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INQUIRY FOR SUITABLE LOCATIONS FOR A DRILLING REGIME AT AN UPSLOPE ROCKY KNOLL OF LAWU ESTATE, WESTERN BYPASS, MINNA, NIGERIA

INVESTIGAÇÃO DE LOCAIS ADEQUADOS PARA UM REGIME DE PERFURAÇÃO EM UMA ELEVAÇÃO ROCHOSA NA ENCOSTA SUPERIOR DA PROPRIEDADE LAWU, CONTORNO OESTE, MINNA, NIGÉRIA

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ABSTRACT

Background: A client requested that the study group help determine locations that would be suitable for a drilling regime at his lot, located at an upslope rocky knoll of Lawu Estate, Minna, Nigeria. **Aim:** The aim of this study is to carry out a purpose-specific survey to pinpoint the best locations in a built-up property at the upmarket Lawu Estate that would be suitable for a drilling regime targeted for household consumption. **Methods:** The study area was reconnoitered by the survey crew in order to georeference the locations that would be occupied for the vertical electrical sounding survey in the 30 m x 20 m lot. Owing to the extensive build-up at this lot, only a four-point traverse along the 30-metric dimension traverse of the frontage of the building was demarcated in the northeasterly direction, thereby limiting the desire of the survey crew to define an appropriate survey grid. The data-acquisition pattern at the 4 x 1 survey stations of the frontage-traverse of the lot followed the “traditional” sequence of Schlumberger array layout measurements, whence the survey crew progressed with current-electrode spacing either end of a survey point located at this frontage-traverse targeting a maximum survey depth of 100 m. **Result:** The acquired vertical electrical-sounding data set for this study was recorded on purpose-specific data sheets. **Discussion:** Based on empirical rules-of-thumb procedures for interpreting vertical electrical sounding data at the Nigerian Basement Complex geological province, “assured” groundwater location and “strongly aquiferous” location, deductive inferences were drawn with regards to only vertical electrical sounding Station 4. **Conclusion:** Thus, it is recommended that VES Station 4 be exploited in the planned drilling program of the client, especially since this survey point checks off 100 percent of the constraints imposed by the rules-of-thumb interpretation procedures.

Keywords: *Geoeolectric; VES; traverse; groundwater; aquiferous*

RESUMO

Introdução: Um cliente solicitou que o grupo de estudos ajudasse a determinar locais adequados para um regime de perfuração em seu lote, localizado em uma elevação rochosa na encosta superior da Propriedade Lawu, Minna, Nigéria. **Objetivos**: O objetivo deste estudo é realizar um levantamento com propósito específico para identificar os melhores locais em uma propriedade edificada na sofisticada Propriedade Lawu que sejam adequados para um regime de perfuração voltado ao consumo doméstico. **Métodos**: A área de estudo foi reconhecida pela equipe de levantamento a fim de georreferenciar os locais que seriam ocupados para o levantamento de sondagem elétrica vertical no lote de 30 m x 20 m. Devido à extensa edificação neste lote, apenas uma travessia de quatro pontos ao longo da travessia de 30 metros da fachada do edifício foi demarcada na direção nordeste, limitando assim o desejo da equipe de levantamento de definir uma grade de levantamento apropriada. O padrão de aquisição de dados nas 4 x 1 estações de levantamento da travessia-fachada do lote seguiu a sequência "tradicional" de medições de arranjo Schlumberger, a partir da qual a equipe de levantamento progrediu com espaçamento de eletrodos de corrente em cada extremidade de um ponto de levantamento localizado nesta travessia-fachada visando uma profundidade máxima de levantamento de 100 m. Resultado: O conjunto de dados de sondagem elétrica vertical adquirido para este estudo foi registrado em planilhas de dados com propósito específico. **Discussão**: Baseando-se em procedimentos empíricos de regras práticas para interpretação de dados de sondagem elétrica vertical na província geológica do Complexo Cristalino Nigeriano, inferências dedutivas foram extraídas em relação apenas à Estação 4 de sondagem elétrica vertical sobre localização "assegurada" de água subterrânea e localização "fortemente aquífera". **Conclusão**: Assim, recomenda-se que a Estação VES 4 seja explorada no programa de perfuração planejado do cliente, especialmente porque este ponto de levantamento atende 100% das restrições impostas pelos procedimentos de interpretação por regras práticas.

Palavras-chave: *Geoelétrico, SEV, travessia, água subterrânea, aquífero.*

1. INTRODUCTION

A client who owns a limited-extent real estate property at the upmarket Lawu Estate requires information of pinpoint accuracy to enable him to determine the best location to invest in drilling a potable-water borehole, albeit after his lot has undergone extensive built-up development. The challenge offered by the client becomes the heart of the problem that the survey crew of this project must solve in light of the fact that, apart from the reality that the lot is already built up, the property is located at an upslope rocky knoll of this estate. This study aims to carry out a purpose-specific survey to pinpoint the best location in a built-up property at the upmarket Lawu Estate that would be suitable for a drilling regime targeted for household consumption. The specific objectives herein are employing the technique of the vertical electrical sounding (VES) mode of the geoelectrical method to achieve this aim in the dual formats of generation of log-log plots and their analyses thereof and generation of an accompanying pseudosection plot and its analysis thereof. The designated area of interest here, a 30 m x 20 m lot located at an upslope rocky knoll, was heavily built-up; thus, the survey crew designated a four-station traverse segmented into 1 x 4 = 4 VES survey stations at the frontage of the built-up compound. The VES survey regime was planned for a total depth of 100 m at each survey location. The wider study area of Lawu Estate is shown in the satellite imagery map of Figure 1. On this map, the built-up area forming the backdrop of the study area has been appropriated demarcated based on the georeferenced information of its edges: Point A at 09°39′50.6″;006°30′50.3″, Point B at 09°39′49.7″;006°30′49.0″, Point C 09°39′49.9″;006°30′49.8″, Point D at 09°39′50.7″;006°30′49.8″. Also indicated in Figure 1 are the four individual points along a linear stretch of the frontage earmarked for the survey (alas, the plotted solid red red triangles for the frontage-traverse are slightly skewed laterally in the northeasterly direction).

***Figure 1**. The satellite imagery map shows the under-construction and partially built-up Lawu Estate, with the core study area appropriately demarcated by solid red triangles.*

According to Obaje (2009), Nigeria's geology is comprised of three major litho-petrological components: the basement complex, younger granites, and sedimentary b*asins*. The Basement Complex, which is Precambrian in age, is made up of the *Migmatite-Gneiss Complex*, the *Schist Belts,* and the *Older Granites.* The Younger Granites comprise several Jurassic magmatic ring complexes centered on Jos and other parts of northcentral Nigeria. They are structurally and petrologically distinct from the Older Granites. The Sedimentary Basins, containing sediment fill of Cretaceous to Tertiary ages, comprise the Niger

Delta, the Anambra Basin, the Lower, Middle, and Upper Benue Trough, the Chad Basin, the Sokoto Basin, the Mid-Niger (Bida-Nupe) Basin and the Dahomey Basin.

The Basement Complex forms a part of the Pan-African mobile belt and lies between the West African and Congo Cratons and south of the Tuareg Shield (Black, 1980). It is intruded by the Mesozoic calc-alkaline ring complexes (Younger Granites) of the Jos Plateau and is unconformably overlain by Cretaceous and younger sediments. The Nigerian basement was affected by the 600 Ma Pan-African orogeny, and it occupies the reactivated region which resulted from plate collision between the passive continental margin of the West African Craton and the active Pharusian continental margin (Burke and Dewey, 1972; Dada, 2006). The basement rocks are believed to be the results of at least four major orogenic cycles of deformation, metamorphism, and remobilization corresponding to the Liberian (2,700 Ma), the Eburnean (2,000 Ma), the Kibaran (1,100 Ma), and the Pan-African cycles (600 Ma). The first three cycles were characterized by intense deformation and isoclinal folding accompanied by regional metamorphism, which was further followed by extensive migmatization. The Pan-African deformation was accompanied by a regional metamorphism, migmatization, and extensive granitization and gneissification, which produced syntectonic granites and homogeneous gneisses (Abaa, 1983). Late tectonic emplacement of granites and granodiorites and associated contact metamorphism accompanied the end stages of this last deformation. The end of the orogeny was marked by faulting and fracturing (Gandu *et al*., 1986; Olayinka, 1992).

According to Yaman *et al.* (2020), the Minna Area is mainly underlain by rocks belonging to the Basement Complex. The authors observed that the main lithological unit that underlies the area is the granites (over 90%), virtually covering the entire map, whilst the other lithological unit is the schist, which occurs in the southeastern part of the area. The cross-section indicates a terrain that is not very rugged but gentle, with the schists forming at higher elevations. The elevation ranges from 240 m to 300 m, the highest point occurring around the Police Secondary School area. The authors remarked that the granites are the youngest of the two rock types.

Jonah *et al.* (2013) were tasked to locate an aquifer at a lot at the Dan Zaria Academic Estate, opposite the Gidan Kwano Campus, Federal University of Technology, Minna. The team members adopted a different approach from the conventional in order to do reconnaissance for the planned survey at this estate; the resistivity type of geoelectrical survey in the VES mode of the Schlumberger array was employed for the reconnaissance and final stages of this investigation. This “unconventional” approach was the acquisition of VES data at shallow depths (i.e., progressively down to 10m) over the area of study in order to determine the point of lowest resistivity instead of the approach to determine the lateral variation of resistivity at these shallow depths using the constant separation traversing (CST) method. The point of lowest resistivity thus identified was surveyed to a final depth of 100m. The authors observed that the 30-40m depth interval at this point was the possible groundwater yield zone.

In fidelity to the “conventional” approach, Jonah *et al.* (2014[a]) prospected for an aquifer at a lot located on a granitic knoll in Minna. At the outset, the client’s property was visually reconnoitered; the extent and preferred traverse directions were noted. The survey crew proposed a north-south (i.e., longitudinal traverse, LT) profiling scheme at a 10 m separation between survey stations and a 10 m separation between profile lines for the constant separation traversing reconnaissance phase to a depth of 15 m. Then, detailed vertical electrical sounding surveys were conducted for locations of “low-ohmic interest” to a depth of 100 m. The result of the reconnaissance phase indicated the lowest resistance value of 1.6348 Ω at “LT4-1.” Upon final VES surveys, it was concluded that the prospect for aquifers of good yield at the area of study was very poor indeed: this conclusion actually corroborated the one drawn from the initial survey that the crew was unaware of.

A third approach in the series of surveys undertaken by Jonah *et al.* (2014[b]) was the “No CST” format, informally described as “not carrying out any reconnaissance survey in order to determine the lateral variation of resistivity.” For this field technique, the VES survey to the 100 m-depth is carried out for each of the selected locations. The survey crew adopted this method to prospect for the suitable location for a desired borehole at a built-up compound of an enclosed bungalow with a self-contained sewage system; only the three corners of the brick fence away from the corner where the cesspool was situated defined in one north-south (longitudinal traverse, LT) and two east-west (transverse traverse, TT) modes were suitable for this survey. Since the client desired a borehole to be drilled at her property, the survey crew considered it inexpedient to do a CST survey, hence the “No CST” format. The derived continuous variation of resistivity with depth model indicated that a four-layer sequence was identified for VES TT1, a four-layer sequence for VES LT1, and a three-layer sequence for VES TT2. The authors based their interpretation of aquifer prospects at the three VES locations on a combination of informal and fairly successful dual empirical rules to determine the likely presence of groundwater in the basement complex geological province. Based on these rules, TT1 indicates the best prospect for groundwater yield in the area of the survey with good showings from the 30m-depth mark down to the 50 m-depth; LT1 could be discounted in water yield terms with respect to TT1, and TT2 satisfies the criteria at the 20m-depth mark and discontinuously still, at the 50 m-depth mark before a spike in “ohmic” values. Also, it was observed that the 50 m-depth mark for TT1 and TT2 correlate very well as a prospective aquifer zone. If drilling must be done at all, then it was recommended that point TT1 be considered a good prospect for groundwater yield over the 20-m “yield window.” Because of the smoothly changing continuum of resistivity values down to the 100 m-depth mark, it was recommended that drilling should be terminated at this maximum or total depth (TD) of the survey in order to tap into the fractured basement at this TD. Incidentally, TT1 was upslope of the sewer pit, which was a plus for this VES station over the possible prospect of TT2.

Ibeneme *et al.* (2014) remark that the different aquifer units within the Lower Orashi River Sub-Basin, Southeastern Nigeria, were delineated using the Vertical Electrical Sounding (VES) technique. The authors observed that twenty-two (22) VES soundings were carried out using the ABEM SAS 4000 Terrameter. The data generated were analyzed using Zohdy software, which outputs modeled curves in terms of depth and resistivity. According to the authors, six profiles were taken in the northeast-southwest and northwest-southeast directions to cover the entire area of study. Four to six geoelectric layers comprising the topsoil, clayey sand, dry sandstone, saturated sandstone, shaley sand, and sandy shale were delineated, with the latter usually occurring as the last layer. The third and fourth layers underlying dry sandstone form the aquiferous unit. This unit was found to have an average resistivity value range of 10.7 – 6060 Ωm and an average thickness of 32 m. It was observed that most of the aquifer units within the area are unconfined, with static water levels varying between 10.6 to 62.8 m. Some of the aquifer units are shallow, with a static water level of less than 40 m, while others are deeper, with a static water level occurring over 60 m below the surface. It was advised that care ought to be taken in drilling and casing at shallow aquiferous areas to maintain proper sanitary conditions so as to reduce the risk of groundwater contamination.

Bahri *et al.* (2016) observe that their endeavor was dedicated to evaluating the quality of groundwater and associated pollution of aquifers at Sukolilo, Surabaya, East Java, Indonesia. They pointed out that the vertical electrical sounding procedure is a geoelectric method used to measure the resistivity of the rocks, and the associated instrumentation of this procedure is used to obtain subsurface information about aquifer depth. The authors employed a water quality tester to determine acidity, conductivity, salinity, oxidation-reduction potential, and total dissolved solid parameters. The authors reported that the prevailing aquifer thickness in the study area is in the region of 3.17 m, and the depth range is between 0.45m and 3.62 m. They also pointed out that local lithology is of an alluvium nature, and this changes toward the north, as indicated by the different depths of the observed rock layers. The authors mention that seawater has intruded into the groundwater at the Sukolilo area, the fact corroborated by high salinity and high total dissolved solid showings. Thus, the authors concluded that water from the unconfined aquifer in Sukolilo was polluted and not suitable for consumption.

Asta and Prasetia (2020), at the MATEC Web of Conferences 331, discussed the application of vertical electrical sounding with a resistivity meter based on a boost converter to estimate the potential of groundwater aquifers in Karang Anyar of Tarakan City, Indonesia. The authors noted that the vertical electrical sounding method is a route that can be used to predict geological and hydrogeological conditions. The authors observed that as a result of the investigation using a resistivity meter based on a boost converter, their result indicated the presence of groundwater at a depth of 7.91m to 44.33 m with a characteristic resistance value of 27.22 Ωm for the estimated lithology of sand.

Pacheco et al. (2023) explained that, in recent years, the occurrence of unexpected meteorological events during the dry season and population growth generated shortages in the supply of drinking water in the city of Pampas, Peru. This situation prompted the authors to look for new search strategies for natural water sources, including underground sources.

The authors observed that faced with this problem, the possibility of detecting and parameterizing these sources was raised, while the design of a tubular well that allows the economic extraction of water from the aquifer was also studied; both of these objectives were achieved through the use of geophysical techniques, generating profile images of geological maps of the strata and the location of the possible water table of the study area.

The authors pointed out that the preferred locations for locating groundwater collections are alluvial fans and fractured valley bottoms. Using the Schlumberger array, eleven (11) vertical electrical soundings were completed up to a depth of 150 m. The acquired resistivity values vary between 6.32 Ωm and 125.23 Ωm. The PQWTS-150-Water Detector equipment was also used to measure the depth of the semi-confined aquifer and to know its groundwater flow.

The authors further noted that the profile of the geological map was described, and in this profile, clayey, silty, sandy, gravelly soils and a combination of them were found. Of particular interest, according to the authors, was VES Point 11, which was surveyed at the location of the nursery in the Daniel Hernández district, the area being flat and humid.

The authors noted that the aquifer at VES Point 11 has good hydrogeological possibilities that made surface recharge possible. The water table was also determined to be between 4 m and 8 m. Subsequently, the tubular well was designed. The authors concluded that the well was designed for a total depth of 115 m.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Hand-Held Global Positioning System (GPS) Unit

The hand-held Garmin GPSmap78® global positioning system unit shown in Figure 2 was employed to georeference the four corners of the lot to be surveyed as well as the individual locations selected for occupation for the VES data acquisition scheme.

***Figure 2**. Hand-held Garmin GPSmap78® global positioning system unit*

2.1.2 Resistivity Meter

The resistivity meter employed for the survey herein, the locally-built Vineyard Geological Survey brand, is shown in Figure 3.

***Figure 3**. A resistivity meter was employed for the survey*

2.2 Methods

2.2.1 Study Area Segmentation

At the outset, the study area was reconnoitered by the survey crew in order to georeference, in a preferred grid format, the locations that would be occupied for the VES survey in the 30 m x 20 m lot. Owing to the extensive build-up at this lot, only a four-point traverse along the 30-metric dimension traverse of the frontage of the building was demarcated in the north-westerly direction, thereby limiting the desire of the survey crew to define an appropriate survey grid. The defined four-point traverse along the frontage of the property becomes desirable in view of the fact that the resulting survey locations will be as far separated from the household below-ground walled septic tank installation as possible. The four-point traverse is indicated in Figure 1.

2.2.2 The VES Survey

The VES data-acquisition pattern at the 4 x 1 (4) survey stations of the frontage traverse of the lot followed the "traditional" sequence of Schlumberger array layout measurements, whence the survey crew progressed with current-electrode spacing on either end of a survey point located at this frontage traverse targeting a maximum survey depth of 100 m. The frontage traverse on the shoulder of an inter-estate roadway means that there was no barrier to the desired progression of the field crew's measurement routine.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Generation of Log-Log Plots

Usually, after determining the resistivity values from the field resistance values, it is desirable to generate curves, commonly log-log plots, showing the variation of resistivity values with the total depth surveyed at that particular sequence for each VES station. It is recognized that the effective depth of penetration is equal to half the current electrode spacing (if distance AB separates the current electrodes, then this AB/2). According to Zohdy (1989), a continuous variation of resistivity with a depth curve is easily derived from a multilayer step-function curve by drawing a curve that passes through the logarithmic midpoint of each vertical and horizontal line on the multilayer step-function model. In view of the fact that the layer depths are logarithmically closely shaped, the derived continuous variation of resistivity with the depth model is equivalent to the original model. This approach makes it easy to construct maps of contoured resistivity values at different depths and contoured geoelectric sections. The field resistivity values were initially subjected to the log-log plot routine of the Windows-compatible WinResist® software, whence corresponding field curves for all the stations occupied were produced. The initial outputs were the "default" graphs. These were further smoothed by iterations, which were done in layers, thus resulting in final "modeled" outputs. The smoothed graphs are those that have connections to all the plotted points on the graph, and these are presented in Figures 4 to Figure 7. The log-log plots of VES Stations 1, 2, 3, and 4, presented as Figure 4, Figure 5, Figure 6, and Figure 7, have been conveniently (though erroneously labeled as those of VES Stations 13, 14, 15, and 16 which do not exist in the archive). Each of the WinResist® log-log plots provides information on the number of layers, the average resistivity values of these layers, their depths of occurrence, and their approximate thicknesses.

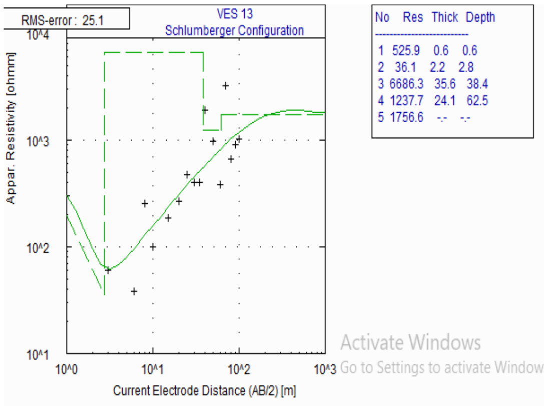

***Figure 4**. Log-log plot of VES Station 1 (erroneously labeled as "VES 13")*

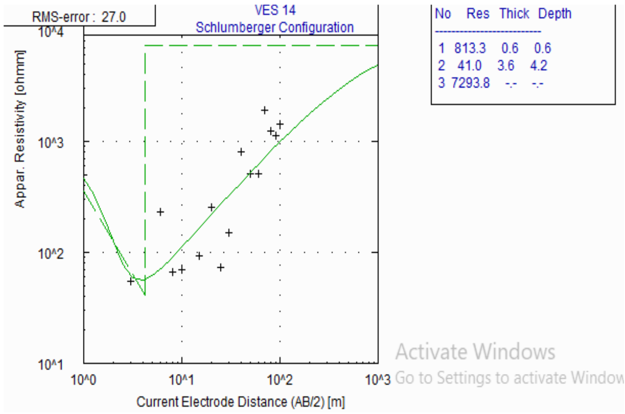

***Figure 5**. Log-log plot of VES Station 2 (erroneously labeled as "VES 14")*

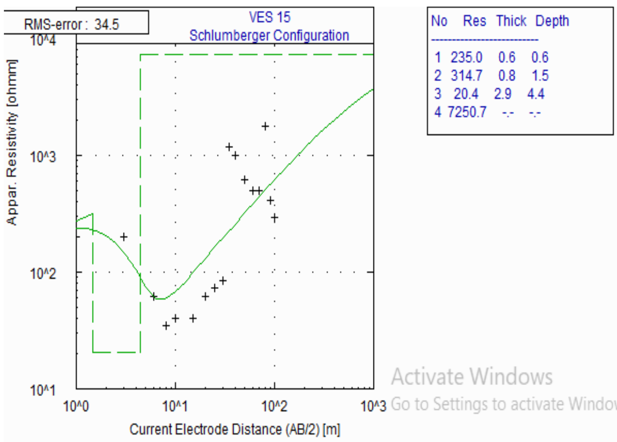

***Figure 6**. Log-log plot of VES Station 3 (erroneously labeled as "VES 15")*

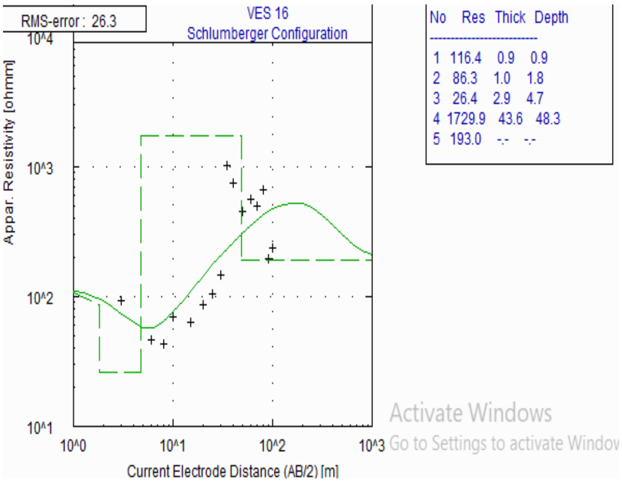

***Figure 7**. Log-log plot of VES Station 4 (erroneously labeled as "VES 16")*

3.1.2 Production of Pseudosection Plot

In order to show the resistivity cross-section along the traverse line of a survey at the study area, a pseudosection plot was generated, and this is shown in Figure 8.

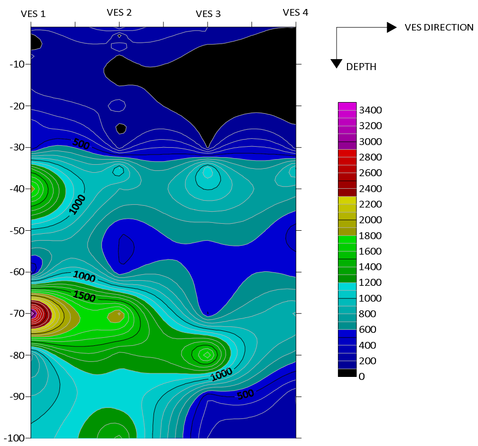

***Figure 8**. Pseudosection plot of study area*

3.2 Discussions

3.2.1 "Tricks" for Groundwater Search at the Nigerian Basement Complex

There exists, for the Nigerian Basement Complex, empirical rules (as complements to the "traditional" interpretation sequences that are taught in schools) by which workers can reliably make deductions with respect to the presence of sustainable groundwater at VES survey points along a line or across an area of study. Loke (2001) quoted Acworth (1981) as stating that "the weathered layer is thicker in areas with fractures in the bedrock." Jonah and Jimoh (2016) examined the validity of an empirical rule for delineating aquifer prospects at the Gidan Kwano Campus Development Phase II, Federal University of Technology, Minna, and this reliable route has been christened "Geoexplore Empirical Standardisation for Minna Area;" the Geoexplore Empirical Standardisation for Minna Area states that resistivity values between 200 Ωm and 300 Ωm at the 20 m depth and less than 200 Ωm at depths greater than 20 m are indicative of possible groundwater prospects. These recognized empirical rules, the veritable "tricks" for groundwater search at the Nigerian Basement Complex, are at the complementary core of the rules-of-thumb employed to determine the location of groundwater in the first and the fourth stage interpretation instances schedule, according to Jonah (2024).

3.2.2 The Log-Log Plots

The log-log plots indicate that, along the four stations of the traverse line of the survey, there is only one station designated as a three-layer location, only one designated as a four-layer location, whilst two stations are designated as five-layer locations. According to Olasehinde (personal communication), the three-layer structure is the expected norm in the local basement geological province. Whereas, too, the norm is to have a comparatively high resistivity value for the third layer of a discerned three-layer geological structure at a general area of survey at the local basement complex geological province in ordinal format, this condition is satisfied for VES Station 2 albeit not in ordinal format. The mid-section layers of the inferred four-layer locations of Figure 6 corresponding to VES Station 3 could be "compressed" into a single layer in order to achieve fidelity to the three-layer specification at the local geological province. In a similar vein, the mid-section layers of the inferred five-layer locations of Figure 4 and Figure 7 corresponding to VES Station 1 and VES Station 4 could be "compressed" into a single layer.

3.2.3 Fidelity to the Log-Log Plots of the First Rule-of-Thumb Schedule to Determine a Groundwater Location

The first rule-of-thumb is recognized herein to be the "traditional" or the "desired outcome" interpretation schedule whence the resistivity of the third layer in a three-layer geological sequence suddenly drops to the below-1000 Ωm values that indicate the presence of fracture for where the prevailing resistivity values of the second layer in this sequence are greater than the 1000 Ωm values that correspond to those for fresh basement.

3.2.3.1 VES Station 1

VES Station 1 is not in fidelity to the first rule-of-thumb schedule.

3.2.3.2 VES Station 2

VES Station 2 is not in fidelity to the first rule-of-thumb schedule.

3.2.3.3 VES Station 3

VES Station 3 is not in fidelity to the first rule-of-thumb schedule.

3.2.3.4 VES Station 4

VES Station 4 is in fidelity to the first rule-of-thumb schedule.

3.2.4 Fidelity to the Log-Log Plots of the Second Rule-of-Thumb Schedule to Determine a Groundwater Location

The second rule-of-thumb is recognized herein to be the protocol of Acworth (1981), henceforth called the Acworth Protocol.

3.2.4.1 VES Station 1

VES Station 1 is not in fidelity to the second rule-of-thumb schedule.

3.2.4.2 VES Station 2

VES Station 2 is not in fidelity to the second rule-of-thumb schedule.

3.2.4.3 VES Station 3

VES Station 3 is not in fidelity to the second rule-of-thumb schedule.

3.2.4.4 VES Station 4

VES Station 4 is not in fidelity to the second rule-of-thumb schedule in a strict sense unless the *circa* 4.7 m thickness of the assumed second layer is considered relatively "thick."

3.2.5 Fidelity to the Log-Log Plots of the Third Rule-of-Thumb Schedule to Determine a Groundwater Location

The third rule-of-thumb is recognized herein to be the Geoexplore Empirical Standardisation for Minna Area.

3.2.5.1 VES Station 1

From examination of the corpus of data collected for this study, VES Station 1 is not in fidelity to the third rule-of-thumb schedule.

3.2.5.2 VES Station 2

From examination of the corpus of data collected for this study, VES Station 2 is not in fidelity to the third rule-of-thumb schedule by and large.

3.2.5.3 VES Station 3

From examination of the corpus of data collected for this study, VES Station 3 is not in fidelity to the third rule-of-thumb schedule by and large.

3.2.5.4 VES Station 4

From examination of the corpus of data collected for this study, VES Station 4 is in fidelity to the third rule-of-thumb schedule by and large, especially at the depth regimes of 20–30 m mark and at the greater depth of 90 m and beyond.

3.2.6 The Pseudosection Plot

The pseudosection plot of the four-station traverse-line study area shows discernible three-resistivity layers, the predominantly low-resistivity trend generally occurring at shallower than the 30 m depth but discernible at greater depth regime at especially the fourth VES station, although there exists a low-resistivity zone of interest at depth beneath the first VES station. The next high-resistivity trend predominates across the traverse line from the 30 m depth downwards, whilst the highest resistivity trend of unmistakable fresh basement character seems to "juts" from VES Station 1 at the 70 m to 80 m depth to seemingly terminate at VES Station 3.

4. CONCLUSIONS

4.1 The Log-Log Plots

4.1.1 Fidelity to the Log-Log Plots of the First Rule-of-Thumb Schedule to Determine a Groundwater Location

4.1.1.1 VES Station 1

As per the constraint of the first rule-of-thumb schedule to determine a groundwater location, VES Station 1 is not "hydro-centric." The term “hydro-centric” is used herein to indicate “water-bearing.”

4.1.1.2 VES Station 2

As per the constraint of the first rule-of-thumb schedule to determine a groundwater location, VES Station 2 is not “hydro-centric.”

4.1.1.3 VES Station 3

As per the constraint of the first rule-of-thumb schedule to determine a groundwater location, VES Station 3 is not “hydro-centric.”

4.1.1.4 VES Station 4

VES Station 4 is tagged “hydro-centric” based on its conformity to the first rule-of-thumb schedule.

4.1.2 Fidelity to the Log-Log Plots of the Second Rule-of-Thumb Schedule to Determine a Groundwater Location

4.1.2.1 VES Station 1

As per the constraint of the second rule-of-thumb schedule to determine a groundwater location, VES Station 1 is not “hydro-centric.”

4.1.2.2 VES Station 2

As per the constraint of the second rule-of-thumb schedule to determine a groundwater location, VES Station 2 is not “hydro-centric.”

4.1.2.3 VES Station 3

As per the constraint of the second rule-of-thumb schedule to determine a groundwater location, VES Station 3 is not “hydro-centric.”

4.1.2.4 VES Station 4

As per the constraint of the second rule-of-thumb schedule to determine a groundwater location, VES Station 4 meets the “hydro-centric” classification under the “relaxed” condition of assuming that a 4.7 m thickness regime of the assumed second layer is relatively “thick.” Moreover, the “hydro-centric” nature and designation of VES Station 4 is assured from fidelity to the first rule-of-thumb schedule.

4.1.3 Fidelity to the Log-Log Plots of the Third Rule-of-Thumb Schedule to Determine a Groundwater Location

4.1.3.1 VES Station 1

As per the constraint of the third rule-of-thumb schedule to determine a groundwater location, VES Station 1 is not “hydro-centric.”

4.1.3.2 VES Station 2

As per the constraint of the third rule-of-thumb schedule to determine a groundwater location, VES Station 2 is not “hydro-centric.”

4.1.3.3 VES Station 3

As per the constraint of the third rule-of-thumb schedule to determine a groundwater location, VES Station 3 is not “hydro-centric.”

4.1.3.4 VES Station 4

VES Station 4 is tagged “hydro-centric” based on its conformity to the third rule-of-thumb schedule.

4.1.4 Percentage Fidelity of VES Station 1 to the Three Rules-of-Thumb: 0%.

4.1.5 Percentage Fidelity of VES Station 2 to the Three Rules-of-Thumb: 0%.

4.1.6 Percentage Fidelity of VES Station 3 to the Three Rules-of-Thumb: 0%.

4.1.7 Percentage Fidelity of VES Station 4 to the Three Rules-of-Thumb: 100%.

4.1.8 Deductive Inference Regarding VES Station 1

Based on percentage fidelity to the three rules-of-thumb, VES Station 1 is not a groundwater location.

4.1.9 Deductive Inference Regarding VES Station 2

Based on percentage fidelity to the three rules-of-thumb, VES Station 2 is not a groundwater location.

4.1.10 Deductive Inference Regarding VES Station 3

Based on percentage fidelity to the three rules-of-thumb, VES Station 3 is not a groundwater location.

4.1.11 Deductive Inference Regarding VES Station 4

Based on percentage fidelity to the three rules-of-thumb, VES Station 1 is an “assured” groundwater location or a “strongly aquiferous” location, “aquiferous” being a term coined by Jonah (personal communication) to indicate association with the likelihood of aquifer in the subsurface.

4.2 The Pseudosection Plot

The pseudosection plot validates the "assured" groundwater location and "strongly aquiferous" location deductive inference drawn with regard to VES Station 4. The reason for not designating VES Station 1, VES Station 2, and VES Station 3 as "aquiferous" locations is obvious from the pseudosection plot.

A 75% "fail" margin for this survey does not come across as a surprise because of the location of the traverse line of the survey in an area of prominent and profuse granitic outcrop showings. In spite of the high 75% "fail" margin for this survey, VES Station 4 "checks off" all the constraints of the groundwater-determination rules-of-thumb for 100% assurance. Thus, it is strongly recommended that VES Station 4 be exploited in the planned drilling programme of the client.

5. DECLARATIONS

5.1 Study Limitations

No limitations were known at the time of the study.

5.2 Acknowledgements

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5.4 Competing Interests

The authors declare that there exists no conflict of interest whatsoever arising from the preparation of this manuscript for publication with any other competing interests, whether they be of the authors' or of second parties and third parties thereof. The data employed in the enunciation of the textual material herein are original, having been duly acquired by the authors as part of the annual undergraduate schedule of project supervision here at the Federal University of Technology, Minna, Nigeria. This body of data field, duly archived for validation and reference purposes, is available for integrity checks anytime.

5.5 Open Access

6. REFERENCES:

1. Abaa, S.I. The structure and petrography of alkaline rocks of the Mada Younger Granite Complex, Nigeria. *J Afr Earth Sci*, **1983**, *3*,107–113.
2. Acworth, R.I. *The Evaluation of Groundwater Resources in the Crystalline Basement of Northern Nigeria*, **1981**, PhD Thesis, Univ. of Birmingham.
3. Asta* and Prasetia, A.M. Application of vertical electrical sounding (VES) method with resistivity meter based on boost converter to estimate the potential of groundwater aquifers in Karang Anyar of Tarakan City. *MATEC Web of Conferences 331,* **2020**. https://doi.org/10.1051/matecconf/202033106001. (*Single-named Indonesian author.)
4. Bahri, F.A., Rismayanti, H.F., and Warnana, D.D. Groundwater analysis using vertical electrical sounding and water quality tester in Sukolilo Area, Surabaya, East Java: Significant information for groundwater resources, Second International Seminar on Science and Technology, Postgraduate Program, Institut Teknologi Sepuluh Nopember ("the Tenth of November Institute of

Technology"), Surabaya, Indonesia, **2016**.
5. Black, R. Precambrian of West Africa. *Episodes,* **1980**, *4*, 3-8.
6. Burke, K.C. and Dewey, J.F. Orogeny in Africa. In: Dessauvagie, T.F.J., Whiteman, A.J. (eds), *Africa Geology*, **1972**, University of Ibadan Press, Ibadan, pp 583-608.
7. Dada, S.S. Proterozoic evolution of Nigeria. In: Oshi, O. (ed.), *The Basement Complex of Nigeria and its Mineral Resources (A Tribute to Prof. M. A. O. Rahaman)*, **2006**, Akin Jinad & Co., Ibadan, pp 29-44.
8. Gandu, A.H., Ojo, S.B., Ajakaiye, D.E. A gravity study of the Precambrian rocks in the Malumfashi area of Kaduna State, Nigeria. *Tectonophysics*, **1986**, *126*, 181–194.
9. Ibeneme, S.I., Okereke C.N., Iroegbu C., Etiefe E.O. Vertical electrical sounding for aquifer characterization around the Lower Orashi River Sub-Basin, Southeastern Nigeria. *Communications in Applied Sciences*, **2014**, *2(1)*, 36–51.
10. Jonah, S.A. *Dual Geoelectrical Survey Regime to Profile Groundwater Occurrence at an East-Central Tranche of the Gidan Kwano Campus, Minna, Nigeria*, **2024**, Unpublished Synopsis for PhD Thesis, Federal University of Technology, Minna, Nigeria.
11. Jonah, S.A. and Jimoh, M.O. Validity of an empirical rule for delineating aquifer prospects at the Gidan Kwano Campus Development Phase II, Federal University of Technology, Minna, Northcentral Nigeria. *Journal of Science, Technology, Mathematics, and Education (JOSTMED)*, 12(2), **2016**, 18-24.
12. Jonah, S.A., James, G.O., Adeku, D.E., Ahmed, F., Alhassan, A., Hamza, S., Igbideba, O. I., Kyari, M., Kwaghhua, F.I., Macaulay, V. F., Olarewaju, S.I., Onyeodili, G., Popoola, G.B., Sofeso, O.A., Switzer, F. K., and Umoh, U.E. A survey for groundwater at a lot at the Dan Zaria Academic Estate, Federal University of Technology, Minna, Central Nigeria. *Journal of Science, Technology, Mathematics, and Education*, **2013**, *9(3)*, 26–38.
13. Jonah, S.A., James, G.O., Adeku, D.E., Ahmed, F., Alhassan, A., Hamza, S., Igbideba, O. I., Kyari, M., Kwaghhua, F.I., Macaulay, V. F., Olarewaju, S.I., Onyeodili, G., Popoola, G.B., Sofeso, O.A., Switzer, F. K., and Umoh, U.E. Pre-drilling geoelectrical survey at a built-up compound at Barkin-Sale Ward, Minna, Niger State, Nigeria. *Journal of Information, Education, Science, and Technology*, **2014[b]**, *1(2)*, 86–97.
14. Jonah, S.A., Umoh, S.E., James, G.O., Adeku, D.E., Ahmed, F., Alhassan, A., Hamza, S., Igbideba, O. I., Kyari, M., Kwaghhua, F.I., Macaulay, V. F., Olarewaju, S.I., Onyeodili, G., Popoola, G.B., Sofeso, O.A., Switzer, F. K., and Umoh, U.E. A blind geoelectrical survey commissioned to affirm or deny the presence of aquifer at a compound at Minna, Central Nigeria. *Journal of Information, Education, Science, and Technology,* **2014[a]**, *1(2)*, 20–38.
15. Loke, M.H. *Tutorial: 2-D and 3-D Electrical Imaging Surveys*, **2001**, Google search, 8th August 2018, 11:08 a.m.
16. Obaje, N.G. *Geology and Mineral Resources of Nigeria*. In: Lecture Notes in Earth Sciences, **2009**, Springer-Verlag, Berlin.
17. Olayinka, A.I. Geophysical siting of boreholes in crystalline basement areas of Africa. *J Afr Earth Sci*, **1992**, *14*,197–207.
18. Pacheco, M. del P.C., Flores, J.A.C., Salvador, D.J.J., and Capcha, T.M. Vertical electrical sounding method to detect groundwater and design of a tubular well for the Pampas District, Peru. *Civil Engineering and Architecture*, **2023**, *11(4)*, 1984-2006. DOI: 10.13189/cea.2023.110423.
19. Yaman, A., Idris-Nda, A., Goro, A.I., and Ejepu, J. S. (). The geology and hydrogeology of parts of Minna Sheet 164 NE. *Minna Journal of Geosciences*, **2020**, *4(2)*, 96-107.
20. Zohdy, A.A.R. A new method for the automatic interpretation of Schlumberger and Wenner sounding curves. *Geophysics*, **1989***, 54(2)*, 245-253.