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Evaluation of Aquifer Protective Capacity and Soil Corrosivity Using Geoelectrical Method

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***Abstract*—**A geoelectric survey was carried out in some parts of Angwan Gwari, an outskirt of Lapai Local Government Area on Niger State which belongs to the Nigerian Basement Complex, with the aim of evaluating the soil corrosivity, aquifer transmissivity and protective capacity of the area from which aquifer characterisation was made. The G41 Resistivity Meter was employed to obtain fifteen Schlumberger Vertical Electrical Sounding data along profiles in a square grid network. The data were processed using interpex 1-D sounding inversion software, which gives vertical electrical sounding curves with layered model comprising of the apparent resistivities, overburden thicknesses, and depth. This information was used to evaluate longitudinal conductance and transmissivities of the layers. The results show generally low resistivities across the survey area and an average longitudinal conductance variation from 0.0237Siemens in VES 6 to 0.1261Siemens in VES 15 with almost the entire area giving values less than 1.0 Siemens. The average transmissivity values range from 96.45 $\Omega.m^2$ in VES 4 to 299070 $\Omega.m^2$ in VES 1. All but VES 4 and VES14 had an average overburden greater than 400 $\Omega.m^2$, these results suggest that the aquifers are highly permeable to fluid movement within, leading to the possibility of enhanced migration and circulation of contaminants in the groundwater system and that the area is generally corrosive.

***Keywords*—**Geoelectric survey, corrosivity, protective capacity, transmissivity

I. Introduction

ELECTRICAL resistivity methods can be applied for studying variations of resistivity with depth or for lateral profiling. These variations arise due to the difference in electrical properties of rocks in the lithologic units of the subsurface and fluid content. The resistivity of coarse-grained, well-consolidated sandstone saturated with fresh water is higher than that of unconsolidated silt of the same porosity, saturated with the same water [1]. The resistivities of identical porous rock samples vary considerably according to the salinity of the saturating water such that the higher the salinity of the water, the lower the resistivity of the rock. Thus, the number and thicknesses of the geoelectric units as determined from VES measurements at a locality may not necessarily be the same as the geological ones [2].

The aim of VES survey is usually to obtain true resistivity logs similar to the induction log of a well in the vicinity without actually drilling a hole. However, because of inherent limitations, the resolution of the method may not be as high as that of the induction log. Nonetheless, the VES method has remained the most inexpensive of subsurface exploration methods with a very good propensity for noble results thereby making the method very suitable for groundwater exploration.

The application of the VES techniques were, until recently, limited to shallow investigations, mainly because electronic measuring devices of sufficient sensitivity were not available except in bulky forms, and partly because deeper penetration would have meant a wider variety of resistivity layers than could possibly be incorporated in any set of standard resistivity curves. These standard curves provided the only means of interpretation by the curve matching techniques. However, with the advancement in technology, culminating in the development of modern scientific equipment and interpretation software, the interpretation of VES data has become much easier.

The demand for water in Lapai has been on the increase due to the growing demand in the commodity for domestic and agricultural uses. Managing existing water supplies to fully satisfy all uses has proven difficult, particularly in dry season. Groundwater is therefore, the likely source that can ameliorate the problem and hence the need to find genuine and effective way of harnessing it. Despite this seemingly important relief, there could be threats of contamination to groundwater occasioned by soil corrosivity and infiltration of contaminants from the surface through the migration paths into the aquifers. It is in trying to monitor the quality of groundwater that we used the VES method to decipher the structure layering of the subsurface in Angwan Gwari area of Lapai local government area (a basement complex) with a view to finding the depth to water bearing formations. Determining the geoelectric characteristics of the aquifers and using this information to determine the soil corrosivity and aquifer protective capacity.

Geophysical investigations have been carried out in different parts of the world for groundwater investigation. Reference [3] used the electrical resistivity method to map fractures, gorges gouge, and faults which act as water reservoirs. Reference [4] carried out groundwater investigations at Darazo on the Kerri-Kerri Formation and concluded that Dar-Zarouk parameters are related to borehole characteristics. According to them, the highest traverse resistance (T) corresponds to the zones with the highest borehole yield. Reference [5] used the electrical resistivity method for groundwater investigation in parts of the Basement terrain in Southwest Nigeria and reported that the weathered layer and the fractured Basement constitute the aquifer zones. Reference [6] used the electrical resistivity method in investigation of geo-electric and hydro-geologic characteristics of areas in Southwest Nigeria. Reference [7]

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carried out groundwater investigation at Igbogbo, Lagos, using seismic refraction and electrical resistivity techniques. They correlated the results from each method and delineated aquifer zones. Reference [8] used very low frequency electromagnetic and vertical electrical sounding techniques in delineating aquifer zones in Modeme area, Ife, Osun State.

II. Location and Geology of the Study Area

Angwan Gwari is situated within, Lapai local government area along Suleja road. The area is located in the basement complex between latitude 9º3'20"N, 9º3'0"N and 9º2'40"N and longitude 6º35'20"E, 6º35'40"E, 6º36'0"E, 6º36'20"E, and 6º36'40"E along Lapai – Minna road. Fig. 1 shows the location map of the study area. The area has a gently undulating topography that is covered with vegetation, stream, farmland, and shrubs. It has fine grain texture of sand; clayey-sand, laterite and few visible exposures of granites.

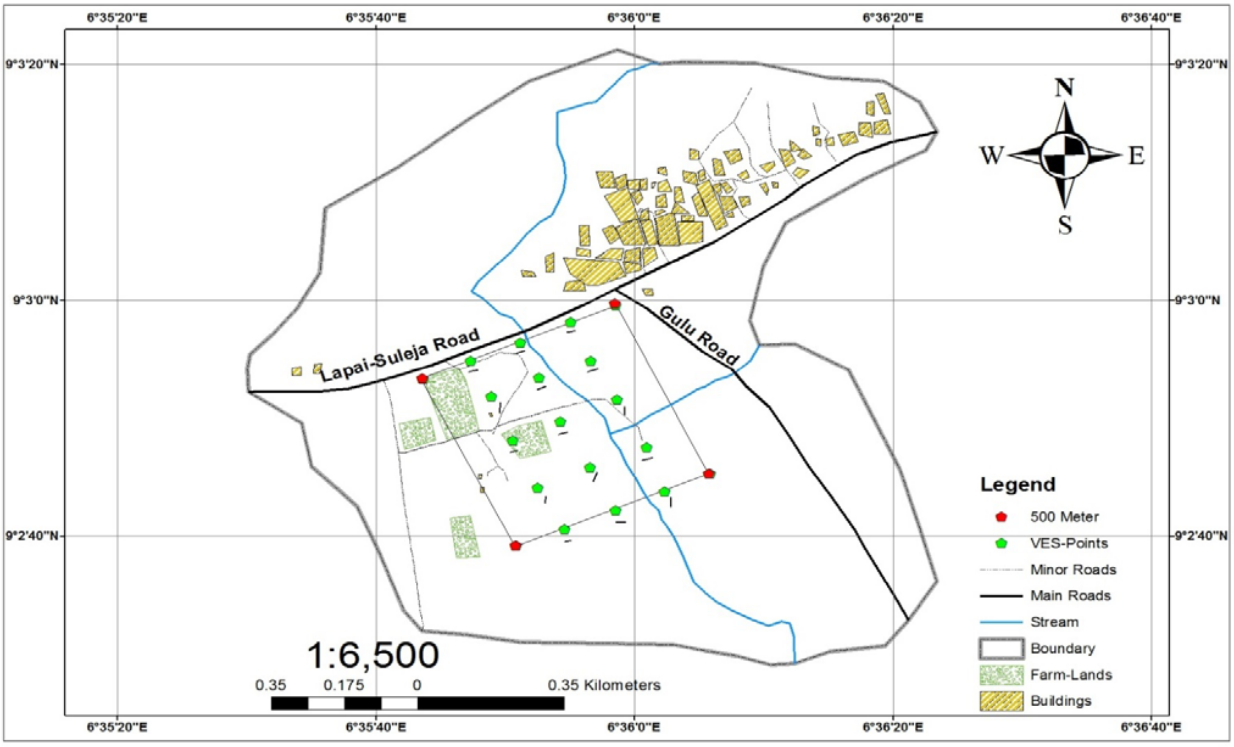


Fig. 1 Location map of the study area

Beneath the area, underlie bedrock of the Precambrian crystalline basement complex including volcanic igneous rocks and younger granites with whale blacks, granite pavements and isolated blocky moulds. The basement complex rock in the area is dominated by granite and granite gneiss which forms the main rock types. In the field, the foliation is broadly oriented north south and marked by a sub-parallel alignment of elongated and closely packed feldspar phenocrysts, mainly microcline, and a corresponding preferred orientation of North-South direction. The medium to coarse-grained granite occurs as small but discrete bodies with variable shape, intruding the main porphyritic biotite granite [9]. The largest area of Basement complex is in North-Central Nigeria with elevations in the region exceeding 500m around Jos, Plateau State, where thermal uplift has taken place related to the intrusion of the Jurassic Younger Granite Ring Complexes, while younger volcanic activities have elevations exceeding 1000m [10].

The local hydrology of the area could be inferred from existing boreholes and dug wells in their close neighborhood which manifest shallow groundwater circulation, as is the usual case in basement areas. The quest to describe the occurrence, structural and stratigraphic relationships, classification, and illustration of the metamorphic history and evolution of the rocks, led [11]-[15] among several others to carry out extensive study of the rocks of the Precambrian Basement Complex of Nigeria. Based on these studies the Basement Complex is divided into the NS trending western zone elongated schist belts separated by migmatites, gneisses and granites; and the eastern zone in which the schist belts are poorly represented, comprising mainly migmatites, gneisses, and granites.

III. Methodology

Electrical resistivity surveys are based on Ohm's law which holds for simple circuits as well as earth materials. According to the law, if R is the resistance and A is the unit cross-sectional area of a material of unit length L through which current passes, then:

$$V = IR \text{ and } \rho = \frac{RA}{L} \text{ or } \sigma = \frac{L}{RA} \quad (1)$$

where ρ is the intrinsic property of the material called resistivity, σ is the conductivity and V is the voltage drop across the material.

If we define the current density, J as:

$$J = \frac{I}{A} \quad (2)$$

then using (1) in (2)

$$J = \frac{\sigma dV}{dl} \quad (3)$$

In three dimensions

$$J = -\sigma\left(i\frac{\partial v}{\partial x} + j\frac{\partial v}{\partial y} + k\frac{\partial v}{\partial z}\right) \quad (4)$$

The electrical resistivity method employs an artificial source of current which is introduced into the ground through a pair of electrodes. The potential difference between two electrodes in the vicinity of current flow id then measured. With the knowledge of the geometric factors, the apparent resistivity, ρ_a of the subsurface is then deduced.

For a single electrode located on the boundary of a semi-infinite, electrically homogeneous medium, which represents an assumed homogeneous earth and the electrode carries a current I, the potential at any point in the medium or on the boundary is giving by:

$$V = \frac{\rho I}{2\pi r} \quad (5)$$

r is distance from the electrode.

For an electrode pair with current I at electrode A, and –I at electrode B as shown in Fig. 2, the potential at a point is giving by:

$$V = \frac{\rho I}{2\pi r_A} - \frac{\rho I}{2\pi r_B} = \frac{\rho I}{2\pi r}\left[\frac{1}{r_A} - \frac{1}{r_B}\right] \quad (6)$$

where $r_A and$ r_B are distances from the point to electrodes A and B respectively.

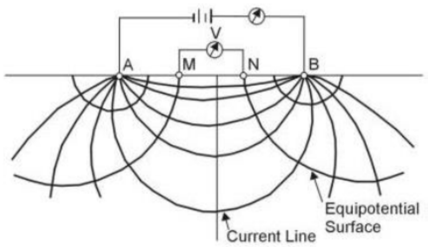


Fig. 2 Electrode configuration

When measurements are made over a real heterogeneous earth, it is apparent resistivity ρa that is measured. These apparent resistivity values from field observations at various locations and with various electrode configurations are used to estimate the true resistivities of the several earth materials present at a site and to locate their boundaries spatially below the surface of the site [16]. An electrode array with constant spacing is used to investigate lateral changes in apparent resistivity reflecting lateral geologic variability or localized anomalous features while the electrode spacing is varied if the changes in resistivity with depth are to be investigated. The types of electrode arrays that are most commonly used are Schlumberger and Wenner. In each case, direct current is passed into the earth at A and received at B. The potential generated in the earth as a result of this current is measured between the potential electrodes $M$and N as shown in Fig. 2.

In a four electrode arrangement,

$$\Delta V = \frac{I\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} - \frac{1}{r_4}\right) \quad (7)$$

where r_i are geometrical parameters that depend on the electrode spacing.

If a heterogeneous earth

$$\rho_a = \frac{2\pi V}{I}\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} - \frac{1}{r_4}\right)^{-1} \quad (8)$$

$$\Rightarrow \rho_a = \frac{K\Delta V}{I} \quad (9)$$

where

$$K = 2\pi\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} - \frac{1}{r_4}\right)^{-1} \quad (10)$$

is known as the geometric factor

A .Soil Corrosivity Evaluation

The first layer resistivity values can be used in generating corrosivity map which is used in the evaluation of the degree of soil corrosivity at shallow depth, in the area, should metal pipes/buried utilities be required for reticulation works in the groundwater development and other engineering utilities. Areas characterized by relatively low resistivity values are considered corrosive while areas with high resistivity values are considered non-corrosive.

B. Overburden Protective Capacity Evaluation

The ability of an earth medium to retard and filter percolating fluid is the measure of its protective capacity [17]. Reference [18] further described the protective capacity of an overburden exerted by retardation and filtration of percolating pollutants as being proportional to its thickness and inversely proportional to its hydraulic conductivity. Clayey material content is generally characterized by low permeability, low resistivity, low hydraulic conductivity, and longitudinal unit conductance values. Hence, the protective capacity can be considered as being proportional to the longitudinal conductance (S). Therefore, the higher the overburden longitudinal conductance of an area, the higher its protective capacity.

If we have $n-1$ layers overlying a semi-infinite substratum of resistivity ρ_n, the Longitudinal Conductance S is obtained according to [19] as:

$$S_i=\sum_{i=0}^{n}\frac{h_i}{\rho_i}(\text{Siemens}) \quad (11)$$

where ρ_i and h_i are the layer resistivity and thickness of the ith layer respectively.

The protective capacity (P_c) of an overburden layer is proportional to its longitudinal conductance S, so that:

$$P_c = S$$

The values of the longitudinal conductance less than 1.0 Siemens indicate that the overburden rock materials have no significant quantity of impermeable clay overlying strata which demonstrates high infiltration rates of surface contaminants into the aquifer.

The Dar Zarouk parameter for transverse resistance (R) is expressed by [19] as:

$$R_i = \sum_{i=1}^{n} h_i \,.\, \rho_i (ohm.m^2) \quad (12)$$

where p_i is the layer resistivity and h_i is the thickness of the ith layer.

Transverse resistance is numerically equal to the transmissivity, T. If the transverse resistance values are >400 Ωm^2 and correspond to zones where the thickness and resistivities of the aquifer are large, the aquifer materials are highly permeable to fluid movement within the aquifer, which may possibly enhance the migration and circulation of contaminants in the groundwater aquifer [19].

C. Methods

The preliminary field techniques involved clearing of profiles, measurements and pegging at prospective electrode points. The G41 Geotron Resistivity Meter was used for data collection, while a global positioning system (GPS) device model 60Cx was used to obtain the coordinates of each VES point. Direct current was introduced into the ground through a pair of steel, non polarisable electrodes driven into the ground. Two potential electrodes closely spaced and symmetrical about the sounding point were sandwiched by two current electrodes. Measurements of the apparent resistivity values were then read from the equipment for each potential, and current electrode spacing along the profiles traversed, at the lowest standard deviation. To increase the depth of investigation, the current electrode separation was increased while the potential separation remained constant. The potential electrodes were however changed whenever a loss in sensitivity was noticed and measurements repeated for the same current spacing.

The apparent resistivity data so obtained were plotted against half electrode separation on a logarithmic scale and interpreted quantitatively using the interpex 1xD sounding interpretation software which provides an automatic means of analyzing and determining models and representation.

IV. Results and Discussion

The resistivity values obtained from the measurement as well as the estimated depths and thicknesses of the layers are as shown in Table I for each of the VES points investigated. A quantitative interpretation of the data collected from different points in the study area revealed basically four litho-sections viz: top lateritic soil, silty/ sandy clay, weathered basement, and fresh basement rock. The interpreted geophysical characteristics of the litho-sections are shown in Table I. Four curve types were also delineated which include the HA, AK, H and KH as shown in Table I with the AK type occurring more frequently.

In order to ascertain the aquifer protectivity, transmissivity and soil corrosivity of the area under consideration, the longitudinal conductance and transverse resistance values were evaluated from the measured resistivity values and the thicknesses of the layers using (11) and (12) respectively as shown in Table II. The results indicate that the average transmissivity values range from 96.45 $\Omega.m^2$ in VES 4 to 299070 $\Omega.m^2$ in VES 1. All but VES 4 and VES14 had an average overburden greater than 400ohm-meter squared, an indication that the aquifers are highly permeable to fluid movement within, leading to the possibility of enhanced migration and circulation of contaminants in the groundwater system.

The longitudinal conductance also shows a variation from 0.0237 Siemens in VES 6 to 0.1261 Siemens in VES 15. On average, all the VES points show values of longitudinal conductance that are less than 1.0 Siemens, suggesting that the overburden rock materials have no significant quantity of impermeable clay overlying strata which demonstrates high infiltration rates of surface contaminants into the aquifer.

The resistivity values as obtained from the measurements show that overburden values are relatively low except that of VES 1. This indicates that the area is generally corrosive. This corrosivity could be attributed to the chemical constituents of the area and may cause structural failure, buried pipelines, storage tanks and cables.

A comparison of the interpreted data with a borehole log in the vicinity of the study area shows a strong correlation in the lithology revealed as shown in Fig. 3. Figs. 4 (a)-(e) show the model curves of some selected VES points in the study area.

V. Summary and Conclusion

The resistivity method has been effectively deployed in obtaining information on the depth to water bearing formations, thicknesses of the aquifer units, soil corrosivity and aquifer protectivity. The G41 Geotron resistivity meter was used in obtaining data from fifteen (15) VES stations in Angwan Gwari area of Lapai Local Government which belongs to the Nigerian Basement Complex. The Schlumberger array was used since it gives a better resolution when deployed for VES studies while the Global positioning system (GPS) map 60Cx device was used to determine the coordinates of each sounding point. The interpex 1xD sounding interpretation software was used for data interpretation with a view to determining the depths and thicknesses of aquifer formations which were used in evaluating the longitudinal conductance and transverse resistance with a view to determining aquifer protectivity and transmissivity.

The results show that all but VES 4 and VES14 had an average overburden greater than Ω.m2, an indication that the aquifers are highly permeable to fluid movement which could lead to the possibility of enhanced migration and circulation of contaminants in the groundwater system. In addition, the VES points also show values of longitudinal conductance that are less than 1.0 Siemens, suggesting that the overburden rock materials have no significant quantity of overburden which validates the assertion of high infiltration rates of surface contaminants into the aquifer. The resistivity values as obtained from the measurements show that overburden values are relatively low, an indication that the area is generally corrosive.

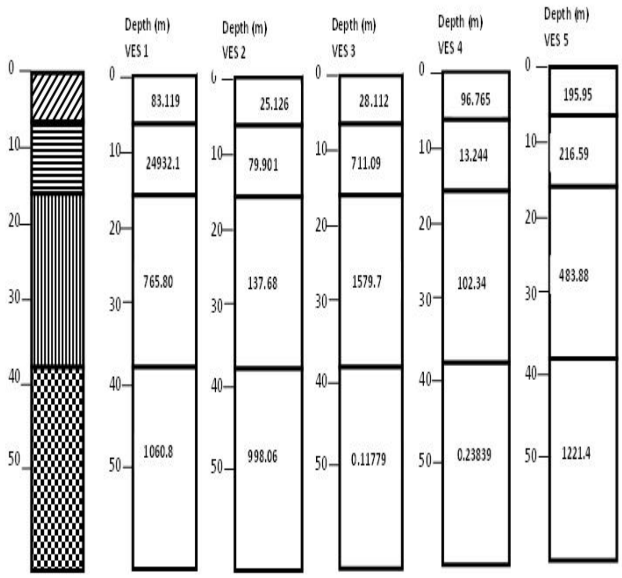
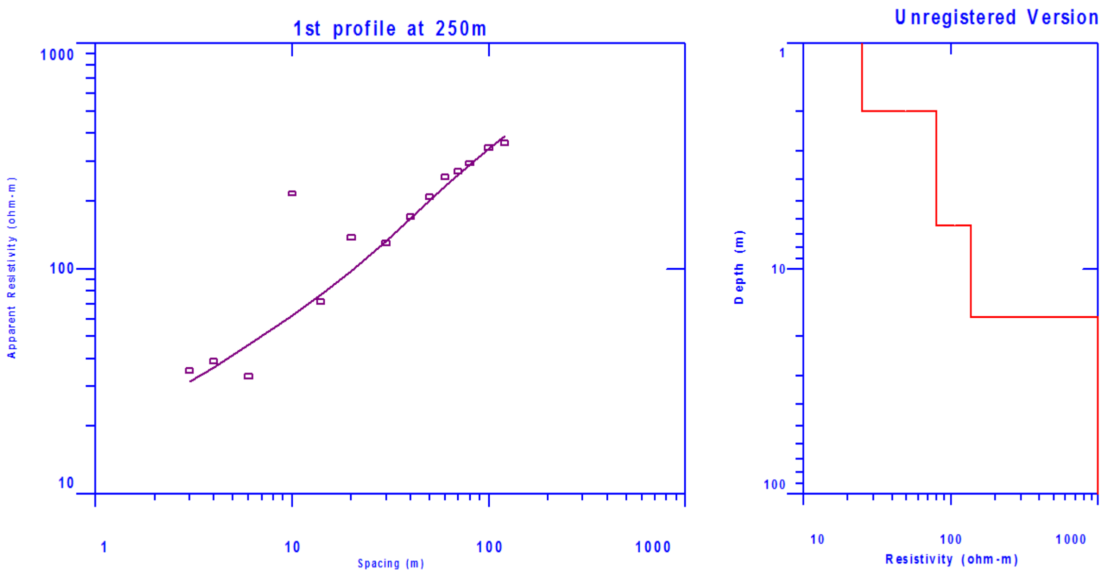
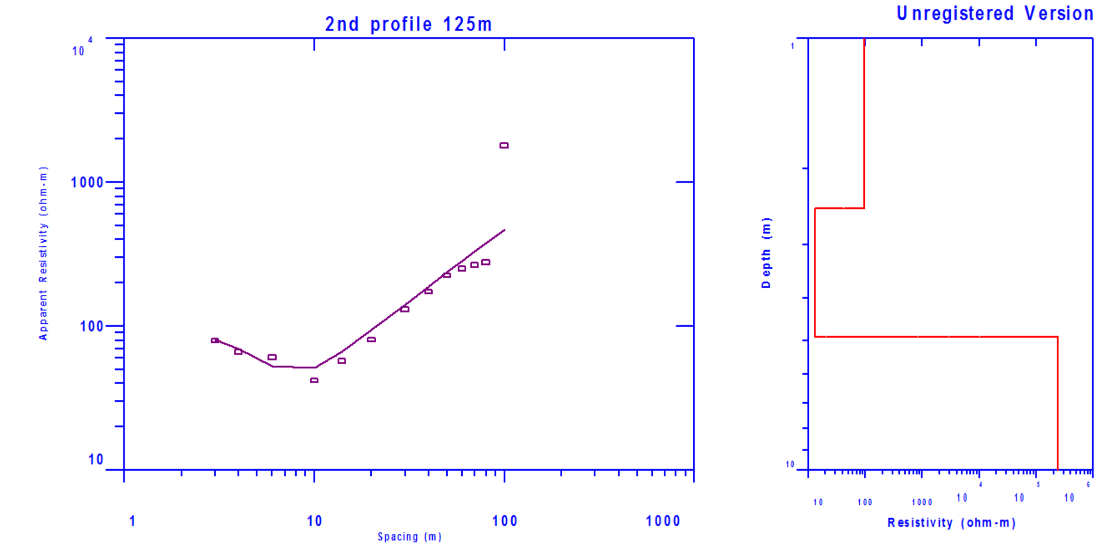


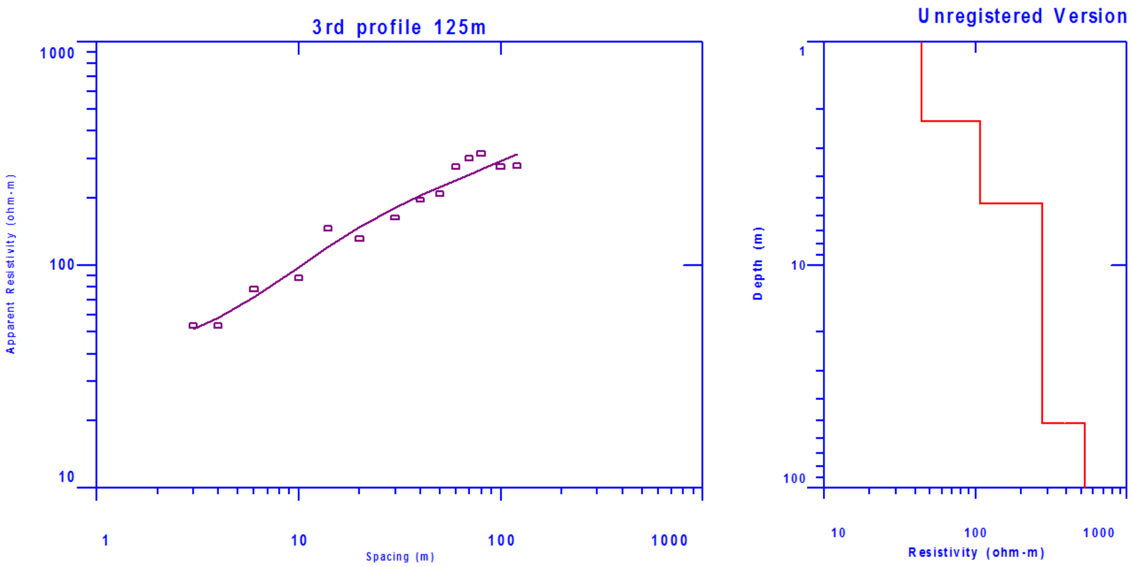
Fig. 3 Resistivity Logs of some VES Points



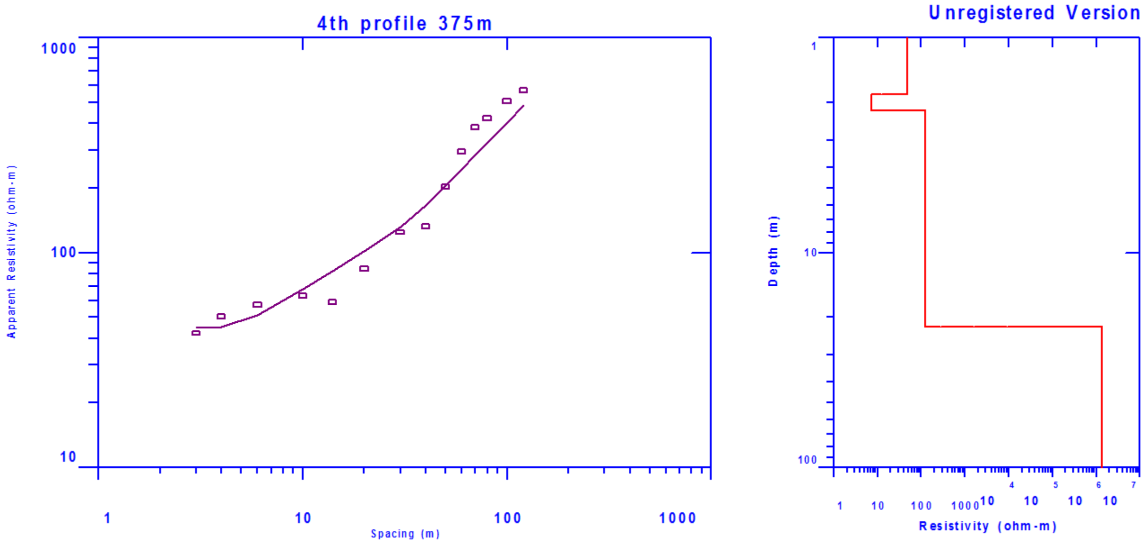
(a)


2nd profile 125m
Apparent Resistivity (ohm-m)
Spacing (m)
Unregistered Version
Depth (m)
Resistivity (ohm-m)

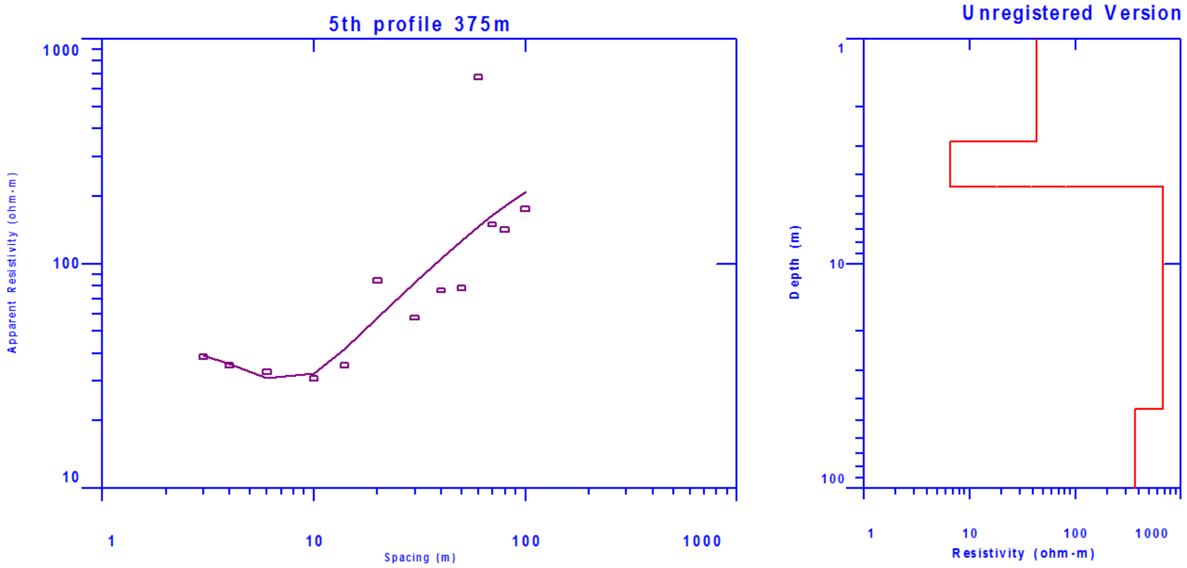
(b)


3rd profile 125m
Apparent Resistivity (ohm-m)
Spacing (m)
Unregistered Version
Depth (m)
Resistivity (ohm-m)

(c)



(d)



(e)

Fig. 4 (a) Selected model curve for first profile, (b) selected model curve for second profile, (c) selected model curve for third profile, (d) selected model curve for fourth profile, (e) selected model curve for fifth profile

TABLE I
LAYER MODEL FOR THE VES STATIONS

VES Point	Coordinates & direction	Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Elevation (m)	Curve Type	Lithology
1	09˚02'57.3N		83.119	17.4	17.4	148.59	HA	Top lateritic soil
	006˚35'59.9E		24932.1	34.7	52.1	113.86		Silty/sandy clay
	166m		765.80	40.0	92.1	73.863		Weathered basement
			1060.8	∞	∞			Fresh basement
2	09˚02'55.6N		25.126	2.00	2.00	159.06	AK	Top lateritic soil
	006˚35'56.3E		79.901	4.40	6.40	154.59		Silty/sandy clay
	161m		137.68	10.0	16.4	144.59		Weathered basement
			998.06	∞	∞			Fresh basement
3	09˚02'53.6N		28.112	6.03	6.03	166.97	AK	Top lateritic soil
	006˚35'52.9E		711.09	1.55	7.59	165.41		Silty/sandy clay
	173m		1579.7	30.0	37.59	135.41		Weathered basement
			0.11779	∞	∞			Fresh basement
4	09˚02'54.4N		96.765	2.47	2.47	168.53	HA	Top lateritic soil
	006˚36'01.2E		13.244	2.45	4.92	166.08		Silty/sandy clay
	171m		102.34	0.14	4.92	166.08		Weathered basement
			0.23839	∞	∞			Fresh basement
5	09˚02'43. 7N		195.95	3.38	3.38	162.62	AK	Top lateritic soil
	006˚36'01.6E		216.59	5.87	9.25	156.75		Silty/sandy clay
	179m		483.88	60.0	69.3	96.747		Weathered basement
			1221.4	∞	∞			Fresh basement
6	09˚02'50.5N		13.780	0.77	0.77	172.23	H	Top lateritic soil
	006˚35'53.6E		214.96	0.67	0.84	172.16		Silty/sandy clay
	173m		1033.7	10.0	10.8	162.16		Weathered basement
			129.83	∞	∞			Fresh basement
7	09˚02'59.8N		44.045	2.27	2.27	174.73	AK	Top lateritic soil
	006˚36'04.6E		107.93	3.05	5.32	171.68		Silty/sandy clay
	177m		275.85	46.0	51.3	125.68		Weathered basement
			525.00	∞	∞			Fresh basement
8	09˚02'47.3N		175.33	0.82	0.82	174.17	AK	Top lateritic soil
	006˚35'59.1E		22.272	0.74	1.57	173.43		Silty/sandy clay
	175m		307.80	54.0	55.6	119.43		Weathered basement
			0.1255					Fresh basement
9	09˚02'45.4N		46.959	2.70	2.70	169.30	AK	Top lateritic soil
	006˚35'54.2E		27.438	1.90	4.60	167.40		Silty/sandy clay
	172m		307.80	54.0	58.6	113.40		Weathered basement
			0.1751	∞	∞			Fresh basement
10	09˚02'48.3N		2.3084	0.14	0.14	151.86	AK	Top lateritic soil
	006˚36'3.8E		101.00	0.41	0.56	151.44		Silty/sandy clay
	152m		527.66	54.0	54.6	97.445		Weathered basement
			2593.0	∞	∞			Fresh basement
11			80.319	1.69	1.69	173.31	AK	Top lateritic soil
	09˚02'47.3N		21.565	0.51	2.20	172. 80		Silty/sandy clay
	006˚35'59.1E		307.80	26.0	28.2	146.80		Weathered basement
	175m		1680.6	∞	∞			Fresh basement
12	09˚02'45.4N		48.945	1.83	1.83	170.17	AK	Top lateritic soil
	006˚35'54.2E		22.460	0.35	2.18	169.82		Silty/sandy clay
	172m		124.50	20.0	22.2	149.82		Weathered basement
			0.1363	∞	∞			Fresh basement
13	09˚02'45.4N		2.4820	0.16	0.16	170.84	AK	Top lateritic soil
	006˚36'05.3E		449. 60	71.0	71.2	99.824		Silty/sandy clay
	171m		588.60	20.0	91.2	79.824		Weathered basement
			7982.8	∞	∞			Fresh basement
14	09˚02'43.7N		142.11	2.03	2.03	176.97	KH	Top lateritic soil
	006˚36'01.6E		16.517	0.37	2.39	176.61		Silty/sandy clay
	179m		97.260	6.00	8.39	170.61		Weathered basement
			102.84	∞	∞			Fresh basement
15	09˚02'42.2N		43.314	2.87	2.87	175.13	HA	Top lateritic soil
			6.6037	1.67	4.54	173.46		Silty/sandy clay
	006˚35'57.8E		676.52	40.0	44.5	133.46		Weathered basement
	178m		365.91	∞	∞			Fresh basement

TABLE II
DAR ZARROUK PARAMETERS FOR THE VES POINTS

VES Point	Coordinates/ Altitude	Longitudinal Conductance S_i (Siemens)	Transverse Resistance T_i ($\Omega.m^2$)	Average Conductance per VES point	Average Transverse Resistance per VES point
1	09°02'57.3N	0.209338	1446.271	0.087654	299074
	006°35'59.9E	0.001392	865143.9		
	166m	0.052233	30632		
2	09°02'55.6N	0.079599	50.252	0.0691	592.8721
	006°35'56.3E	0.055068	351.5644		
	161m	0.072632	1376.8		
3	09°02'53.6N	0.213432	168.672	0.082638	21651.29
		0.010688	5404.284		
	006°35'52.9E 173m	0.023796	59380.92		
4	09°02'54.4N	0.025834	241.925	0.072008	96.45087
	006°36'01.2E	0.188822	33.1		
	171m	0.001368	14.3276		
5	09°02'43.7N	0.017249	662.311	0.056116	10322.16
	006°36'01.6E	0.027102	1271.383		
	179m	0.123998	29032.8		
6	09°02'50.5N	0.058055	11.024	0.023662	3499.499
	006°35'53.6E	0.003256	150.472		
	173m	0.009674	10337		
7	09°02'59.8N	0.051538	99.98215	0.082187	4372.726
	006°36'04.6E	0.028267	329.095		
	177m	0.166757	12689.1		
8	09°02'47.3N	0.004677	143.7706	0.071115	5593.817
		0.033229	16.4798		
	006°35'59.1E 175m	0.175439	16621.2		
9	09°02'45.4N	0.057501	126.7812	0.100727	5600.039
	006°35'54.2E	0.069242	52.136		
	172m	0.175439	16621.2		
10	09°02'48.3N	0.060648	0.323176	0.055682	9511.791
	006°36'03.8E	0.004059	41.41		
	152m	0.102339	28493.64		
11	09°02'47.3N	0.021041	135.7391	0.043054	2716.512
	006°35'59.1E	0.023649	10.99815		
	175m	0.08447	8002.8		
12	09°02'45.4N	0.037389	89.56935	0.071205	862.4768
	006°35'54.2E	0.015583	7.861		
	172m	0.160643	2490		
13	09°02'45.4N	0.064464	0.39712	0.085454	14564.67
	006°36'05.3E	0.157918	31921.6		
	171m	0.033979	11772		
14	09°02'43.7N	0.014285	288.4833	0.032792	292.7182
	006°36'01.6E	0.022401	6.11129		
	179m	0.06169	583.56		
15	09°02'42.2N		124.3112	0.126092	9065.38
	006°35'57.8E	0.06626	11.02818		
	178m		0.252889	0.059126	27060.8

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