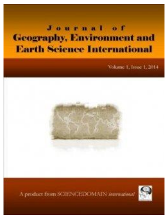

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Determination of Aquiferous Zones in the Freshwater South-East Niger Delta, Using Vertical Electrical Sounding (VES) Method

Uko Etim D.[1*]

[1]Department of Physics, Rivers State University of Science and Technology, P.M.B.5080,
Nkpolu-Oroworukwo, Port Harcourt, Nigeria.

Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

Vertical Electrical Sounding (VES) was applied in investigating the subsurface layers along Adibawa-Zarama pipeline route in the Niger Delta, Nigeria in an attempt to determine the depth of aquifer. A total of thirty (30) VES sets were executed using Schlumberger array of a maximum half current electrode spacing of 50m and interval distance of 250 m along the 6.75 km Adibawa-Zarama route. The fundamental parameters of resistivity, conductance, anisotropy and depths were computed using Resist software. Transverse resistivity is generally higher than longitudinal resistivity, and it ranges from 70.49Ωm to 936.30Ωm while those of longitudinal ranges from 31.37Ωm to 585.81Ωm. Anisotropy value ranges from 1.01 to 1.75 which is an indication that the layers are laterally inhomogeneous. The 1st layer has a resistivity range of 40.00Ωm - 453.00Ωm the 2nd layer resistivity range is 17.00Ωm - 320Ωm, 3rd layer has resistivity range of 130.00Ωm - 1400.00Ωm, 4th layer has resistivity ranges from 23.00Ωm - 1450.00Ωm, the 5th layer has resistivity range of 220.00Ωm - 4950.00Ωm, while the 6th layer has resistivity range of 600.00Ωm - 3997.00Ωm. The minimum and maximum thicknesses for the respective first five layers in

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**Corresponding author: Email: e_uko@yahoo.com;*

sequence are: 1.45 m and 3.0 m, 0.75 m and 4.10 m, 1.42 m and 15.04 m, 3.10 m and 23.20 m, and 7.00 m and 18.90 m. The saturated layers occur mostly in third, fourth and fifth layers are at depths 12.87 m and 26.02 m and 38.97 m respectively. Clay was located at a depth from 0m to 5m, while beyond these depths the formation is clayey sand to sandy clay, fine sand, clayey sand and sand of various grades. Tying results of the geoelectric survey to various lithologies reveals that resistivity is affected by lithology and fluid content of the rock. The aquifer is thick and is located between 12.87 m and 38.97 m.

Keywords: Aquifer; Dar Zarouk parameters; vertical geoelectric sounding; aquifer depth; lithology; freshwater; Niger Delta; Nigeria.

1. INTRODUCTION

Owing to their intrinsic physical and chemical properties, soils display intermediate electrical properties [1]. Electric properties of soil depend on its conductive lithologic layers, depth of burial, thickness, and nature of pore-fluid and lateral extent. Halvorson and Rhoades [2], and Austin and Rhoades [3] applied a four-electrode probe to locate saline-intruded aquifers. In this study, an attempt is here made to use VES four-electrode Schlumberger array method to determine freshwater aquifer depth in the coastal Niger Delta Nigeria. Though the initial aim of the VES survey in the area of study was to determine the characteristics of the soils for underground petroleum-pipeline installation, an opportunity is here used of the data availability to establish potable aquiferous zones using Schlumberger configuration. Koefoed and Dirk [4] had demonstrated that a good knowledge of aquiferous properties can help in the understanding of the dynamics of the subsurface with respect to the strength of the formation for construction purpose, electrical earthing, corrosion mitigation, groundwater resource exploration, management and planning.

2. GEOLOGY, PHYSIOGRAPHY AND HYDROGEOLOGY OF THE AREA OF STUDY

The area of study for this work is Adibawa, a community in Rivers State, in the South-Eastern Niger Delta, Nigeria with coordinates: 5º10'34"N, 6º29'42"E shown by Fig. 1. The study area and the environs located within the freshwater environment. This zone is characterized by considerable thickness of greyish silty-clay coastal plain sands of the Benin geologic Formation [5,6,7].

The Niger Delta basin which includes the study area has three major sedimentary subsurface stratigraphic units namely, the Benin, the Agbada and the Akata Formations [5,6]. The Benin Formation consists of loose and unconsolidated sands, and is about 1800 m thick. The underlying Agbada Formation consists of sandstone and shales. It is up to 3000 m thick and is underlain by the Akata Formation which consists of shales. Osakumi and Abam [8] have identified four major physiographic units within the Niger Delta basin The first unit is the freshwater swamp located close to the River Niger, where annual flooding and deposition occurs up to 45 km from the river's course, here the soil is alluvial, hydromorphic and lacustrine [9]. The second physiographic unit is the mangrove swamp area described as brackish, having been invaded by the sea water since large amounts of freshwater have ceased flowing into it. The third unit is located in the coastal plain consisting of alluvial soil. The fourth and final unit is the upland Niger valley where the soil is dry, ferral and loose sandy sediments [10,11]. The Niger Delta has average rainfall of about 266.5 mm in the coastal areas and 1905 mm in the extreme north. Rainfall is heaviest in July. Temperature increases from the south to the north [12].

3. MATERIALS AND METHODS

3.1 The Theory of Geoelectric Survey

A geoelectric layer can be described by its resistivity (the property of a material to resist the flow of electric current) ρ_i and its thickness h_i, where the subscript i indicates the position of the layer in the section (i = 1 for the uppermost layer). The Dar-Zarrouk geoelectric parameters longitudinal unit conductance [reciprocal of resistance] (S), transverse unit resistance (T), and coefficient of anisotropy (λ) are derived from its resistivity and thickness. These geoelectric parameters can be used to describe a geoelectric section consisting of several layers, and to define aquifer geometry, and to infer aquifer transmissivity and storativity [12,13,14]. The longitudinal conductance (S) is a measure of the impermeability of a rock layer [15]. Electrical anisotropy is measure of stratified rock which is generally more conductive in the parallel plane than in the perpendicular plane [16,17]. Anisotropy also influences the flow direction of fluids, and this knowledge is important for accurate design of flow and transport problems in the subsurface systems [18]. Anisotropy also varies for different rock types and geologic layers [13]. The equations [12,13] governing these parameters are:

Longitudinal unit conductance, $S_L = \frac{h_i}{\rho_i}$ (1)

Transverse unit resistance, $T_t = h_i \rho_i$ (2)

Longitudinal resistivity, $\rho_L = \frac{h_i}{s_i}$ (3)

Transverse resistivity, $\rho_t = \frac{T_i}{h_i}$ (4)

Anisotropy, $\lambda = \sqrt{\frac{\rho_i}{\rho_L}}$ (5)

For isotropic layer $\rho_i = \rho_L$ therefore $\lambda = 1$ (6)

For a section made up of several layer (n layers): Total longitudinal conductance is given by:

$$S = \sum_{L=1}^{n} \frac{h_l}{\rho_L} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \ldots \frac{h_n}{\rho_n} \qquad (7)$$

$$T = \sum_{t=1}^{n} h_t \rho_t = h_1 \rho_1 + h_2 \rho_2 + \ldots h_n \rho_n \qquad (8)$$

Average longitudinal resistivity is:

$$\rho_L = \frac{H}{S} = \frac{\sum_1^n h_1}{\sum_1^n \frac{h_l}{\rho_l}} \qquad (9)$$

Average transverse resistivity is:

$$\rho_t = \frac{T}{H} = \frac{\sum_1^n h_t \rho_L}{\sum_1^n h_i} \qquad (10)$$

Hence anisotropy is:

$$\lambda = \sqrt{\frac{\rho_t}{\rho_L}} = \frac{\sqrt{TS}}{H} \qquad (11)$$

The parameters (S, T, ρ_l, ρ_t and λ) were derived by considering a column of unit cross-sectional area (1x1 meter) cut out from a section of infinite lateral extent. Assuming current flows vertically through the section, the different layers in the section act as resistors arranged in series, and the total resistance of the section becomes:

$$R_t = R_1 + R_2 + R_3 + \ldots R_n \qquad (12)$$

$$R = \rho_1 \frac{h_1}{1x1} + \rho_2 \frac{h_2}{1x1} + \rho_3 \frac{h_3}{1x1} + \rho_n \frac{h_n}{1x1} \qquad (13)$$

$$= \rho_1 h_1 = T \qquad (14)$$

When current flows parallel to the bedding plane, the layers in the column act as resistors connected in parallel and the conductance becomes:

$$S = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n} \qquad (15)$$

$$S = \frac{1 \cdot h_1}{\rho_1 \cdot 1} + \frac{1 \cdot h_2}{\rho_2 \cdot 1} + \ldots + \frac{1 \cdot h_n}{\rho_n \cdot 1} \qquad (16)$$

$$S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \ldots + \frac{h_n}{\rho_n} \qquad (17)$$

$T = \rho_1 h_1 + \rho_2 h_2 + \ldots \rho_n h_n$

where S = total longitudinal conductance, T = total transverse resistance, h = thickness, ρ = resistivity.

In a Schlumberger array, the voltage electrodes are kept small and fixed while only the current electrode spacing C1C2 is changed as illustrated in Fig. 2. By convention A, B, M and N in the formula below is equal to C1, C2, P1 and P2 respectively, ΔV is the potential difference between P1 and P2. This work was based on the principle that the distribution of electrical potential in the ground around a current-carrying electrode depends on the electrical resistivities and distribution of the surrounding soils and rocks. It was also assumed that the geoelectric layers were horizontal and isotropic.

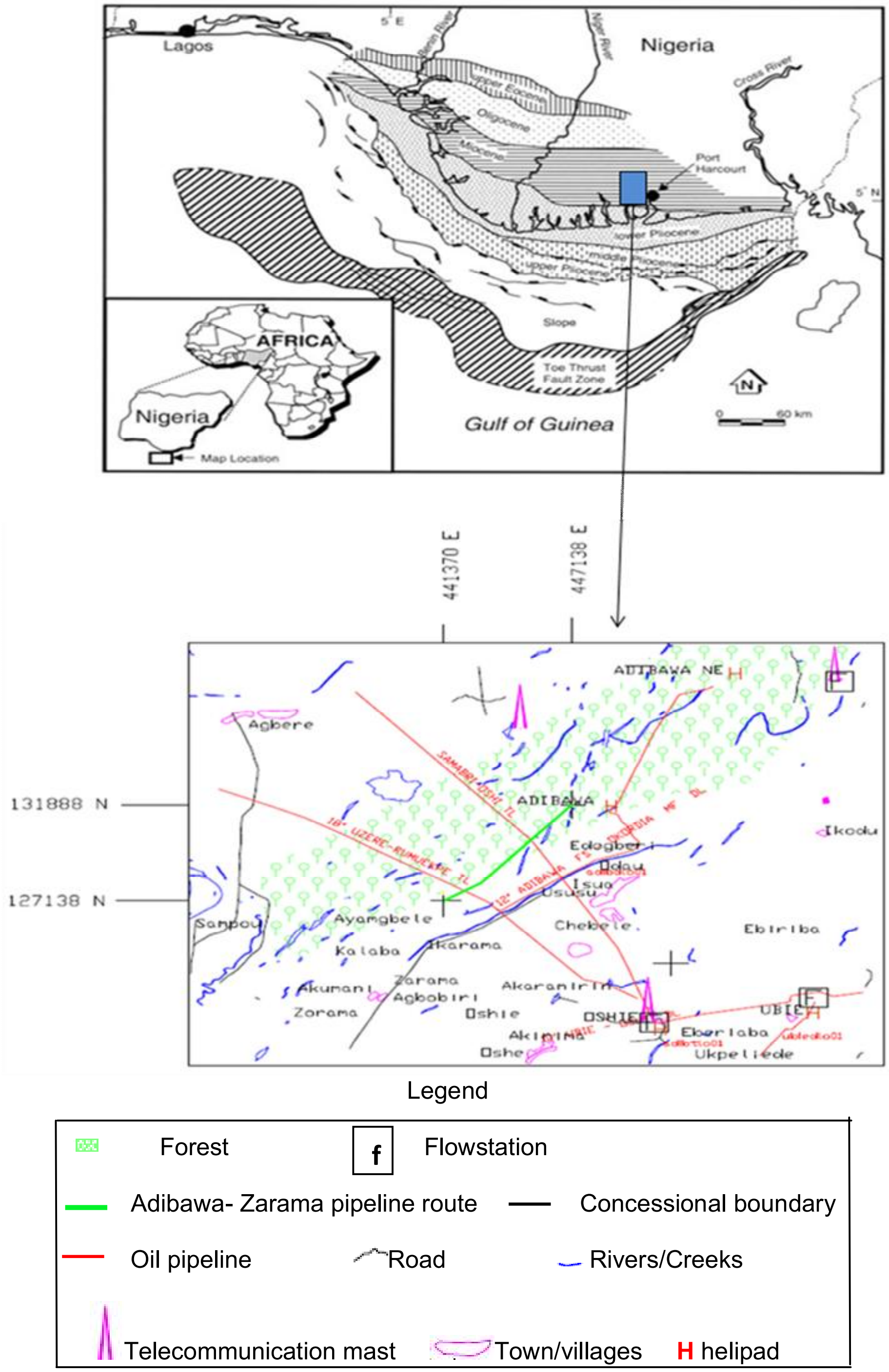


Fig. 1. Map of Niger Delta showing the study area

Apparent resistivity ρ_a is calculated using the relation:

$$\rho_a = \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \frac{\Delta V}{I} \tag{18}$$

Resistivity was measured by injecting known current into the ground through the two current electrodes (C1, C2). The resulting potential difference was measured between the potential electrodes (P1, P2). As the electrode spread (C1, C2) was increased, the depth of the investigation increased. All resistivity techniques require the measurement of ground resistance (R) which is converted to apparent resistivity (ρ_a**)** by multiplying with a geometric factor (K), a term that describes the geometry of the electrode configuration such that [19,20,21,22,19]:

$$\rho_a = \pi \cdot R \cdot a \left(\frac{b}{a} + \frac{b^2}{a^2}\right) \tag{19}$$

$$\rho_a = KR \tag{20}$$

where R = resistance value read on the resistivity meter (Ω); K = geometric factor; a = distance between both inner electrodes in metres; b = distance between inner and outer electrodes in metres; ρ_a = average resistivity in Ωm of an equivalent soil layer which is equal to 75% of the distance between the inner and outer electrodes (0.756).

3.2 Determination of Electrical Resistivity

The VES locations were identified with the aid of global positioning satellite system (GPS) and Total Station Survey equipment. Thirty (30) VES soundings were carried out. Resistance of the ground between the two inner electrodes were measured. Resistivities were obtained from the resistances. Using Resist software apparent resistivity curves were generated from which the thickness of the geoelectric layers of the area were determined.

The field array type used in this research was the Schlumberger array. The configuration has the advantage of being able to delineate small intervals of soil horizons; the method makes use of less number of labour force and the equipments are less cumbersome to carry about. This method also has added advantage over other methods owing to the fact that the fraction of total current flowing at depth varies with the current-electrode separation. The field procedure used a fixed centre with an expanding spread, thus the presence of horizontal or gently dipping beds of different resistivities is best detected by the expanding spread. Hence the method is useful in determination of depth of overburden, deep structure and resistivity of flat lying sedimentary beds as also confirmed by [4,22].

With the Schlumberger array, the potential (MN) electrodes separation was kept constant while the current electrodes AB or (L) spacing is increased in steps. A maximum current electrode separation (AB) of 100m was marked out in this work. In each measurement, the digital averaging instrument, Abem Terrameter SAS 300 Model, displayed the resistance directly. The readings are made possible as the four electrodes driven into the ground are connected to AB and MN terminals of the meter through the reels of cables. This procedure is repeated for each location along the marked profile as the depth of penetration of current into the ground is increased in the electrode separation.

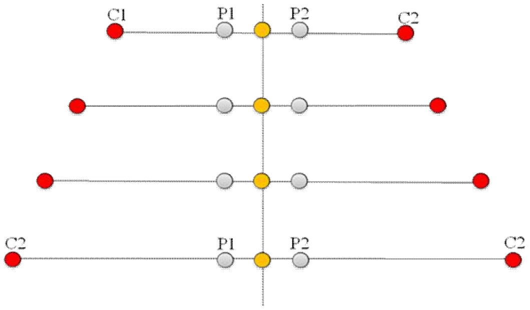


Fig. 2. Schematic diagram of expanded schlumberger array

ABEM Terrameter (SAS) 300 model with a liquid crystal digital readout was used for data acquisition. Schlumberger array was adopted because of its economy of space and less physical movement of electrodes. Under this configuration, the potential electrodes (P1, P2) are placed at a fixed spacing (P2 – P1 = b) which is not more than one fifth of the current electrode half spacing (a), Fig. 2. The current electrodes were placed at progressively larger distances. When the measured voltages between P1 and P2 falls to very low values, the potential electrodes are spaced more widely apart (spacing b). The measurements are continued and the potential electrode separation increased again as necessary until VES is completed.

3.3 Determination of Borehole Lithology

At every resistivity location, a borehole was drilled to 40 meters depth using rotary method. Soil samples were collected at every 3 m-depth interval, and drill cuttings were described to establish lithology with depth and classified based on Wentworth Grade Scale.

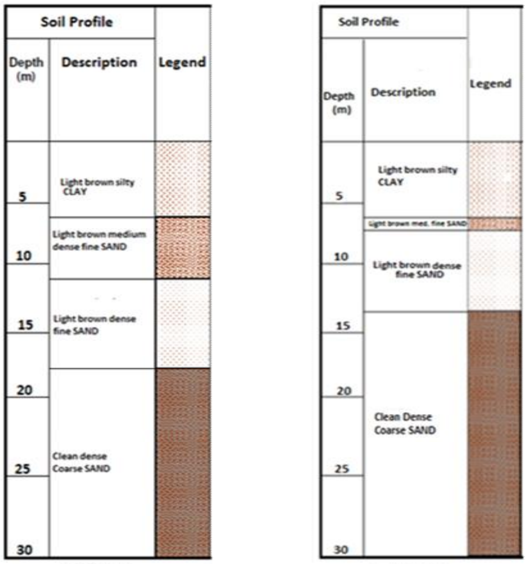
4. RESULTS AND DISCUSSION

Lithology-depth profiles of two of the 30 wellbores are presented in Fig. 3. The results of the survey from the field geoelectric sounding for the 30 stations are presented by Table 1, and four examples of the corresponding VES curves are shown in Fig. 4. Also, presented are the interpreted layers, their thicknesses and their corresponding resistivities are computed using Resist software program. The stations traverse through the length of the pipeline route from Adibawa to Zarama. The number of layers, their thicknesses and resistivities vary from station to station with a minimum of four (4) layers to a maximum of seven (7) layers. Low resistivity values are observed in the upper three, four layers from the surface 0 m to a depth of about 15 m, while the fifth to the seventh layers have higher resistivity values indicative of less conductive regions.

In the 2D model of the electric section (Fig. 5), colour identification is an important factor to recognizing the various geoelectric bands. The colour scale is a minimum of 17Ωm and a maximum of 5000Ωm. Calibrating the resistivity with reference to depth and the geology of the study area, 17-100 Ωm is mostly clay as found at the depth of 0 to 5 m. However, below this depth is clayey sand and sand of various grades and thicknesses. The full interpretation the electric section was matched with the borehole data and the result of this is illustrated in Fig. 6. This geoelectric section has been able to correlate resistivity with depth, lithology and the lateral extent. The thickest area is marked inside the red square box and the flow of groundwater is likely to radiate from this region towards less thicker regions. Geological information reveals that the depth domain is made up of clayey to silty clay materials.

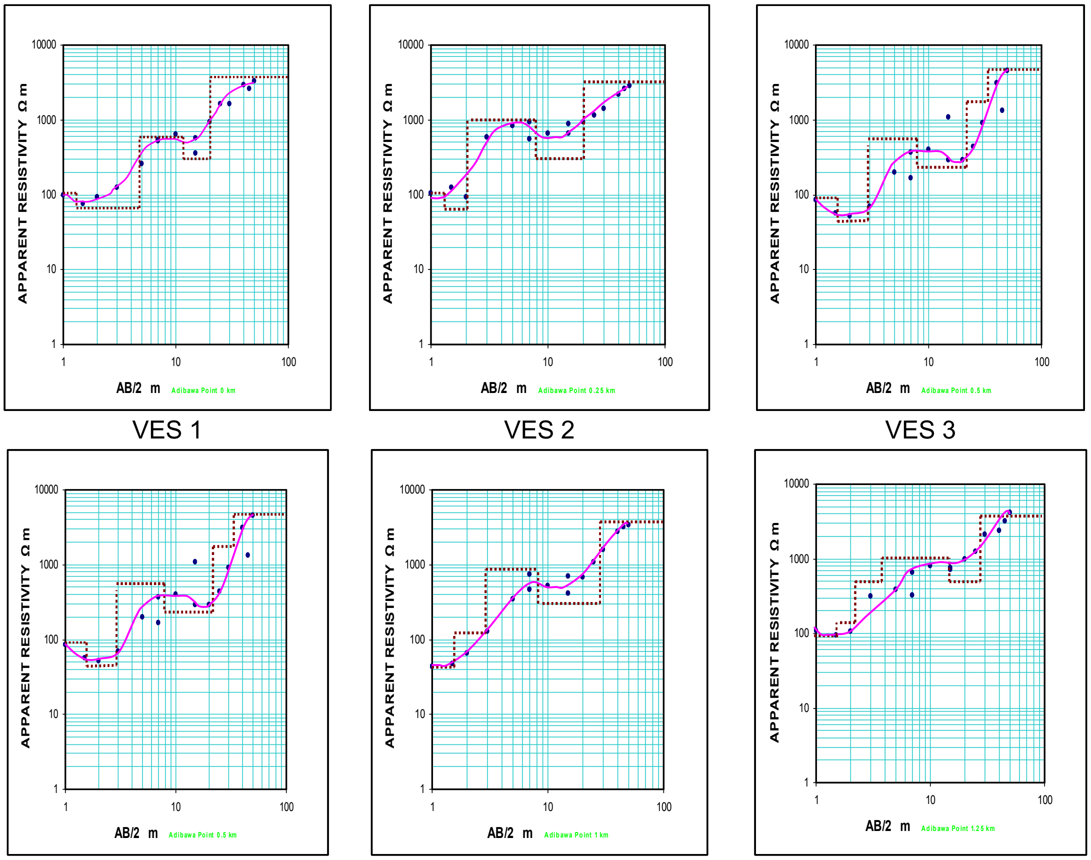
Table 1. Table showing summary of geoelectric parameters

VES no.	Total layer hickness, h (m)	Longitudinal resistivity, ρ_L Ωm)	Transverse resistivity, ρ_t (Ωm)	Anisotrophy, λ
1	22.00	215.12	389.55	1.35
2	21.50	272.88	431.62	1.26
3	34.00	293.65	901.50	1.75
4	35.00	378.98	930.40	1.57
5	28.00	362.51	465.41	1.13
6	28.80	585.81	929.85	1.26
7	28.90	545.50	853.33	1.25
8	28.90	580.63	936.30	1.27
9	28.70	315.55	730.41	1.52
10	25.00	354.43	738.05	1.44
11	30.60	358.05	698.81	1.40
12	27.64	425.25	597.87	1.19
13	30.60	412.79	565.48	1.17
14	28.00	339.96	486.21	1.20
15	27.60	347.40	418.01	1.10
16	28.00	226.50	357.27	1.26
17	24.87	185.09	208.15	1.06
18	30.39	257.63	315.33	1.11
19	28.00	207.41	366.72	1.36
20	27.62	339.63	459.24	1.16
21	27.00	318.83	523.13	1.28
22	28.00	299.11	555.23	1.36
23	29.00	82.56	168.66	1.42
24	29.50	140.83	189.38	1.15
25	27.48	159.23	165.43	1.01
26	28.70	31.37	70.49	1.49
27	26.00	128.91	145.45	1.06
28	33.00	50.11	80.49	1.26
29	25.00	111.34	141.56	1.12
30	13.96	228.18	388.54	1.30



Well-1 Well-2

Fig. 3. Typical examples of depth-lithology in the penetrated boreholes Wells 1 and 2 in area of study



VES 1 VES 2 VES 3

VES 4 VES 5 VES 6

Fig. 4. Six examples out of 30 stations of interpreted resistivity curves

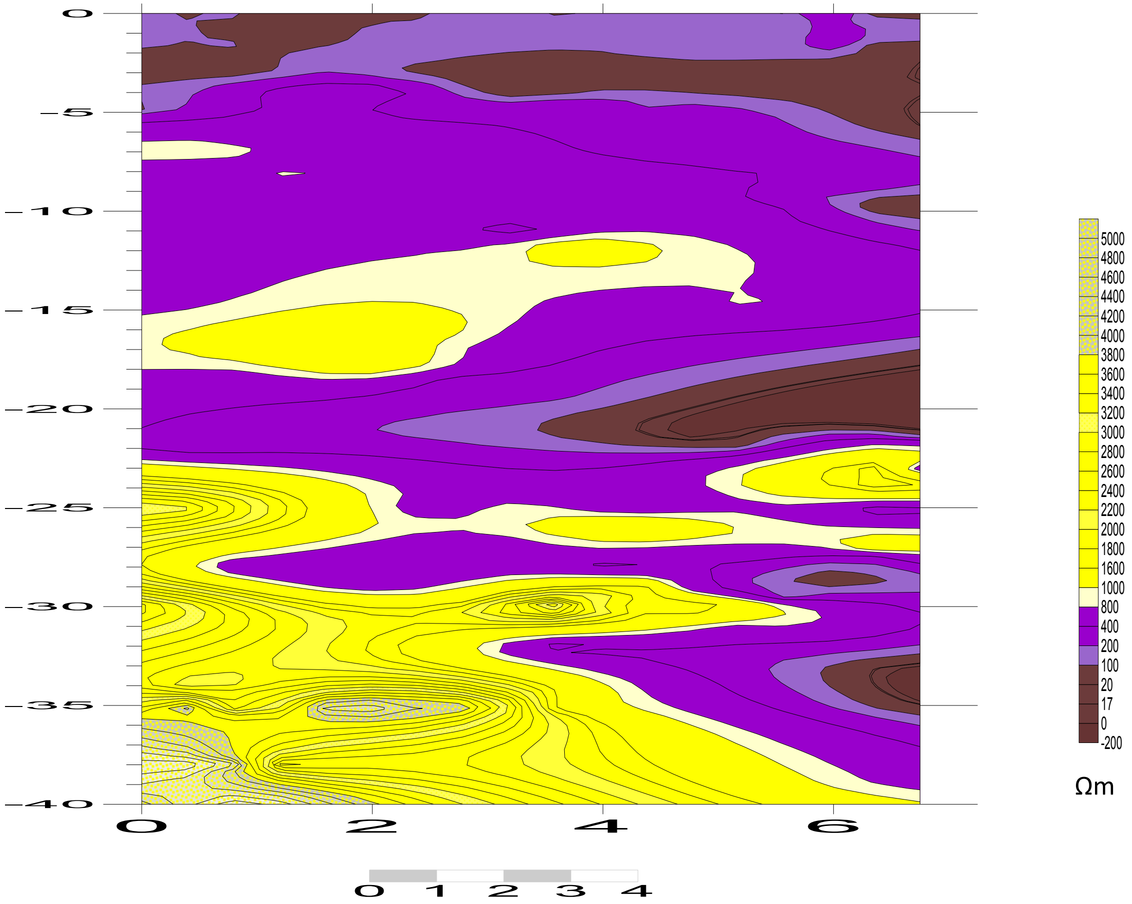


Fig. 5. 2D model of the geoelectric section showing depth and resistivity values

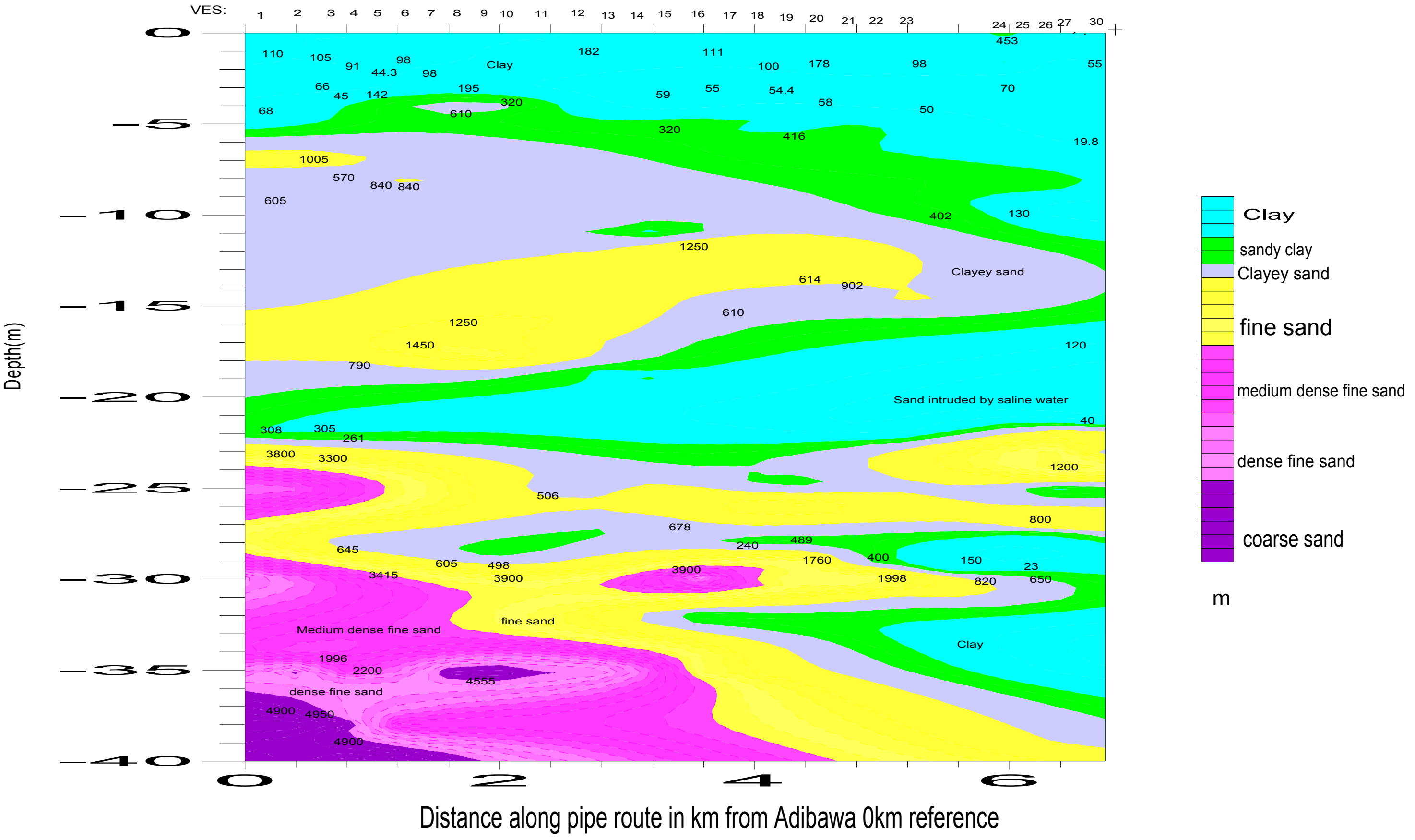


Fig. 6. 2D geoelectric section showing variation of resistivity with depth, lateral extent and lithologic units

4. CONCLUSION

Vertical Electrical Sounding (VES) was applied in investigating the subsurface layers along Adibawa to Zarama pipeline route, Niger Delta, Nigeria. The field array type used in this research is Schlumberger of a maximum half current electrode spacing of 50 m. A total of thirty (30) VES sets were executed at an approximate interval distance of 250 meters along the 6.75km.

Transverse resistivity is generally higher than longitudinal resistivity, and it ranges from 70.49Ωm to 936.30Ωm while those of longitudinal ranges from 31.37Ωm to 585.81Ωm. Anisotropy value ranges from 1.01 to 1.75 which is an indication that the layers are laterally inhomogeneous. The 1st layer has a resistivity range of 40.00Ωm - 453.00Ωm the 2nd layer resistivity range is 17.00Ωm - 320Ωm, 3rd layer has resistivity range of 130.00Ωm - 1400.00Ωm, 4th layer has resistivity ranges from 23.00Ωm - 1450.00Ωm, the 5th layer has resistivity range of 220.00Ωm - 4950.00Ωm, while the 6th layer has resistivity range of 600.00Ωm - 3997.00Ωm. The minimum and maximum thicknesses for the respective first five layers in sequence are: 1.45 m and 3.0 m, 0.75 m and 4.10 m, 1.42 m and 15.04 m, 3.10 m and 23.20 m, and 7.00 m and 18.90 m. The saturated layers occur mostly in third, fourth and fifth layers are at depths 12.87 m and 26.02 m and 38.97 m respectively. Clay was located at a depth from 0 m to 5 m, while beyond these depths the formation is clayey sand to sandy clay, fine sand, clayey sand and sand of various grades.

The results of the geoelectric survey were tied to various lithologies by calibrating the geoelectric values with borehole data. The resistivity variation at various depths and the soil profile reveals that resistivity of any given layer is seriously influenced by the soil or rock materials and the fluid content contained therein. The results of this work can also serve as input to the earthing engineers, cathodic protection engineers, drillers and geoscientists.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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