Electrical Resistivity Characterization of Near-Surface Lithology in Otuoke Community:

An Inquiry into Localized Geoelectrical Lithologic Logging in Bayelsa State, Niger Delta, Southern Nigeria.

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***Abstract*—Electrical resistivity characterization of near-surface lithology was carried out in Otuoke community, Ogbia local government area Bayelsa State. The aim of the study was to establish a practical and researched basis for interpreting lithofacies from electrical resistivity probes in the study area. Correlation of 2D Electrical Resistivity Tomography (ERT) and drill log samples was employed to establish useful resistivity to lithology links. Results from drilling showed that all petro-physically distinguishable near surface rock units in the study area rarely exceed 10 m of depth beyond which major sand bodies (aquifers) are predominant. Results from drill log to ERT correlation linked the top soils, made of clays and mud, to a resistivity range of 7 – 50 Ωm while silty sands have a resistivity range of 48 – 116 Ωm. On the other hand, fine to medium grained sands have resistivity range of 78 – >164 Ωm. The very low conductivity of top organic layers is thought to have resulted from conducting clay minerals, whereas low conductivity at depth (often in saturated layers) is believed to have been caused by presence of conducting minerals in the pore fills of porous rocks, both of which put a limit on the precision of the dividing line between co-relatable lithology and resistivity values. However, the range of values identified constitute useful reference guide for engineering and environmental control applications.**

Keywords—Electrical resistivity, characterization, lithologic logging, geo-electrical logging.

INTRODUCTION

Generally, the quantitative determination and recording of a physical phenomenon as a function of depth is referred to as logging. In the field of applied sciences and engineering, logging constitutes a veritable tool for solving scientific and engineering problems. But when it comes to subsurface geophysical logging, there is no physical contact between the logger and the logging environment, rather the scientist or engineer relies on signals he receives from the logging tool where the tool is actually in contact with the logging environment. In the case of logs derived from surface measurements as obtainable with geo-electrical survey probes, even the measuring tool is remote to the zone of interest. However, technological developments over the years have been able to institute methods of surface based geo-electrical measurements that are repeatable hence globally standardized ([1]; [18]; [5]; [9]; [15]; [13]. The open ended part of this entire technological package is the aspect of interpretation; while tools have been standardized to produce repeatable recordings, interpretation of these signals remain a subjective exercise and varies from individual to individual depending on knowledge, experience and professional background. In recognition of the fact that geo-electrical resistivity signals are controlled by background or local geology, the interpreter is faced with the problem of drawing a precise dividing line of regional and/or global significance between adjacent identifiable lithologies, which in practice is not achievable because of the influence of local geology and subsurface geochemistry, even though the responses of the intrinsic subsurface rocks may not have changed. It suffices to say that if the lithological evaluation is of engineering significance or for scientific application, then the need for accuracy and precision on a local scale cannot be overemphasized especially in areas with paucity of near surface litho stratigraphic data. [4] used similar methods as employed in this study to characterize subsurface lithology in parts of Edo state where it was noted that a dependable litho facies characterization from geo-electrical resistivity data cannot be achieved in isolation of local geology. Also, it is interesting to note that some aquiferous sand units in parts of Bayelsa State and its environs occur as lenses embodied in clay intercalations identified by their resistivity

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signals, while a qualitative analysis based on local geology aided the quantitative geo-electrical resistivity characterization of the near surface lithology; it was noted that the region suffers paucity of related technical data [11]. This of course constitutes a scientific problem.

LOCATION OF THE STUDY AREA

The study area is located in Otuoke community which includes the Federal University Otuoke and the premises of the Federal government integrated water project all in Ogbia local government area of Bayelsa State, Niger Delta Nigeria. Geospatially, the study area is bounded by Longitudes $6^0\ 18'\ 00''$E and $6^0\ 19'\ 30''$E, and Latitudes $4^0\ 47'\ 00''$N and $4^0\ 48'\ 00''$N which falls within the transition zone of the Niger delta.

Figure 1A: Map of the Niger delta showing Bayelsa State and Yenagoa as the capital. (adapted from STRATFOR.com)

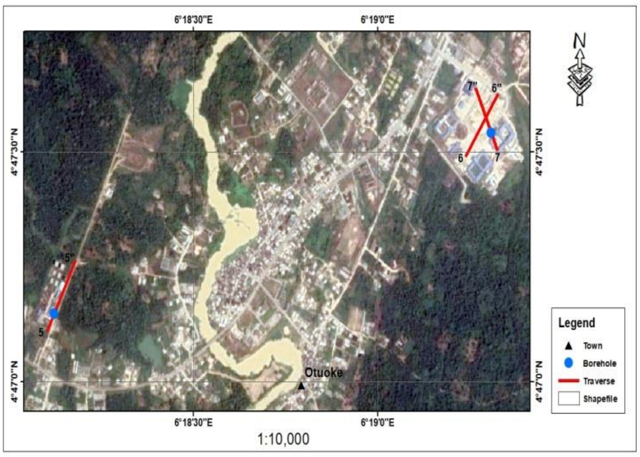

Figure 1B: Google earth imagery of the study area showing 2D resistivity traverses and borehole points (www.google/earth/imagery/)

GEOLOGY OF THE NIGER DELTA

The geology of Niger Delta has been extensively discussed by many authors; the following literatures; [12], [14], [17], [18] are worthy of note and provide the foundational information about the subsurface geology of the Niger Delta. Three major depositional sequences or formations have been identified which include: the Akata formation, the Agbada formation and the Benin formation [12].

Benin Formation

This is the uppermost unit of the delta complex consisting mainly freshwater bearing massive continental sands and gravels deposited in an upper deltaic plain environment. Intercalation of sedimentation is notable specifically in the transition zones composing of sandstone, silts and clays with the presence of carboniferous organic matter in some places [8].The sands and gravels of the Benin formation were deposited as bars by braided streams and channels fills on natural levees of high energy environment, while the finer sediments like shales were deposited in the back swamps. The youngest and topmost of the three major formations is the Niger delta which is chronostratigraphically interpreted to be Miocene to present in age, composed of continental coarse to medium grain sands with subordinate silt and clay lenses of fluviatile and shallow marine environments [10]. Also identifiable is another rather sparse Quaternary deposit that is irregular in horizontal and lateral dimensions as well as thickness overlying the Benin formation in some parts of the Niger Delta. They are mainly gravel, sands, clay and silt of continental origin. The facies associated with the formations identified earlier have been deposited in different sedimentary environments; [14] has identified three major sedimentary environments with smaller subdivisions; (1) ancient/ modern sea (2) coastal flats (3) river and lagoon beaches, sand bars, flood plains, seasonally flooded depressions, swamps, ancient creeks and river channels. But [10] reported five major sub environments/ geomorphologic units as follows; (i) active/abandoned coastal beaches (ii) saltwater, mangrove swamps (iii) freshwater swamps, back swamps, deltaic plain alluvium and meander belts (iv) dry deltaic plain with abundant freshwater swamps (Sombreiro-Warri) deltaic plain (v) dry flat land and plains. The average thickness of the Benin formation is estimated to be about 2 km.

Agbada Formation

The Agbada formation overlies the Akata, it consists mainly of massive sand bodies of continental origin and thick marine shales which form hydrocarbon seals. This formation is associated with syndepositional growth fault [8] and is known to harbour most of the hydrocarbon reserve of the Niger delta. The sandstone is poorly sorted with grain sizes varying from fine to coarse, unconsolidated but slightly consolidated with calcareous cement,lignite streaks and limonite in some places [12].

Akata Formation

The basal unit of the Cenozoic delta complex, the Akata formation is composed mainly of marine shales deposited as the high energy delta advanced into deep waters. Akata ranges in age from Eocene to present day

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conceptually deep water Paleocene Imo shale and even late cretaceous Nkporo shale are lateral equivalent of Akata facies. The near shore Akata pro-delta shales were deposited on a shallow marine shelf and are rich in benthonic foraminifera. Akata shales also extended down on continental slope and rise in front of the deltaic complex. The uniform shale development is only broken by continental beds which were deposited in deeper waters. Separations of continental crust beneath the Gulf of Guinea troughs, the Gabon troughs and the Abakaliki troughs up to Gboko transform faults [8].

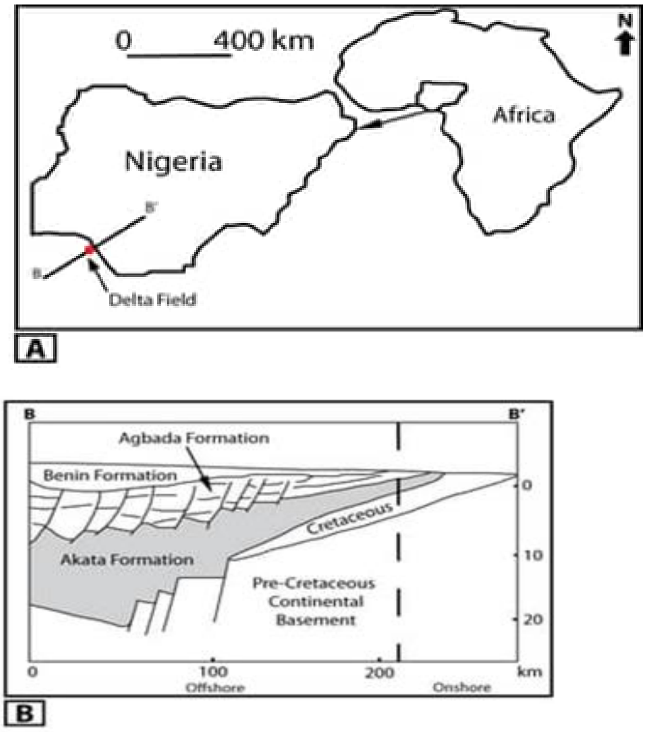
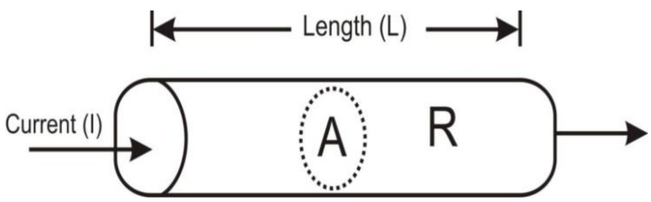


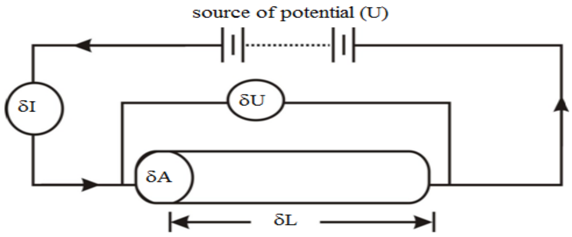
Figure 2: (A) Location of the Niger delta relative to the African plate (B) Cross section showing the three major Niger delta formations and their depths (Ugbena et al., 2020)

THEORETICAL BASIS OF STUDY

From Ohm's law (Kearey and Brooks, 1991), we present the basic mathematical statement connecting voltage, current and resistance in an electric circuit (figs 3A and 3B).



(A)



(B)

Figure 3: (A) Current flowing through a cylindrical Conductor of Length 'L' and cross sectional area 'A'; (B) Parameters for defining the resistivity of a regular shaped material

From fig (3A);
$U = IR$

So that $R = \frac{U}{I}$ (1)

Where U = potential difference (volt)
I = current (amp)
R = resistance (ohm)

Furthermore, it is pertinent to note that the dimension or geometry of a material relative to the direction of flow of electrical current has remarkable influence on its resistance to the passage of current. The resistance offered by a physical material to the flow of electric current is directly proportional to its length and inversely proportional to the cross sectional area involved [6]. The above fact in conjunction with the vector form of Ohm's law establishes the physics and mathematical build-up (theoretical aspect) for all resistivity methods.

If we consider further that our simple cylindrical shaped conductor of cross sectional area A (m^2) and length L (m) is connected to a voltage source U (volt). Also, let δL be an elemental length and δA be an elemental area of the cylindrical conductor with elemental resistance δR. If δI be the elemental current and δU the elemental potential; adhering to the labeling of figure 3A,

We write;

$$R \propto \frac{L}{A}$$

$$R = \frac{\rho L}{A} \quad (2)$$

Where ρ is the constant of proportionality called resistivity with dimension $\Omega m^2/m$; an intrinsic property of a physical material that accounts for its behavior in terms of electrical resistance to the flow of current through it. Combining equations (1) and (2) to eliminate R

$$\frac{U}{I} = \frac{\rho L}{A}$$

$$\therefore \rho = \left(\frac{U}{I}\right)\left(\frac{A}{L}\right) \quad (3)$$

Now if a current I (Amp) is passed through the cylindrical conductor of fig (3A) causing a potential drop -δU in association with the elements δL, δR and δA. See fig (3B).

We apply Ohm's law thus:

$$-\delta U = I * \delta R \quad (4)$$

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But $R = \frac{\rho \delta L}{\delta A}$, from equation (2)

$$-\delta U = I * \frac{\rho \delta L}{\delta A}$$

$$-\frac{\delta U}{\delta L} = \rho * \frac{I}{\delta A} \qquad (5)$$

For computational convenience, we replace the elemental components with partial derivative which could be in favor of any direction or component so that equation (5) becomes

$$-\frac{\partial U}{\partial L} = \rho * \frac{I}{\partial A}$$

$\frac{\partial U}{\partial L}$ Defines the electric field intensity (E) and $\frac{I}{\partial A}$ defines the current density (J). So that

$$E = -\rho * J \qquad (6)$$

E has dimension (volt/m) and J (Amp/m^2).
[5] refer to equation (6) as the continuity equation, the vector form of Ohm's law, valid everywhere underground provided there are no boundaries or layers in the earth. By imposing certain boundary conditions, eqn. (6) is the fundamental equation for all field applications involving electrical method in geophysics and can be modified to suit various field situations.
Boundary condition 1

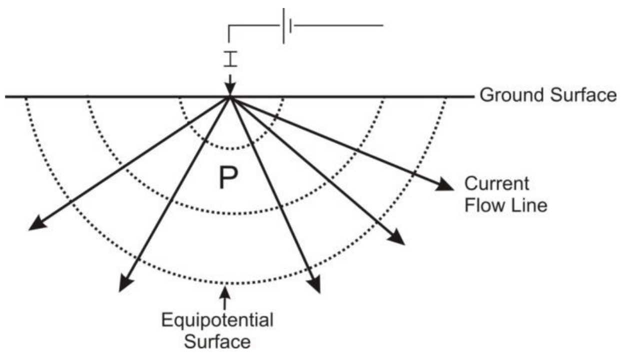


Figure 4: Current flow from a single surface electrode. After Kearey and Brooks (2002)

Considering a single current point source placed on the surface of a homogeneous medium with uniform resistivity (ρ) fig 4. For this semi infinite half plane, the current 'I' flow radially into the medium from the point source setting up a potential field perpendicular to the direction of current lines with strength being a function of distance from the point source. Also, if we consider the ground-air boundary on the earth's surface as an insulator, then (fig 4) will become the plane of a hemisphere cut from its centre with radius 'r'.
Thus we express the current density 'J' as;
$J = I/2\pi r^2$ And $E = \partial U/\partial r$, so that equation (6) becomes

$$\frac{\partial U}{\partial r} = -\rho I/2\pi r^2$$

$$\partial U = -(\rho I/2\pi r^2)\partial r$$

$$\int \partial U = -\int (\frac{\rho I}{2\pi r^2})\partial r$$

$U = -\frac{\rho I}{2\pi r} + C'$ Where C is a constant of integration

Boundary condition 2

At r = ∞; C = 0
Meaning that at great distance from the point source, the associated potential becomes infinitesimal such that the influence of 'C' can be neglected. Hence, as r → ∞
Thus;

$$U = \rho I/2\pi r \qquad (7)$$

Equation (7) is the expression for the potential generated by a point source at a distance r in a subsurface of uniform resistivity where there are no boundaries.

Boundary condition 3

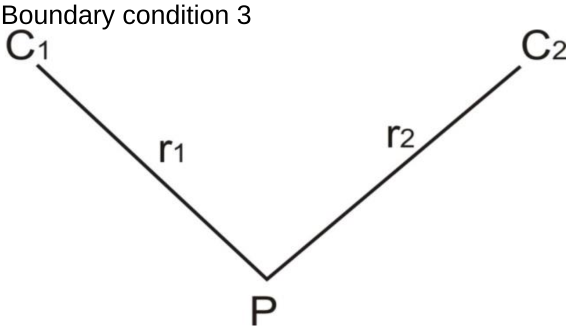
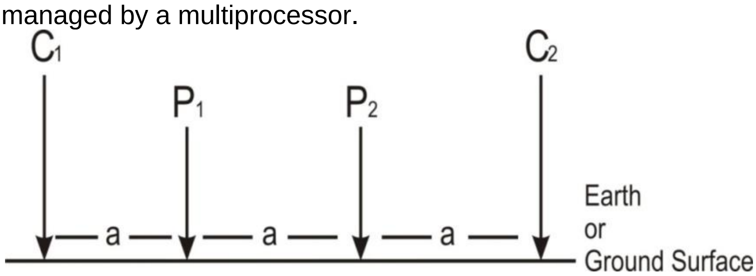


Fig 5: Schematic of a bipolar arrangement in a homogeneous material of uniform resistivity.
For a bipolar arrangement (fig 5), the potential at 'P' is a contribution from C1 and C2 since in practice, we have current going down from one point and leaving at another. Therefore, potential at any point due to this bipolar arrangement is given by

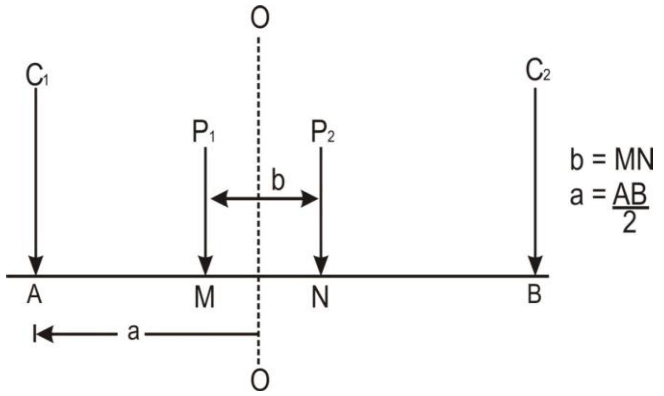
$$\Delta U = \rho I/2\pi\{\frac{1}{r_1} - \frac{1}{r_2}\} \qquad (8)$$

Where r_1 and r_2 are distances of the point 'P' from the two electrodes C1 and C2 respectively.
Equation (8) establishes the potential at any point on the earth surface for such bipolar arrangement and constitutes the fundamental theoretical basis for all methods involving ground electrical resistivity measurement.

MATERIALS AND METHOD
Pasi earth resistivity meter model 16GL-N was used, a modern optimal instrument with technical specifications that enhanced the reliability of field results as evident in the following technical details: 16 bit floating point with signal sensitivity of 600 nV and 126 nA; capable of averaging signals 3 times before final output in each cycle of measurement, and suppresses noise up to 96 dB at 50-60 Hz with instrument-range automatic adaptation to observable field signals using automatic filtering all managed by a multiprocessor.



(A)



(B)

Fig 6: (A) Wenner array; (B) Schlumberger array.

Combined Wenner-Schlumberger survey geometry was employed using a 20 electrode system with spacing of 10m or 5m in some profiles depending on the availability of space (figure 6). Four realms of wire; two potential and two current electrode wires each provided with crocodile clips at the ends. A seven man crew consisting of an instrument operator (technologist), four electrode men and two line men was deployed for the field operation. 2D field geoelectric resistivity survey procedures as prescribed by [9] was used wherein the instrument recorded voltage and currents as input signals and outputs resistance (R) measurable in ohms. It takes about 5 - 90 seconds for the instrument to complete 3 cycles of a single reading, and exactly 90 individual instrument readings to generate data that completely covers a single 2D profile. Technical and safety precautions taken include repetition of suspicious or spurious readings, and also ensuring that all electrodes are vertically inserted to the ground.

Data Processing

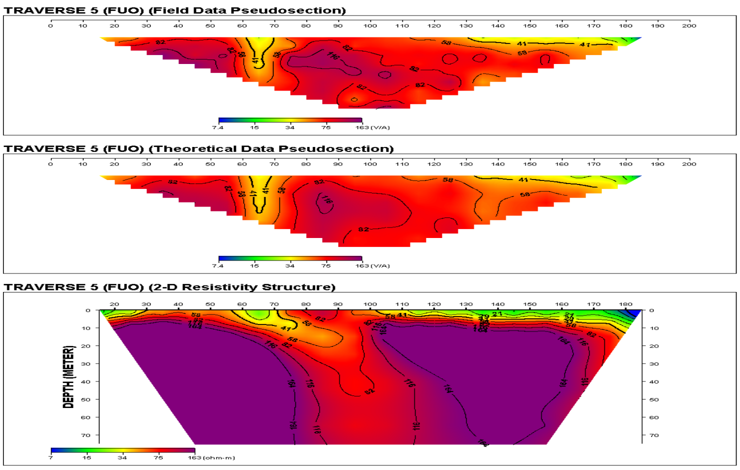
From equation (3), the data processing task was basically the convolution of instrument field resistance '**R**' recordings with a geometric factor '**k**' representing the influence of the earth's geometry with respect to the acquisition array on the observed field recordings [7]; [3]; [2]. The multiplication of instrument reading '**R**' and the geometric factor '**k**' for each field observation as simplified by eqn. (9) produced an apparent resistivity value of the subsurface layer under investigation.

$$\rho_a = KR \qquad (9)$$

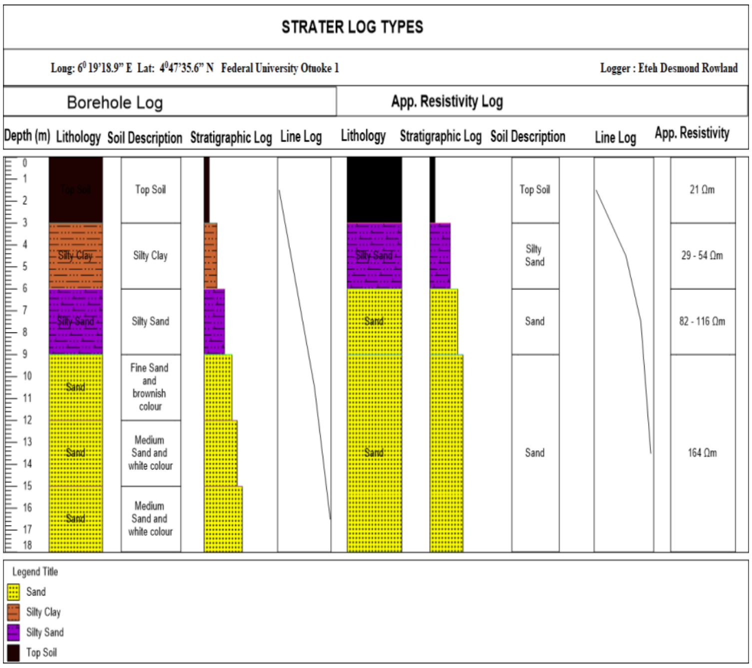
Where ρ_a is apparent resistivity (Ωm)
R is the resistance (Ω) of the subsurface obtained from surface readings and
K, the geometric factor which according to (Loke, 2004) is given by the formula;

$$K = \pi n(n+1)a\ . \qquad (10)$$

Finally, borehole drilling was done at the points indicated on the project map and lithologic logs produced which were correlated with quantitative resistivity values derived from the 2D electrical resistivity tomography which laid the foundation of the method implemented in this research.

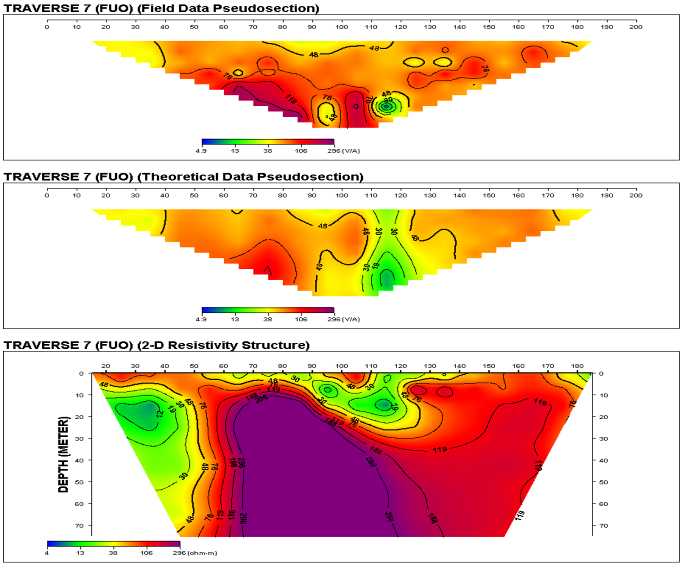


(a)

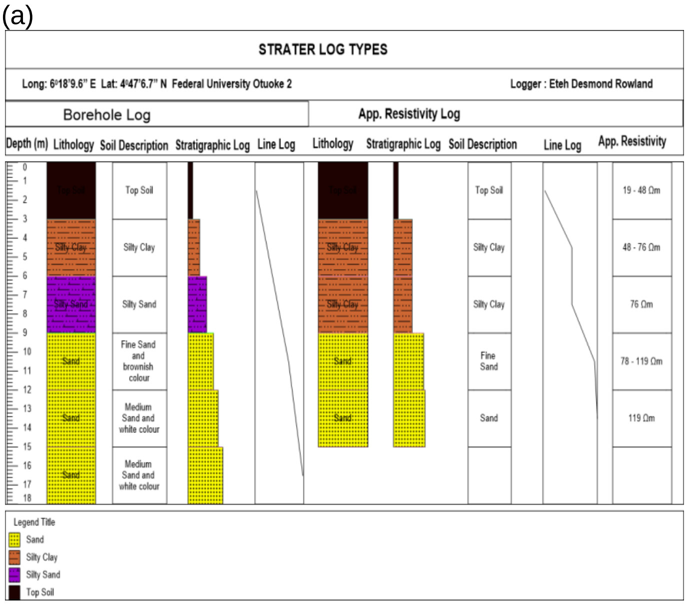


(b)

Figure 7: (a) 2D Resistivity Image Showing Theoretical, Pseudo and Inverted Structural Sections of Traverse 5-5[1]; (b) Correlation of Borehole Derived Lithologic Log with Subsurface Resistivity of Profile 5-5[1]



(a)



(b)

Figure 8: (a) 2D Resistivity Image Showing Theoretical, Pseudo and Inverted Structural Sections of Traverse 7-7[1]. (b) Correlation of Borehole Derived Lithologic Log with Subsurface Resistivity of Traverse 7-7[1].

DISCUSSION

Looking at figure 7, it could be seen that top soils in the survey profiles have resistivity in the range of (7-24)Ωm up to a depth of 3 m (figure 7a). The borehole derived lithologic log (figure 7b) interpreted this zone to be 'top soils' which, within the context of this study, composed basically of admixtures of decomposed organic matter, clays and silt with varying bio-textural characteristics. At depths of (3-6) m, resistivity falls within the range (41-58) Ωm while the lithologic log interpreted this zone to be 'silty clay'. Going down to 9 m depth, the lithologic log classified this depth interval as 'silty sand' probably as a result of noticeable dominance of sands over silt size particle. On correlation, this interval corresponded to a resistivity range of (82-116) Ωm, and beyond 9 m the litho log interpreted sands corresponding to a maximum resistivity value of 164 Ωm. Furthermore, top soil with resistivity within the range (19-48) Ωm identifiable within the first 3 m figure 8: (a & b). At depths (3-6) m, the resistivity to lithology correlation matched silty sands to resistivity range of (48-76) Ωm while sands were linked to resistivity range of (78-119) Ωm.

CONCLUSION

From the forgoing discussion, we thus integrate our observations with respect to each interpretation using the upper and lower limits of readable resistivity values to build a local quantitative reference frame for near surface lithologic interpretation from surface resistivity data in the study area according to the following scheme:

Resistivity	**interpretation**
Top soils	(7-50) Ωm
Silty sand	(48-116) Ωm
Sands	(78- >164) Ωm

In view of the fact that there are no clear cut boundaries, as is the case with all lithology – resistivity interpretations; it suffices to conclude that another limiting factor aside geology, in interpretations of this kind, is the influence of geochemistry. For instance, variation in concentration of conducting minerals within the pore fills of porous rocks can adversely affect data as observed in the present work, some of which may originate from surface pollution like landfills, sewage, industrial wastes and oil spills.

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