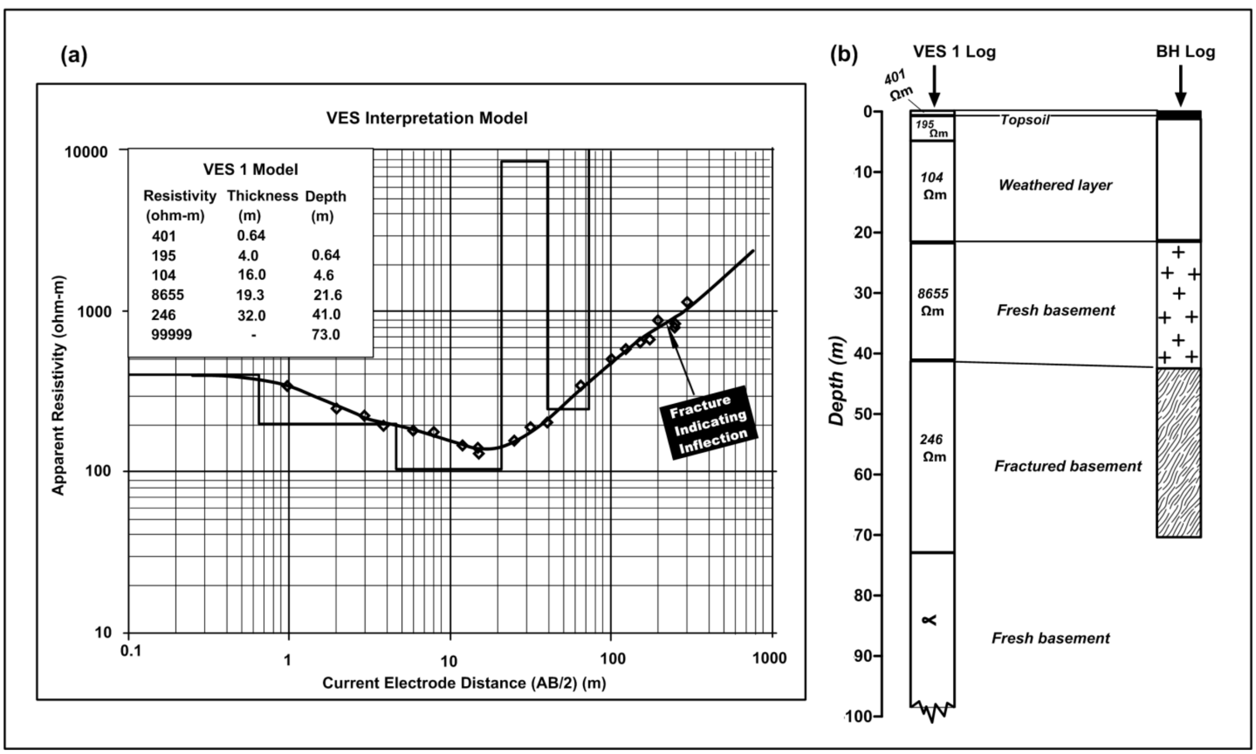

Figure 13: (a) VES1Interpretation Model (QHKH Type) (b) Correlated VES and Borehole (BH) Lithological Logs with Description of Subsurface Layers.

DISCUSSION

While 2D resistivity imaging provides an overview of the subsurface and the geoelectric layering in resistivity distribution, the VES data interpretation provides details of the subsurface layering, layer thickness and depth estimates needed to identify aquifer unit(s) and control borehole drill depth.

Where confined fractured basement column is significantly thick (> 50 m) with relatively low resistivity (< 200 Ωm) probably due to high fracture density and groundwater accumulation with the overlying confining basement rock displaying moderately high resistivity (< 500 Ωm) and relatively shallow depth of burial < 25 m, its effect is significant on the VES curve with manifestation of clear inflection or trough, as observed in Case Studies I and II. In both cases, the resistivity reflection coefficients (K) of -0.72 and -0.81, respectively, between the resistive confining fresh basement and the confined fractured basement column fall within the threshold of -0.92 to -0.56 established by Ojo and Olorunfemi (2013) for detectable confined fractured basement columns on the VES curves.

However, where the confined fractured basement aquifer is moderately thick (< 50 m) with moderately high resistivity (> 200 Ωm) possibly due to masking effect of very high resistivity (> 8500 Ωm) confining basement rock or low fracture density and moderately high depth of burial (> 39 m), the fractured basement is prone to be suppressed as observed in Case Studies III and IV. In these two cases, the resistivity reflection coefficients (K) of -0.97 and -0.94, respectively, between the resistive confining fresh basement and the confined fractured basement column fall outside the threshold of -0.92 to -0.56 established by Ojo and Olorunfemi (2013) with consequent suppression of the confined fractured basement columns on the VES curves.

In situations like this, 2D resistivity images will provide the additional information needed to constrain the interpretation of the VES curve to delineate the potentially suppression prone confined fractured basement columns.

CONCLUSION

The non-uniqueness in the interpretation of 1D VES data could be due to principles of equivalence and suppression; highly resistive or conductive topsoil or near-surface soils; and masking effect of a very resistive subsurface layer overlying a low resistivity confined fractured basement column. Ambiguities in VES interpretation could be reduced if the VES curve interpretation is constrained by subsurface information from boreholes or wells. However, most times, especially where pre-drilling geophysical investigations for groundwater development are carried out, such information is rare.

This paper has demonstrated that in such situations, 2D electrical images can provide alternative subsurface information needed to constrain VES interpretation to identify groundwater bearing confined fractured basement whose influence is suppressed on the VES curve due to the overlying very high resistivity fresh basement rock or whose thickness is too small to make an impression on the VES curve.

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