

Minireview Paper

Hydrocarbon spill site characterization by Electrical Resistivity Tomography and Ground Penetrating Radar methods - A Review

ABSTRACT- *Assessment of the source and geometry of contaminated soils by hydrocarbon spills is the first step towards designing an effective remediation programme. Electrical Resistivity Tomography and Ground Penetrating Radar are shown in this review to easily delineate spills under certain conditions. On a 2D-geoelectric profile of the subsurface, recent hydrocarbons spills are reflected as highly resistive anomalous zones, as biodegradation occurs spills become more conductive and may be masked by conductive soil. On a radargram fresh hydrocarbon spills are observed in zones of saturation where resistive fresh hydrocarbon spills displace water in pore spaces which is conductive creating anomalous zones. Accurate interpretation of geoelectric profiles and radargrams in the Niger Delta requires knowledge of the lithology of the site of contamination which could easily be obtained by shallow drilling or pitting.*

Keywords: *Electrical Resistivity Tomography, Ground Penetrating Radar, Hydrocarbon spills, Soil Contamination.*

INTRODUCTION

The Niger Delta is the largest wetland in Africa and also the third largest in the world. For decades oil exploited from the Niger Delta has been the major source of foreign exchange for Nigeria, which has been amongst the top ten oil producing nations in the world. Statistics in public domain show that over the last three decades, more than 400,000 metric tonnes of crude oil has been spilled into the creeks and soils of the Niger Delta, some 70% of which are yet to be recovered (UNDP, 2006). The National Oil Spill Detection and Response Agency (NOSDRA) declared it had located 1,150 oil spill sites abandoned by various oil companies within the Niger Delta (Thisday, 2008). These spills which are largely due to aging facilities, operator errors and sabotage have massively devastated the biodiversity, air, land, surface and underground water bodies of the Niger Delta, whose local inhabitants are mainly farmers and fishermen.

Geophysical methods offer a relatively fast, non-invasive, cost effective and efficient process for characterizing hydrocarbon contaminant plumes in the subsurface. These methods employed independently or integrated with other geophysical or non-geophysical methods have been used successfully determine the source and geometry of plumes which served as a basis for efficient remediation procedure designs (Sauck, 1998; Atekwana et al, 2000; Hamza et al, 2008; Nwankwo and Emujakporue, 2012)

This research x-rays the principles and methodology of Electrical Resistivity Tomography and Ground Penetrating Radar methods. It highlights their application in hydrocarbon spill detection and mapping with some likely expected results and drawbacks of these methods in mapping and monitoring soil contamination in areas devastated by spills in the Niger Delta.

PHYSIOGRAPHY AND GEOLOGY OF THE STUDY AREA

The Niger Delta is a complex prolific basin formed by an extensional rift system in the Niger Delta and Gulf of Guinea, on a passive continental margin near the west coast of Nigeria between latitudes 3°N and 6°N and longitudes 5°E and 8°E (Reijers et al, 1996). It is one of the largest sub areal basins in Africa with an expanse of about 75,000 km, a total area of 300,000 sqkm, sediment fill of up to 500,000 cubic km and a sediment fill of 9 – 12 km (Fatoke, 2010). The Niger Delta is bound on the northwest by a subsurface continuation of the Benin flank, on the east by the Calabar flank and to the south by the Oban Masif (Murat, 1972). The major lithostratigraphic units observed on a well section through the Niger Delta consist of an upper delta top facies, a middle delta front lithofacies and a lower pro-delta lithofacies (Reijers et al, 1996). The lithostratigraphic units correspond respectively with the uppermost Benin Formation aged Oligocene to recent, the Agbada Formation which lies beneath the Benin Formation aged Eocene to recent and the lowest lying Akata Formation aged Paleocene to recent (Short and Stauble, 1967). The Akata Formation is composed mainly of marine shales with sandy and silty beds which are believed to have been laid down as turbidites and continental slope fills with an estimated thickness of 7,000 m. The Agbada Formation which the the petroleum bearing unit in the Niger Delta, consists mostly of shoreface and channel sands with minor shales in the upper parts and an intercalation of sands and shales in equal proportion in the lower parts, with a thickness of over 3,700 m (Doust and Omatsola, 1990). The Benin Formation consisting of

58 continental sands and gravels is about 280 m thick and maybe up to 2,100 m in the region of
59 maximum subsidence (Whiteman, 1982).

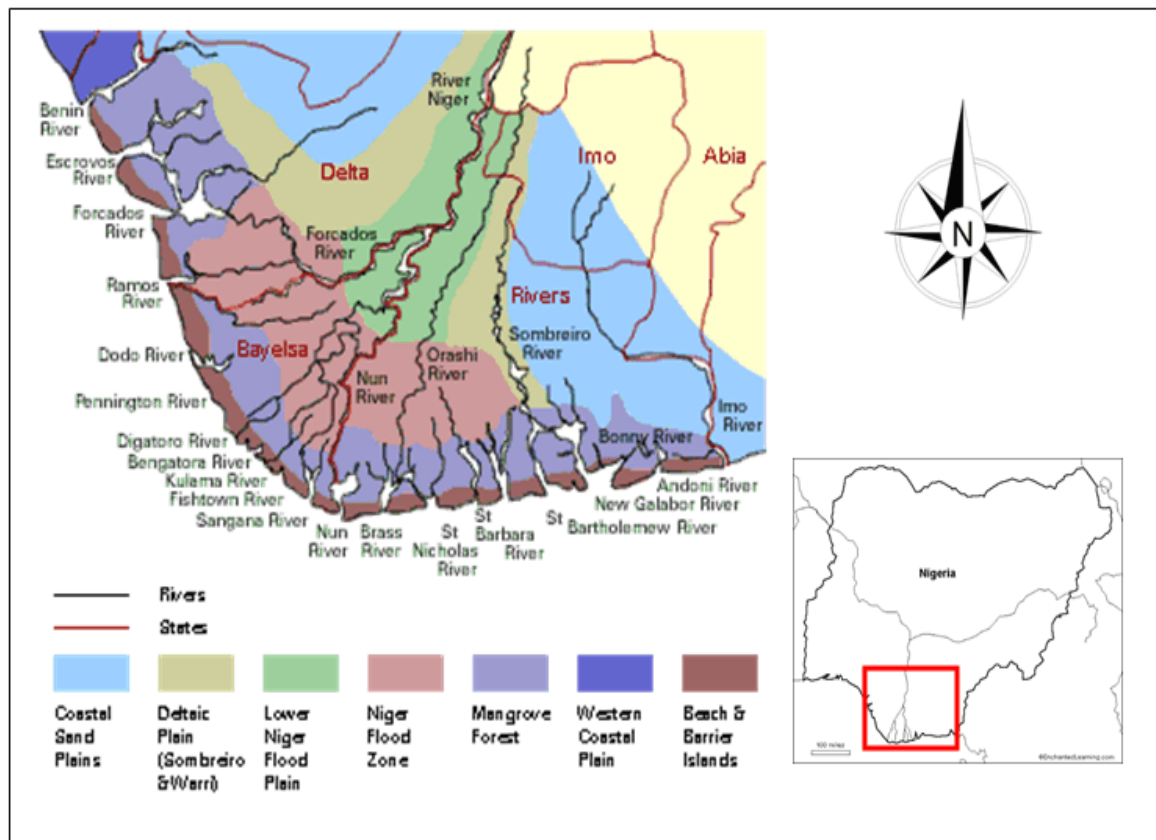


Fig 1 Map of the Niger Delta

METHODOLOGY AND RESULTS

Electrical Resistivity Tomography

This method involves introducing electrical current into the subsoil with the aid of a resistivity machine through current electrodes and measuring the resistance of the earth material to the flow of electricity by potential electrodes. Data is acquired repeatedly along profile lines to give a 2D image of the subsurface (fig. 2) which shows the lateral and vertical variation of the earth's electrical resistance, a method commonly referred to as Electrical Resistivity Profiling, Imaging or Tomography.

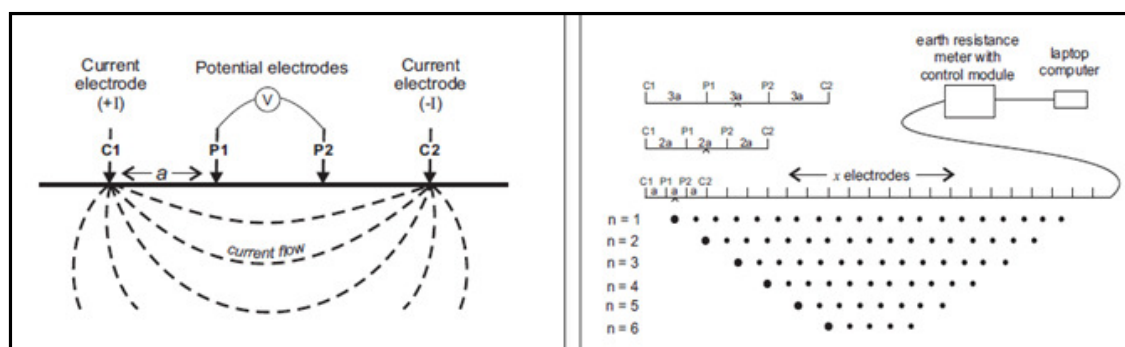


Fig. 2 Basic Electrical Profiling Configuration

The lateral extent using this method is dependent on the electrode array spread, whereas, depth of investigation increases by an increase in electrode spacing for a constant array spread. Investigations could extend to a few hundreds of meters before resolution becomes compromised. Electrode array configurations employed depends largely on the interest of the survey. Wenner array is the most common array, it is usually employed where there is an equal interest in vertical and lateral resolution, in cases where lateral resolution is of greater interest dipole-dipole arrays have been employed (Yi et al, 2001; Loke, 1997). In acquiring 2D apparent resistivity data, the lateral coverage must extend reasonable across the target of interest, there must also be a detectable variation in the electrical resistance of the target from the surrounding country rock. Data acquired is then fed into a resistivity inversion software to produce 2D geo-electric profiles of the surveyed area. Gridded 2D investigation at regular intervals can be used to generate 3D profiles across the area of interest (for more details of Electrical Resistivity method see Loke and Baker, 1996b; Loke, 1997).

The theoretical basis for the application of geo-electrical method for hydrocarbon spill detection and mapping in the subsurface is dependent on the contrasting electrical properties of hydrocarbons, soil and groundwater (McNeill, 1990; Benson et al, 1991). The magnitude of the contrast depends mainly on the hydrocarbon contaminant age and some environmental processes. Early research established that recent hydrocarbon spills are associated with high resistivity anomalies, whereas, mature spills showed reduced resistivity anomalies (Mazac et al, 1990; Olhoeft, 1992). In mature hydrocarbon contamination sites increased conductivity was as a result of increased Total Dissolved Solids in pore water in the soil. Other physical, chemical and biological factors like soil type, microbial activity, organic matter, cation exchange and water

95 table depth compounded to cause increased conductivity observed (Sauck, 1998 & 2000;
 96 Atekwana et al, 2000). As such, during resistivity profile interpretation environmental factors as
 97 well as age of spills must be taken into account to forestall misleading conclusions (Uchegbulam
 98 and Ayolabi, 2014; Oki et al, 2015; Ehirim et al, 2015). Some results of 2D and 3D survey
 99 profiles across spill sites in the Niger Delta showed agreement with early literature. Results of
 100 two Electrical Resistivity Imaging profiles across a zone of recurrent hydrocarbon spills in
 101 Oshika community of Ahoada in Rivers state (Nwankwo and Emujakporue, 2012) showed fresh
 102 spills where characterized by high resistivity response in the subsoil (fig. 3).

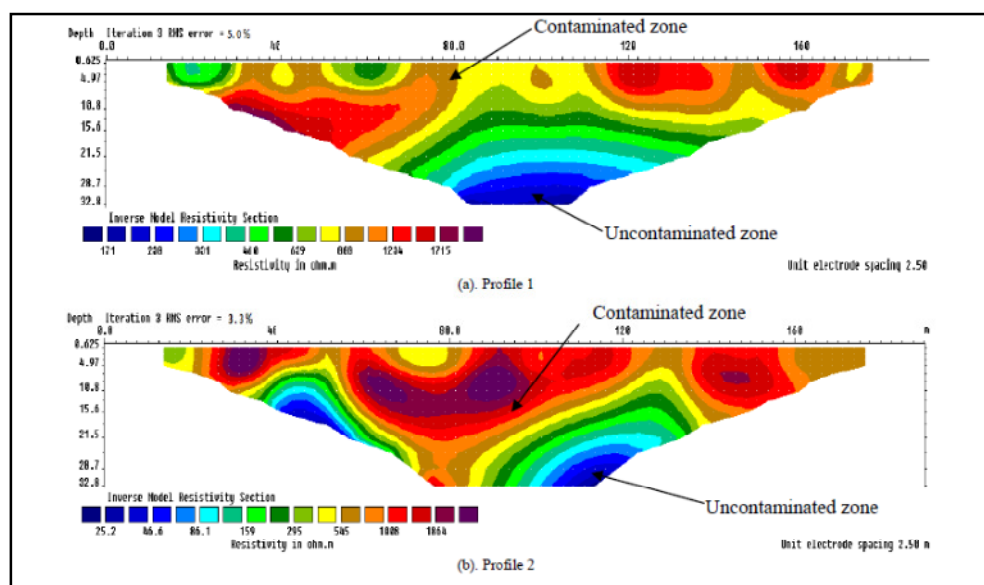


Fig 3 2D geoelectric profile across recent hydrocarbon contaminated site in Ahoada

(Nwankwo and Emujakporue, 2012)

106 Using Electrical Resistivity Tomography to investigate the impact of recent hydrocarbon spills
 107 on a shallow aquifer system in Sapele town of Delta state (Uchegbulam and Ayolabi, 2014) also
 108 showed results with high resistivity values at subsurface spill accumulation points (fig. 4). Oki et
 109 al (2015), showed low resistivity associated with mature spills (fig. 5) which was in line with
 110 early literature, while investigating mature spills along hydrocarbon pipeline routes in Yenagoa.
 111 3D depth slices of Electrical Resistivity Images on an hydrocarbon contaminated site with fresh
 112 spill over matured spill at Forcados in Delta state (Atakpo and Akpoborie, 2011) showed freshly
 113 contaminated sites had higher resistivity than much older spills (fig. 6). Older spill had a higher

114 resistivity response than saline background subsoil. A major drawback of this method would be
 115 observed when sampling mature spills in the commonly saline clay rich subsoil in the Niger
 116 Delta. It becomes dicey in determining the source of observed low resistivity values.

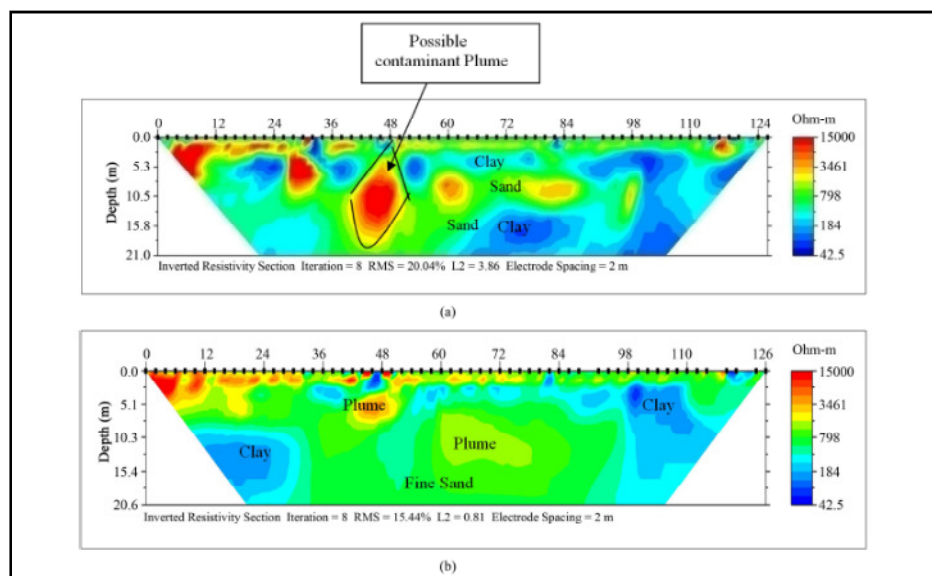


Fig 4 2D geoelectric profile across recent hydrocarbon contaminated site
 (Uchegbulam and Ayolabi, 2014)

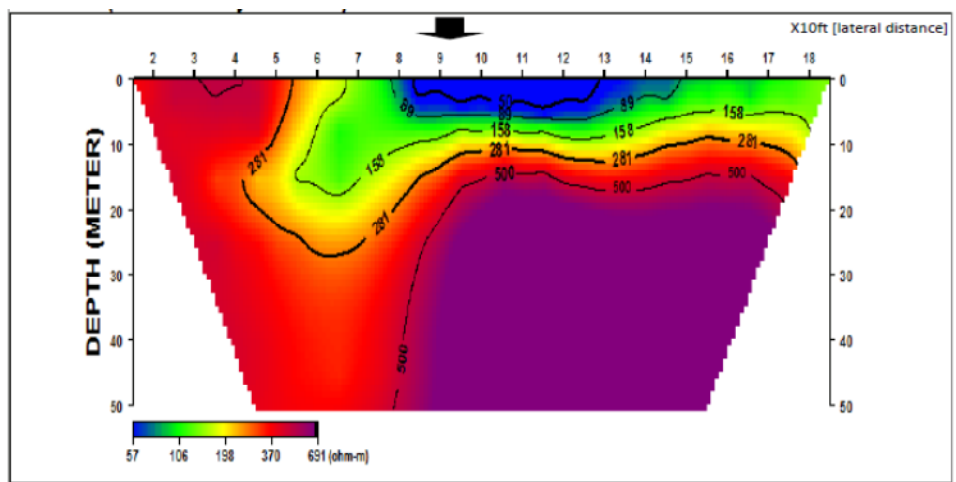


Fig 4 2D geoelectric profile across mature hydrocarbon contaminated site
 (Oki et al., 2015)

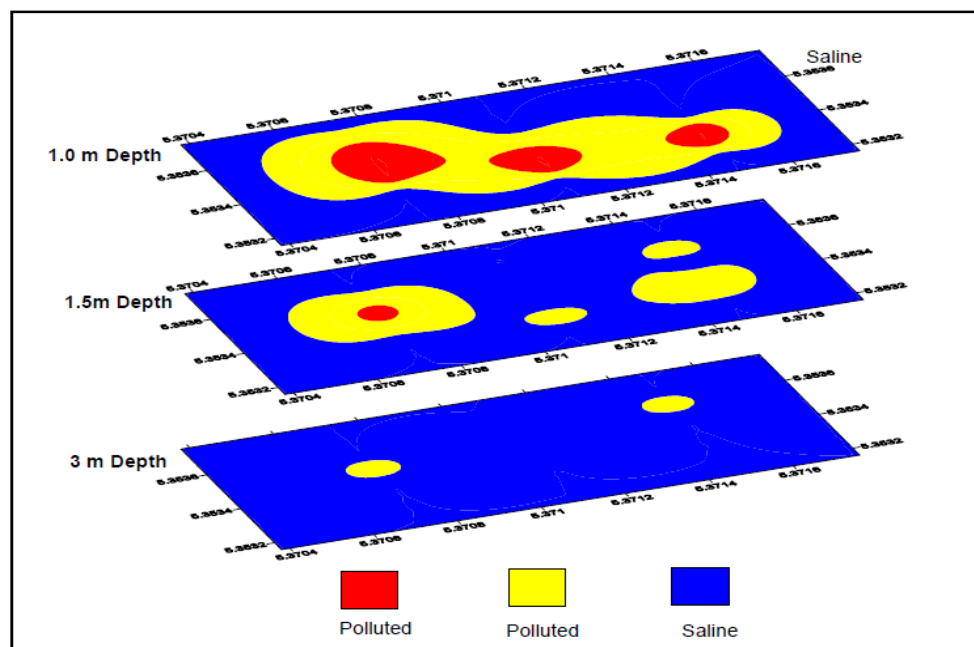


Fig 6 3D depth slices of a geoelectric profile across recent hydrocarbon contaminated site at Forcados (Atakpo and Akpoborie, 2011)

Ground Penetrating Radar

The GPR method involves a technique of imaging the subsurface at high frequencies, it makes use of a radio wave transmitter to transmit electromagnetic waves at frequencies between 50 MHz and 2.5 GHz in short pulses of less than 20 ns into the subsurface structure (Davis and Annan, 1989). When transmitted waves are incident on an interface of significant dielectric contrast, some of the energy is reflected back to the surface where it is measured by a receiver (fig. 7). Variation in the reflected arrivals on the receiver is a factor of the number of interfaces with dielectric contrast the transmitted wave encountered. Transmitted signals with low frequency have a greater penetration but produce low resolution received signals. The radar frequency employed for a given survey is thus chosen to provide an acceptable trade-off between penetration and resolution (Hamza et al, 2008). The receiver measures the variation in strength of reflected signals with time to produce 1-D representation of the subsurface beneath the antennas called a Scan.

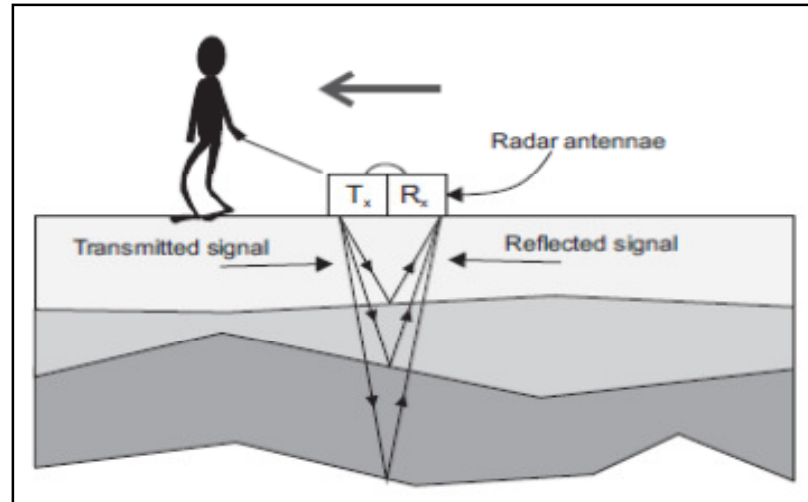


Fig 7 Schematic of GPR data collection system

To build a 2-D profile of the subsurface referred to as a Radargram, the antenna is traversed across the surface of interest to obtain a number of adjacent scans. Stacking of adjacent Radargrams generates 3-D Radargram cubes from which depth slices of interest can be extracted.

Surface GPR surveys generate high vertical resolved images of boundaries between horizontal layers, where there is a distinct variation in water content of these layers. In the unsaturated zone this depends solely on water retention capacity of the subsurface material, the water table is usually a clear boundary in a sandy aquifer system (Ghinda et al, 2013).

Some drawbacks of the GPR method are depth limitation and requirement of an even ground surface for data collection. Depth limitation is primarily caused by attenuation of radar signals by clay rich soil, saline groundwater and blocky subsurface materials like landfill, cobbles and rebars, as such, GPR works very well in low loss material like sands and gravel and performs poorly in highly conductive materials like clays (for more details of how the method works see Keary et al., 2003; Reynolds, 1997).

The GPR has been shown to have a potential in certain field conditions for delineating the geometry of hydrocarbons in the subsoil (Olhoeft, 1986; Daniels et al, 1995). This potential exist when the electrical properties of such contaminants vary from water. For instance, when hydrocarbons and air are present in the pore spaces of dry quartz sand there is no significant

contrast in the relative permittivities of these materials (ϵ_r Air = 1, ϵ_r Dry Hydrocarbons = 3 to 5, ϵ_r Dry quartz = 5), as such, detection becomes challenging. However, in a case where hydrocarbons exists with water (ϵ_r Water = 81), a significant and detectable contrast exists in areas where hydrocarbon displaces water relative to areas where no water has been displaced. Air, hydrocarbon and dry quartz are relatively high velocity media for propagating radar energy when compared to water and clays. A detectable decrease in radar wave attenuation should suffice in areas where fresh hydrocarbons displace water (Kim et al, 2000). This concept changes in cases of mature hydrocarbon spills, which available early literature showed increased in conductivity with time, as such, becomes a low velocity medium with time (Sauck, 1998 & 2000; Atekwana, 2000).

In a 2-D GPR study of hydrocarbon contaminated soils south-west of Kuala Lumpur in Malaysia (Hamza et al, 2008) results showed three distinct reflection patterns (fig. 8) representing a top sandy-silt layer with flat high amplitude reflections, an oil contaminated middle zone characterized by discontinuous chaotic reflections and a thick underlying soft clay zone where radar waves were highly attenuated due to high conductivity of clays, usually referred to as a free reflection zone were identified.

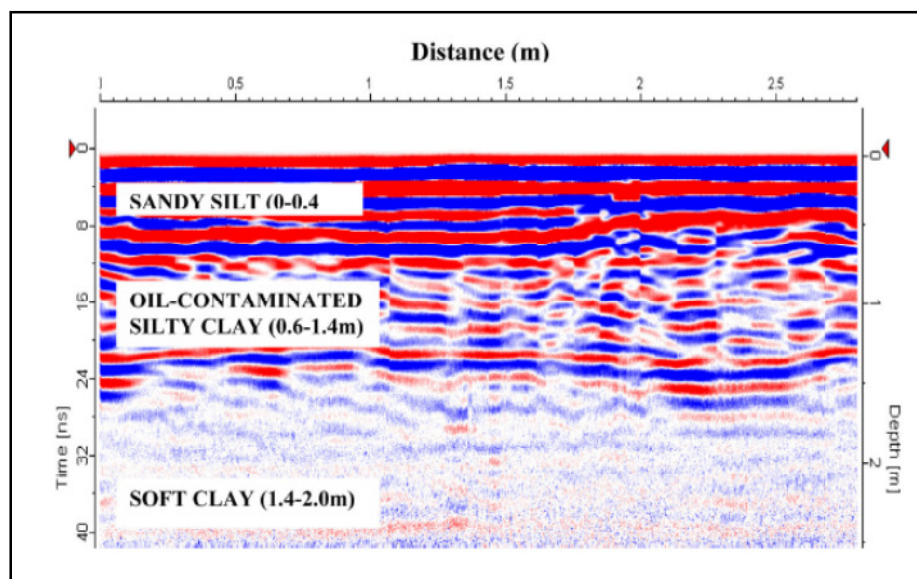


Fig. 8 Radargram of hydrocarbon contaminated soil in Kuala Lumpur (Hamza et al., 2008)

178 Radargram from a survey mapping hydrocarbon plumes in Ibeno, L. G. A. of Akwa Ibom State,
 179 Niger Delta of Nigeria (Udotong et al, 2015) presented horizontally stratified near surface high
 180 amplitude events, indicative of sand units. Below the first zone are barely visible chaotic
 181 reflection events observed at depths of about 2.5 m. Attenuation of radar waves was due to high
 182 conductivity of saline based hydrocarbon plumes. Beyond the second zone on the application of
 183 high gain, high amplitude horizons indicative of sands occur (fig. 9).

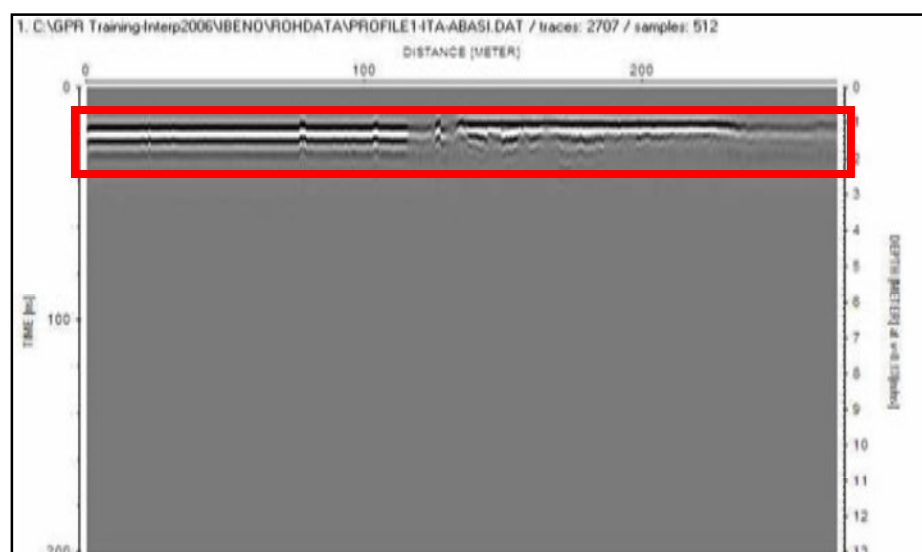


Fig. 9 Radargram of hydrocarbon plumes in soil at Ibeno L. G. A (Udotong et al., 2015)

SUMMARY AND CONCLUSION

188 This review has shown the effectiveness of non-invasive geophysical methods for the
 189 characterization of hydrocarbon spills in the soil, it also highlights some important factors and
 190 drawbacks of both the Electrical Resistivity Tomography and Ground Penetrating Radar
 191 methods. Most parts of the Niger Delta have a characteristic thin clayey or sandy top soil, the
 192 sub-soil is mostly an intercalation of sand and clays and this layer is underlain by sandstones
 193 which is usually the shallow or first aquifer in a multi-aquifer hydrogeologic system.

194 Most areas of the deltaic environment have shown pockets of saline water intrusion especially
 195 along the coast. While acquiring Electrical Resistivity Tomography and Ground Penetrating
 196 Radar data in the Niger Delta, it is important to carry out rough plots in the field to ascertain

anomalous zones. Pitting with a Hand Auger on anomalous and non-anomalous zones (as control) across the survey profile must then be done to corroborate information of the local lithology and establish its impact or non effect on the acquired data, this would greatly aid in drawing informed conclusions.

Electrical Resistivity Tomography and Ground Penetrating Radar data have been shown in this review to work best on fresh hydrocarbon spills, owing to the increasing conductivity of spills as the age. Mature spills are easily masked by conductive clayey soils and saline environment, as such, for efficient results to be obtained, remediation designs and data acquisition must be carried out as soon as the spill occurs.

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