Application of Electrical Resistivity Tomography in Mapping Subsurface Hydrocarbon Contamination

Elijah A. Ayolabi[1], Adetayo F. Folorunso[1,2] & Samuel S. Idem[1]

[1] Department of Geosciences, University of Lagos, Nigeria

[2] College of Marine Geosciences, Ocean University of China, Qingdao, China

Correspondence: Elijah A. Ayolabi, Department of Geosciences, University of Lagos, Nigeria. Tel: 234-803-720-6074. E-mail: eojelabi@yahoo.com; eayolabi@unilag.edu.ng

Abstract

The subsurface soil around Baruwa community was reportedly contaminated by hydrocarbon not because the area falls within oil-producing community but it suffers from inceasant leakage from petroleum pipeline that supply petroleum products to hydrocarbon terminar located within the area. Thus, to ascretain the extent of contamination of the subsurface soil around the area, an integrated geophysical methods involving vertical electrical sounding (VES) and electrical resistivity tomography (ERT) supported with induced polarization (IP) and spontaneous potential (SP) methods were carried out. The hydrocarbon contaminated layers were marked out beneath each VES point by high resistivity ranging between 943Ωm and 4749Ωm at a depth of 1 to 35.44m below the surface. Similarly, ERT result shows that the subsurface soil around the investigated area has been contaminated at a shallow depth of about 2m downward with resistivity value above 1000Ωm. IP and SP data were Integrated to identify the sandy contaminated layers from clayey layer. IP value of 0 to 10mV/V and SP values of <+10mV were obtained over the sandy formation. The work shows that hydrocarbon leaking from the pipeline laid a few meters beneath the earth surface actually flow both upwardly (possibly due to seasonal variation in the water table which is usually close to the surface during rainy season) to the surface and downwardly at greater depth into the subsurface, through a porous medium - sandy layer. This may probably accounts for the reason while most of the handdug wells in the area are reportedly contaminated with hydrocarbon products.

Keywords: contamination, hydrocarbon, sandy formation, tomography, resistivity-depth model, geoelectric layer

1. Introduction

The study area (Figure 1), though not physically located in oil-producing community within the country, shares almost the same fate as the people in the oil-rich Niger Delta. This is not unconnected with inceasant hydrocarbon spillage owing to pipeline leakage and/or vandalization of pipeline facility. The pipes have become old, rusted and leak in some locations thus polluting the groundwater and wells sunk in the area for the inhabitants' domestic water supply. This is not without its health implications on residents of the community as it was reported that the people complain of a number of health problems such as skin rashes (Guardian Thursday 25, 2004). Aside health hazards, the immediate effect of oil spillage is massive destruction of lives and properties through inferno (Figure 2). When this happens, the ecosystem suffers tremendously. Both surface and underground water may be negatively affected as the percolating water already contains signatures of burnt materials (animals, substances, plant and decomposed organisms). Thus, the need to ascertain the extent the subsurface water has been affected by hydrocarbon leakage from the pipeline. The study aims at isolating the contaminated layers and possibly infer the uncontaminated layer where fresh water could be tapped for the use of residents around Baruwa in Lagos.

Electrical resistivity methods have been extensively used in a number of near surface explorations since the first application around 1830 (Parasins, 1962). These include groundwater exploration (Ayolabi, Folorunso, Eleyinmi, & Anuyah, 2009c), mapping subsurface structures (Khali, 2009), geotechnical and engineering site investigations (Giao, Chung, Kim & Tanaka, 2003; Akintorinwa & Adesoji, 2009; Ayolabi, Folorunso, & Oloruntola, 2010c; Folorunso, Ayolabi, Ariyo, & Oyebanji, 2012), exploration and evaluation of ore deposit (Ramazi, Nejad, & Aenollah, 2009), mapping soil and groundwater contamination (Cahyna, Mazac, &

Vendhova, 1990), groundwater quality assessment (Ayolabi, Atakpo, Adeoti, Otobor, & Arerin, 2009b), among other uses. Most early explorations make use of 1D (VES) method until lately when VES method changed greatly into a new technology named Resistivity Imaging (RI) or Electrical Resistivity Tomography (ERT) with 2D and 3D data interpretations (Shevnin, Delgado-Rodríguez, Mousatov, Hernández, Martínez, & Ryjov, 2006; Ayolabi, Folorunso, Adeoti, Matthew, & Atakpo, 2009a). With the new advancement, subsurface characteristic is revealed which enhances better understanding of geologic condition as at the time of survey. More areas of application of resistivity methods are being developed as knowledge increases and challenges in many aspects of human endeavour call for attention. Among such development are applications of geophysical methods in agriculture, soil characterization and mapping hydrocarbon contamination (Loke, 2004; Delgado-Rodriguez, Shevnin, Ochoa-Valdes, & Ryjov, 2006; Sudha, Israil, Mittal, & Rai, 2009).
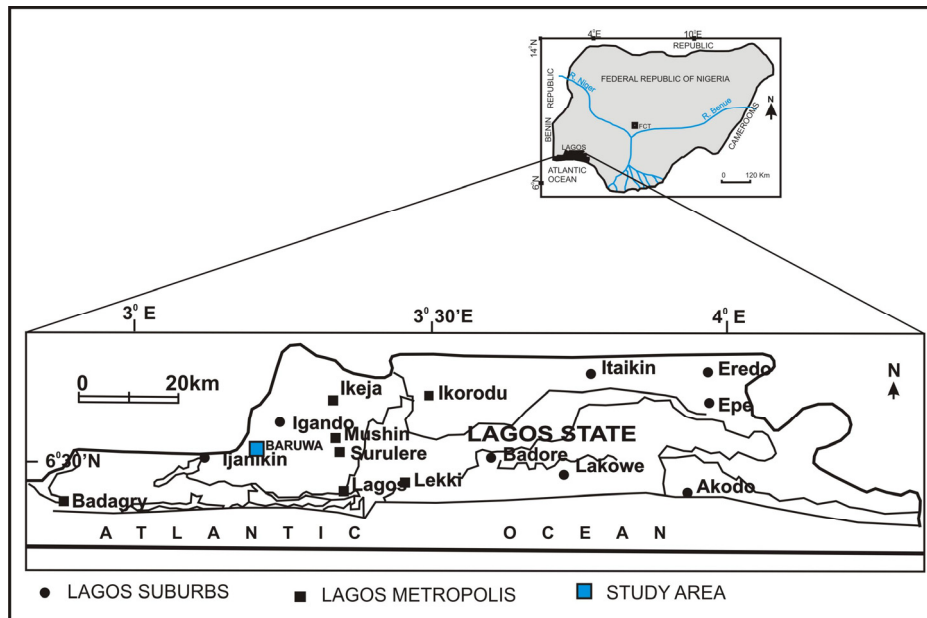

Figure 1. Map of Lagos showing the study area

Figure 2. A recent petroleum pipeline explosion in Nigeria (Punch, 16 Dec. 2009)

2. Geology

The study area is located in Baruwa within Lagos State, southwestern Nigeria. It falls within the Eastern Dahomey basin of Nigeria. Geology of the basin has been variously studied and reported by many authors such as Jone and Hockey (1964), Adegoke (1977), Omatshola and Adegoke (1981), Agagu (1985) and Nton (2001). The oldest formation recognised by these authors are Abeokuta formation, upgraded to group status by Omatshola and Adegoke (1981). There are three formations in the group, the oldest being Ise formation, consisting essentially of continental sands, grits and siltstones, unconformably overlying the basement complex. Overlying Ise formation is the coarse to medium-grained sandstones with variable interbeds of shales, siltstones and clay called the Afowo formation. This is overlain by Araromi formation consisting of sand, overlain by dark-grey shales, siltstone and interbedded limestone, marl and occasional lignite bands.

Overlying Abeokuta Group is the Imo Group divided into Ewekoro and Akinbo formations. Ewekoro formation consists of shaly limestone, which tends to be sandy and it is highly fossiliferous with abundance of coralline algae, gastropods, pelecypods, echinoid fragments and other skeletal debris (Ogbe, 1972). Akinbo Formation overlies Ewekoro Formation and it comprises of shale, glauconitic rock, and gritty sand to pure grey and with little clay. Lenses of limestone from Ewekoro Formation grades literally into the Akinbo shale very close to the base. The base is characterized by the presence of a glauconitic rock.

Oshosun formation overlies the Imo Group as a sequence of mostly pale greenish-grey laminated phosphatic marl, light grey-pupple clay with interbedded sandstones. Claystone underlain by argillaceous limestone of phosphatic and glauconitic materials in the lower basal part of the formation also characterized the stratigraphy of this formation (Agagu, 1985). Overlain Oshosun formation is the regressive deposit of sandstone unit of Ilaro formation consisting of massive yellowish and poorly consolidated cross-bedded sandstone, which represents coarse sandy estuarine deltaic and continental beds that show rapid lateral facies change. The youngest sedimentary unit in the eastern Dahomey basin is the coastal plain sand. It consists of soft, poorly sorted clayey sand and pebbly sands.

The exposed lithologic units of Lagos is made up of coastal plain sand (otherwise called Benin formation (Jones & Hockey, 1964)) and Recent lithoral alluvia deposits. The Coastal plain sand consists of thick yellowish ferruginised and white sands (Jones & Hockey, 1964). It is pooly sorted of loosed sediments ranging from silt, clay and fine to coarse grained sand with intercallation of shale, clay lenses and sandy clay with lignite. The sands are in part cross bedded and show transitional to continental characteristics according to Jones and Hockey (1964), Omatshola and Adegoke (1981), Agagu (1985), Enu (1990) and Nton (2001).

3. Hydrogeology

Lagos metropolis is blessed with aquatic splendor located within the Nigerian Coastal Zone, being a zone of coastal creeks and lagoons (Pugh, 1954). Plethoral of surface water in forms of streams and rivers complement the ocean and lagoon as sources of domestic water for the municipal after treatment. The practice continued untill 1980s when there was increased awareness of the large stock of underground water (Longe, Malomo, & Olorunniwo, 1987).

Three aquifer horizons have been delineated under Lagos metropolis subsurface; these are categorized to first aquifer horizon thought to belong to the Recent lithoral/alluvial deposit and the Benin formation (Longe et al., 1987). This is mostly exploited through hand-dug wells and stand the risk of pollution because of its nearness to the surface and being a water table aquifer (depth of 2.0-15.0 m below the surface) according to Longe et al. (1987) and Adepelumi Ako, Ajayi, Afolabi, and Omotoso (2008). This being the case, the hydrocarbon contamination at the study area falls within the first aquifer. The second aquifer horizon is made up of sands and clay thought to be the coarse sandy estuarine deltaic and continental beds of Ilaro formation (Jones & Hockey, 1964; Longe et al., 1987), while the third aquifer layer consists of alternating sequences of clayey and sandy strata. The second and third aquifer layer were exempted from the contamination possibly owing to the clay seal, but with time, could be proned to contamination through other processes like faulting and pressure on the overlying strata.

4. Methods of Investigation

Both vertical electrical sounding (VES) and elecrical resistivity tomography (ERT) mehtods were employed to delineate hydrocarbon layers in the study area. Self Potential (SP) and Induced Polarization (IP) data were also acquired along with VES data to assist in differentiating geologic layers that may probably give the same resistivity signatures because of their fluid contents. Example of such senerio is found between clay and sandy soil contaning saline or brakish water. Both give low reisitivity signature difficult to interppret except with the

presence of additional information form other geophysical methods such as IP, which produces high signature over a clay layer as against low IP over sandy layer (See Ayolabi et al., 2009b; 2010a; 2010b; Murali & Pantangay, 2006). Six ERT profiles were run using wenner array with electrode separartion 'a' varying from 3.0m to 20.0m. The choice of small value for electrode spacing is to capture the near-surface effects of the contamination without necessarily omiting any information (Loke, 2004). The maximum length of the profiles is 150.0m parallel to the pipeline on both sides for profiles 1-3, while profiles 4-6 were perpendicular to the pipe line as indicated in Figure 3. Equally, six VES points were established, each on the ERT profiles using schlumberger array with AB ranging between 80m and 600m owing to space constraint. SP and IP data were acquired concurrently with VES data using the same electrode configurarion (Murali & Pantangay, 2006). All data were obtained with the aid of Syscal Junior Resistivity meter. It is a high-powered, fully automated resistivity meter for dc electrical surveys. It has been used extensively in a number of surveys such as groundwater exploration, environmental studies, civil engineering and structural geology investigation.
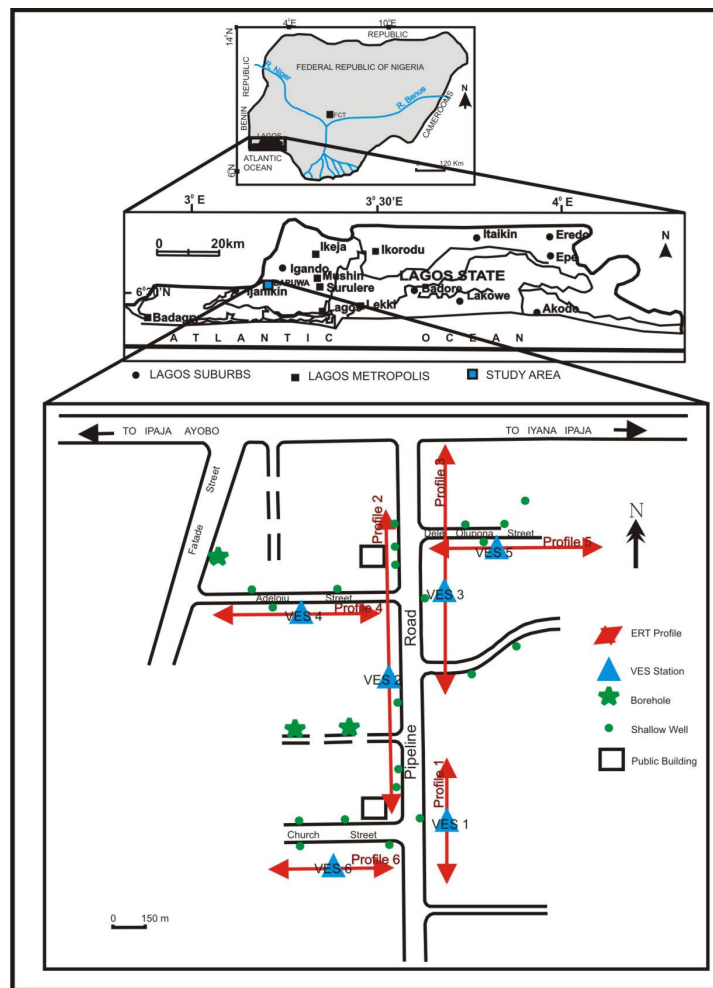

Figure 3. Data acquisition map

VES data were interpreted using WINGLINK program to give the aquifer parameters read from resistivity-distance graph, shown in Figure 4. The programme has been tested and proven reliable for the interpretation of sounding data when right commands are supplied (Folorunso, 2009). The 2-D data were processed and inverted using Earth Imager (an AGI inversion software). These programs generate the inverted resistivity-depth image for each profile line based on an iterative smoothness constrained least-squares inversion algorithm after deGroot-Heldin and Constable (1990) and Loke and Barker (1996). These inversion routines involve a cell-based inversion technique; it subdivided the subsurface into a number of rectangular cells whose positions and sizes are fixed and then used to determine the resistivity of cells that provides a model response

which agrees with the observed data (Loke, 2000; 2004). The differences between the observed and calculated blocks were minimized to obtain an acceptable agreement of the fitting process (Loke & Barker, 1996). A measure of this difference is given by the root-mean-square error (RMS%). However, the lowest RMS error may show large and unrealistic variations in the model resistivity values and might not be the best from a geological concept. Notwithstanding this, reasonable values of RMS (5.96-7.11) were maintained for all the profiles.
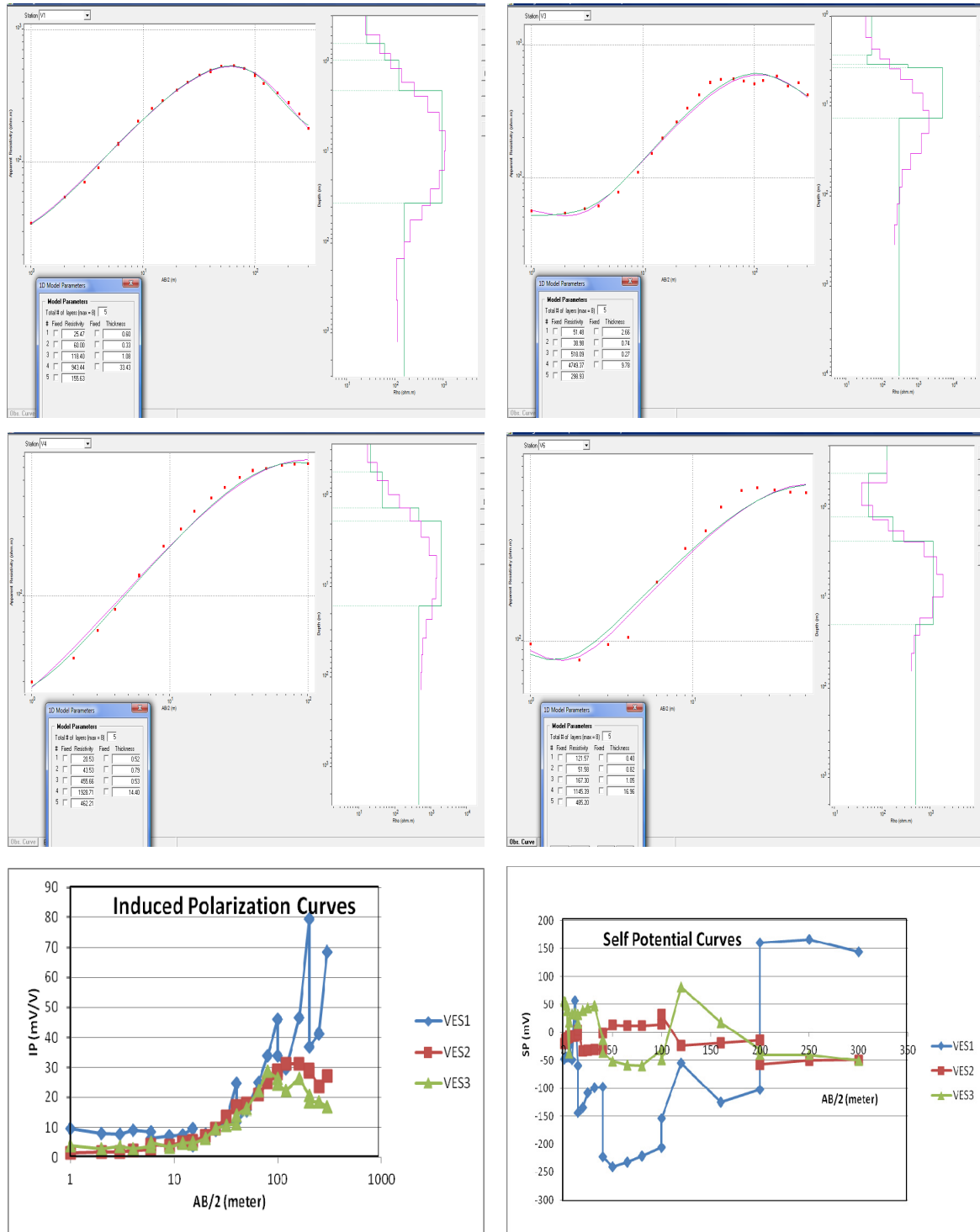

Figure 4. Typical Curves for VES, IP and SP Soundings in the Area

5. Results

5.1 Electrical Resistivity Tomography (ERT) Results

The results of ERT for the six profiles are displayed as resistivity-depth sections. The 2-D resistivity section for profile 1 closed and parallel to the pipeline, Figure 5 reveal**s** that the high electrical resistivity values in the near surface between electrode positions 0-50m could be attributed to hydrocarbon contamination as reminiscence of the activities of oil bunkers in the area. However, a close look at the resistivity-depth section shows strong protective capacity of the clayey soil to the underlying sand layer. The clay layer is relatively thick (about 4 m thick). Where this type of stratigraphical section abounds there is high confidence for the protection of groundwater aquifer. However, we suggested the contamination here resulted from puncture of the pipeline or that the contaminant percolated down through other means which could be cracks on the overlying layers or holes usually made by the bunkers.
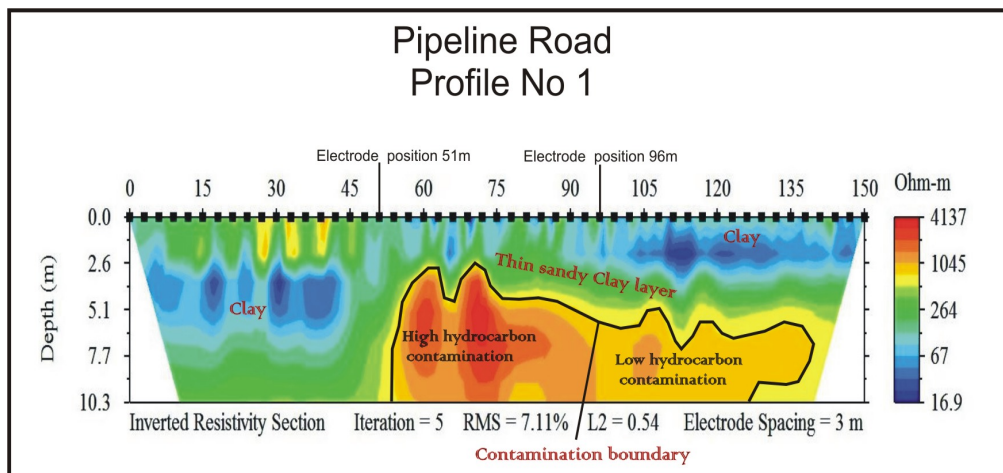

Figure 5. Resistivity-Depth Structures of Profiles 1

Near surface resistivity distributions in the second part (about two-third of the profile) depicts an opposite conditions with a clay layer (< 50 Ωm), to a depth of about 2.5m, between electrode positions 51m to 150m, as the top soil followed by a thin layer of uncontaminated sandy clay soil, at a depth between 2.5m-3.1m apparently above the buried pipeline. The layer shows no evidence of pollution as the resistivity values obtained represents that of sandy clay - an interface between the top clayey layer and the bottom sand horizon (Keller & Frischknecht, 1966; Daniels & Alberty, 1966). This was the general trend in all the profile. Geologically, it may typify succession of paleo-depositional regime of the area.

The third layer was a porous sandy but contaminated zones of high resistivity signalling the possible presence of hydrocarbon in the layer. We categorized the polution effect into high (>1000Ωm) and low (650Ωm-1000Ωm) hydrocarbon contamination based only on the observed resistivity signatures. In practice, we understand that contaminant concentration is always higher at the source of pollution than the surrounding. The pipeline was said to be buried at about 2m to 3m beneath the surface. A vivid look at the result of this profile shows that the leaking petroleum product occurs within the range of 3.1m-10.3m as evident beneath the electrode positions between 54m-150m. This suggests downward flow of the leaking oil from the depth of burial of the pipeline. On the other hand, the surface position 9m-42m appears to be reminiscence of the bunkers' activities on the surface, having sharp contrast in near surface resistivity value compared to near surface from other section of the profile.

On profile 2, resistivity-depth model reveals a clayey layer of resistivity <80Ωm in the near surface (to a depth of 3.0m) along the profile length with pocket of high resitivity materials in the first half (Figure 6). Similar pocket of high resistivity material in the near surface of profile line cut along access road has been attributed to exotic materials (broken blocks, bricks and stones) usually used for land reclaimation or temporary road construction (Ayolabi et al., 2010c). Beneath the clay layer is a thin sandy clay horizon having resistivity of 160Ωm-250Ωm, which serves as a transition zone for the upper clay layer and the lower sandy layer. This was followed by a contaminated, porous and permeable sandy formation with resistivity above 1000Ωm between electrode positions 84m-132m below 5.1m depth. The extent of the contamination varies and this is only

significant in the second half of the profile length (i.e between electrode positions 84m and 132m) below 5.1m depth in the subsurface. It appears that the hydrocarbon contamination extends below the maximum depth delineated in the profile going by the synclinal structural feature of the polluted area.
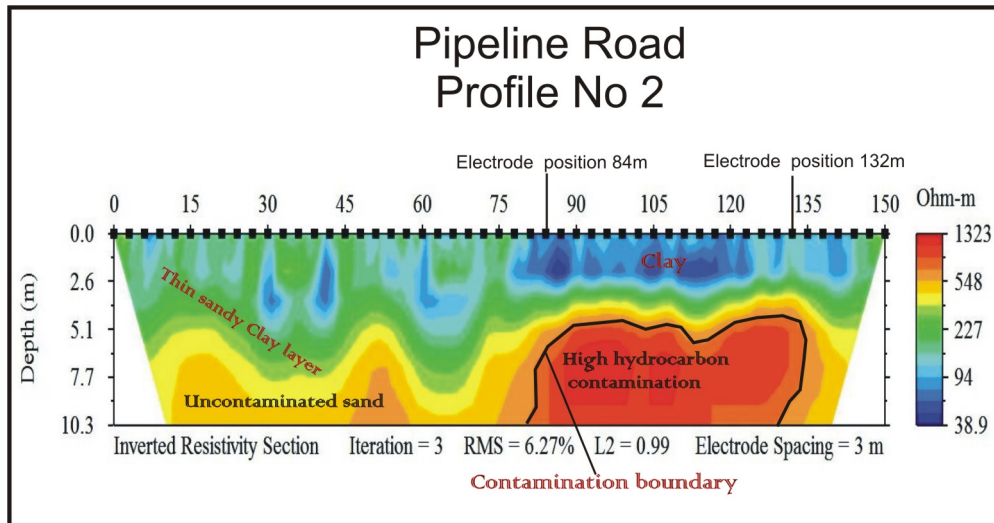

Figure 6. Resistivity-Depth Structures of Profiles 2

Resistivity-depth model obtained along profile 3 reveals that the electrical resistivity values generally increase with depth from surface to a depth of about 10.3m while very low to intermediate values (30Ωm-75Ωm) are found to be associated with clayey soil (Figure 7). A thin sandy clay layer was found next with resistivity between 100Ωm-200Ωm just as in other profiles. The third layer was a contaminated sandy horizon. Hydrocarbon contamination occurred at the depth of 5.1m downward, the contaminated zone having a resistivity of over 1100Ωm as shown between electrode positions 18m-66m and 84m-132m and appears to be spreading vertically and laterally downward. It is suffice to note that profiles 1, 2 and 3 have high proxy and are parallel to the pipeline, in fact, not more than 7.0 meters away, and the three profiles are collinear, as shown in Figure 3.
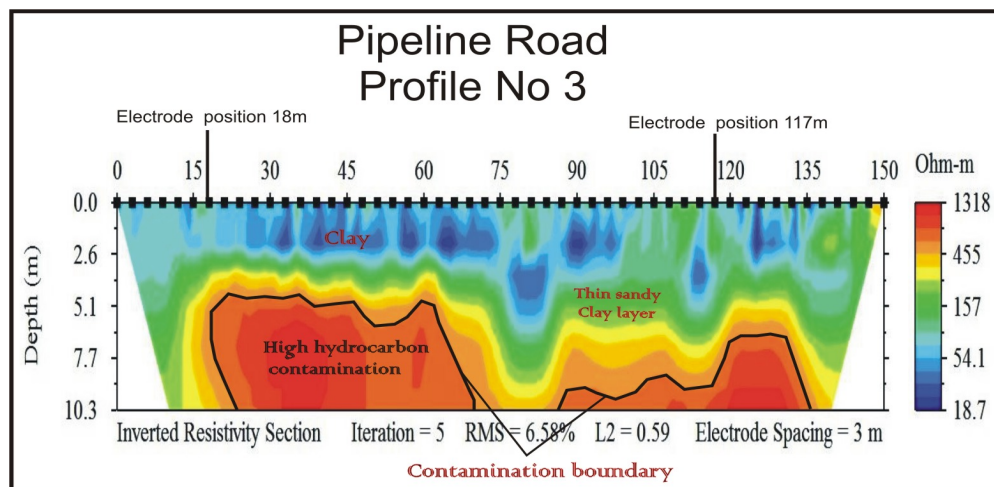

Figure 7. Resistivity-Depth Structures of Profiles 3

Profile 4 presents a different scenerio as resistivity increases down the earth with no sign of contamination anywhere. The profile is located adjacent to the pipeline. Three different layers were delineated with clayey top soil of resistivity below 85Ωm. Though pockets of high resistivity materials exist in this layer they may not be

unconnected with the presence of exotic materials as earlier mentioned. The underlain sandy clay layer has resistivity range of 120Ωm-270Ωm as shown in Figure 8. The third layer is a sandy soil with no indication of contamination having resisitivity below 550 Ωm. However, it could be noted that the anticlinal nature of the sandy layer (between electrode positions 9.0m-63.0m) being delimited by sandy clay (low permeability and porosity material) prevented the hydrocarbon from contaminating the horizon since the pipe is burried at a depth between 2.0m and 3.0m adjacent to the profile, which falls within the clay and sandy clay layers.
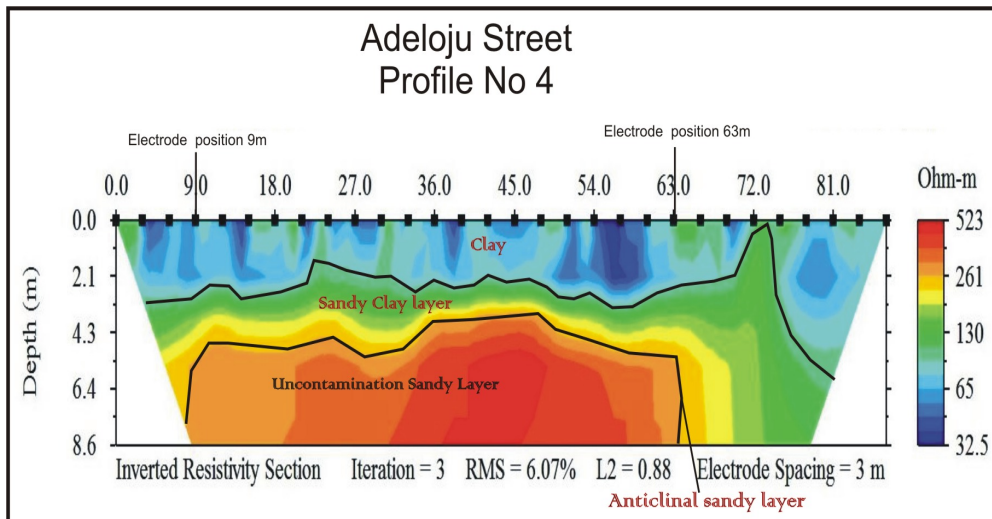

Figure 8. Resistivity-Depth Structures of Profiles 4

Similarly, the result from profile 5, adjacent and a bit far from the pipeline shows no possible contamination from the surface to 10.3m depth being maximum depth probed in this study. The only difference is that the exposed litho-section comprises a clay soil of resistivity below 90Ωm (between electrode positions 3m-9m and 24m-33m); sandy clay of resistivity values between 120Ωm-250Ωm (between electrode positions 9m-18m and 36m-45m); and a sandy soil of resistivity >370Ωm (between electrode positions 48m-50m) (Figure 9).
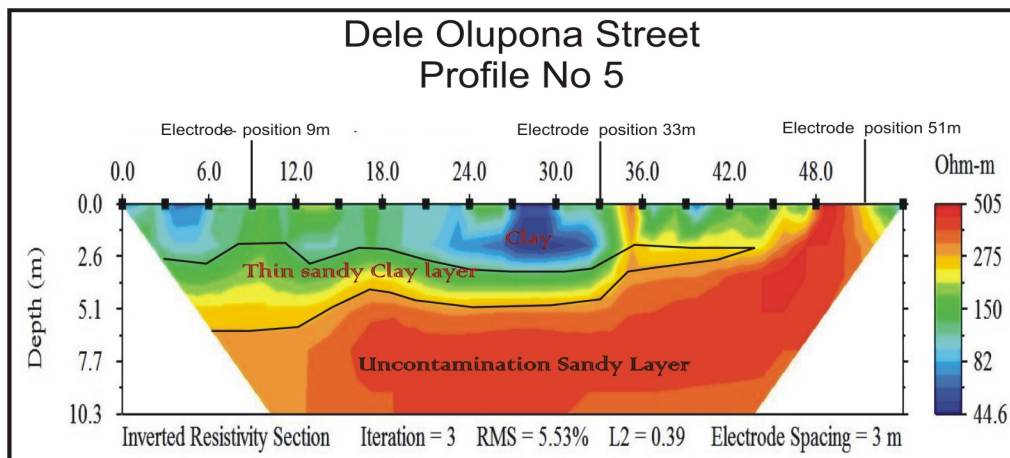

Figure 9. Resistivity-Depth Structures of Profiles 5

In addition, other layers equally observed in the profile, characterized based on their resistivity range, are thin sandy clay (120-250Ωm) between electrode positions 3.0m-42.0m, at a depth below 2.6m and uncontaminated sand layer (>300 Ωm) between electrode positions 6.0m-48.0m at a depth of 5.1m downward.

Inverted resistivity-depth section from profile 6 shows that resistivity variations increase downward from the surface to the last layer. Two major geologic layers differentiated into three geoelectric layers are delineated here. The first layer is clay / sandy clay layer with resistivity values of 20Ωm to 200Ωm. The second geologic layer is sand divided to uncontaminated sandy horizon and highy contaminated sandy horizon. The contaminated zone was encountered at near surface depth of 4.0m to about 10.3m between electrode positions 12.0m-39.0m (Figure 10). The contamination here is prominent and comparable with those of profiles 1 to 3 possibly because of its high proxy to the the pipeline.
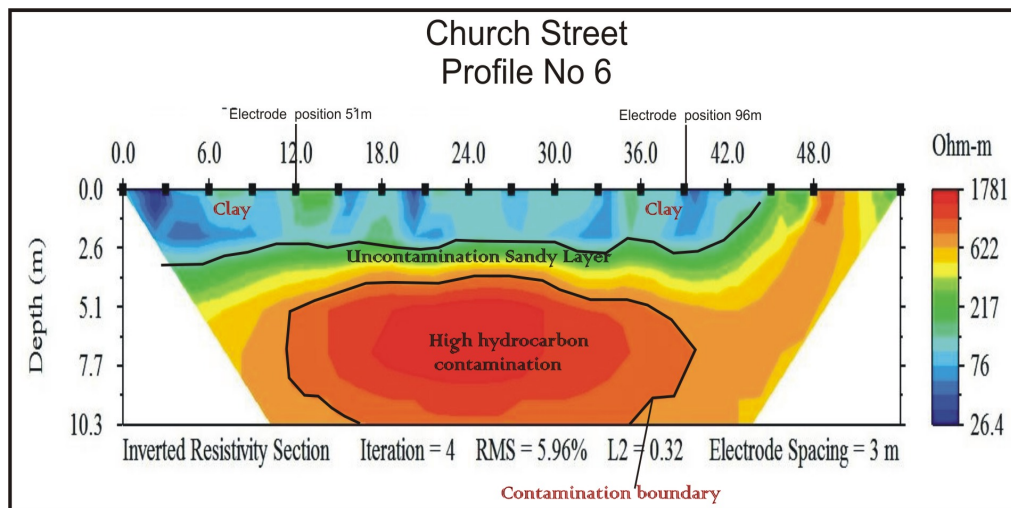

Figure 10. Resistivity-Depth Structures of Profiles 6

5.2 VES, IP and SP Results

Six VES stations were established along six ERT profiles in the area, (Figure 11). The interpretation of VES was done in conjuction with the IP and SP because of the ability to differentiate between moist clay formation and saline sandy formation from the IP response (Sastry & Tesfakiros, 2006; Ayolabi et al., 2009b). Five geoelectric layers were delineated in all the stations. The first layer (top soil) is characterised by clay/clayey sand in all the layer with resistivity range of 13Ωm-122Ωm. The IP and SP signals for top soil range from 1.5mV/V to 10mV/V and -60mV to 38mV respectively. The intermediate values of IP (10mV/V) confirm the clayey sand for some of the stations. The clay top soil has the capacity to prevent aquifer contamination should the contaminant emanates from the surface. However, the source of contamination been investigated is a subsurface phenomenon usually below three meters down as revealed from all the profile.

The second layer composed of clayey and contaminated sandy soil as revealed from integration of both data . The clayey soil has resistivity values ranging between 39Ωm and 69Ωm at the maximum depth of 0.93m-3.4m, while the contaminated sandy horizon is encountered in the subsurface soil under VES 2 having a high reisitivity of 953Ωm from the depth of 0.9m to 6.2m. The SP and IP of the clayey layers range from -150mV to 32mV and, 0.5mV/V to 10.5mV/V respectively while across the contaminated sandy layer the SP and IP values are -28mV to -26mV and 6mV/V to 9mV/V respectively which indicate the sand layer (from IP value) and contamination status (from SP signature). The third layer is clayey (23Ωm in VES 5) and sand (118Ωm-518Ωm) layers. There is little or no contamination in the subsurface soil under this VES station. The depth range of this layer is from 0.27m to 5.5m.

The fourth horizon comprises oil contaminated sandy layer having high resistivity of 943Ωm, 4749Ωm, 1929Ωm and 1145Ωm in VES atations 1, 3, 4 and 6 respectively, at depth range of 1.16m- 34.55m. The thickness range of the contaminated zone is 9.78m-33.43m. The low values of IP (< 10 mV/V) confirmed the layer to be sand while the SP values range between -230mV and 80mV. The petroleum pipeline was reportedly laid 2m-3m below the surface, when vandalised its content (oil) flows through the porous meadia (e.g. sand) laterally as well as vertically cutting across different lithologic sections, if no lithologic barriers are encountered along the flow path. This could possibly informs the high thickness of contaminated horizon as delineated in this study (as thick as 33.44m in VES 1). The last layer investigated is a sandy horizon in VES stations 2 (473Ωm), 4 (462Ωm), 5

(456Ωm) and 6 (485 Ωm). It follows that for water borehole to be completely free of hydrocarbon contamination in the study areas, such borehole should be dug deeper than 50m and possibly overlain by impervious seal.
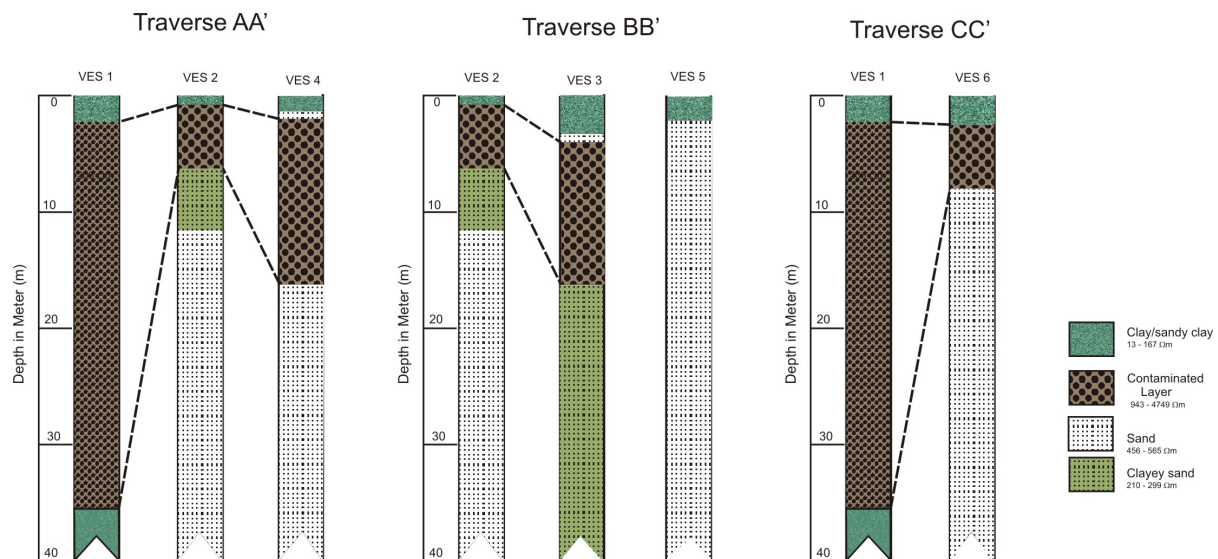

Figure 11. Geoelectric section from VES results

6. Conclusions

2D and 1D electrical resistivity supported with induced polarization and self potential methods carried out at hydrocarbon contaminated site have been reported in the work. Interpretation of electrical resistivity tomography shows high pollution of the subsurface soils around the study area from a depth of about 2.6m up to a depth of 10.3m. This was further confirmed by VES except on profile 1 where the VES indicate pollution to the depth above 30m. This depth falls within the first aquifer horizon where average inhabitants of the area exploit groundwater for domestic uses. Incidentally, the pipes were laid about 2m to 3m within the earth. The thick depth of contamination indicates that the subsurface soil beneath the pipes is porous and permeable. Both ERT and VES also delineate sand horizon as the layer affected by the contamination. The resistivity of the contaminated layer is above 943Ωm as revealed by both VES and ERT. Interpretation of IP and SP data were used to constrain resistivity results for delineation of the contaminated sandy horizons. IP value of 0 to 10mV/V and SP values of <+10mV were obtained over the sandy formation. Contamination of subsurface soil in the study area accounts for a number of health-related challenges the inhabitants of the area are facing as a result of drinking hydocarbon contaminated water. Any borehole or water well not deeper than 50m may not be free from hydrocarbon contamination, as revealed by both ERT and VES results.

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