

Full Length Research Paper

The application of integrated geophysical methods in oil sand exploration in Agbabu area of Southwestern Nigeria

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In this study, the occurrence and structural settings of the Agbabu tar sand deposit have been investigated because of the economic importance of bitumen as a readily available alternative source of energy. This investigation was carried out by employing integrated geophysical methods of magnetic and electrical resistivity (VES and dipole – dipole). Ten vertical electrical sounding (VES) points using Schlumberger array with maximum half way spread length (AB/2) of 225m, dipole - dipole with potential spacing of 50m and sixty three magnetic stations at 20m station interval were occupied along three established traverses across the study area. The resistivity curves obtained revealed up to a maximum of five geoelectric layers and the inversion of the geoelectric parameters of both the VES and 2D electrical resistivity (tomography) indicate the possible presence of oil sand in the fourth layer with relatively high apparent resistivity value ranging between 385 to 13,012 Ohm-m at a mean depth of 50m. This result was corroborated by boreholes drilled in the area. The interpretation of forward modeling of the ground magnetic shows the presence of thin dyke and fault, the nature of the basement topography and the indication that the tar sand in the study area is characterized by good lateral continuity. The results of this study have offered important geologic information that will aid the mine design and economic exploitation of the Agbabu tar sand deposit.

Keywords: Electrical resistivity, Tar sand, Magnetic modeling, Lateral continuity and Exploration

INTRODUCTION

Tar sand (bitumen) deposits are defined as consolidated or unconsolidated sedimentary deposits containing in-situ hydrocarbon, characterized by their high viscosity and high density (low API density) at reservoir conditions (Gwynn and Hanson, 2007). This natural bitumen is the remnants of very large volumes of conventional oils that have been generated and subsequently degraded, principally by bacterial action (Attanasi and Meyer, 2007). The resource base of Nigeria bitumen is enormous and can make a major contribution to oil supply if it can be extracted and transformed into useable refinery raw material at costs that are competitive with alternative

resources. Beside, bitumen is a useful mineral resource in road and building construction.

Previous studies on the Nigerian tar sand deposit included, research of its occurrence, geology and geochemical by Enu, 1985 and Ekweozor and Nwachukwu, 1989. Its nature and occurrence were described by Enu (1985); he also remarked that the tar sand porosity ranges from 16% to 35%. Ekweozor and Nwachukwu (1989) determine the Nigerian bitumen origin and identify the causative factor for its transformation to asphaltic residues. Studies using geophysical method for sub-surface understanding of Nigeria tar sand deposit have been carried out in recent time (Ako et al., 1983; Odunaike et al, 2010 and Akinmosin et al, 2011). Some other examples of the application of geophysical methods employed in tar sand exploration have also been reviewed in this work i.e. Cristall et al., 2004; Bauman,

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Table 1. Interpretation Result of Resistivity Curves in the study Area

Ves No	Thickness (m)	Resistivity (Ωm)
	$d_1 / d_2 / \dots / d_{n-1}$	$\rho_1 / \rho_1 / \dots / \rho_n$
1	0.7 / 2.6 / 8.1 / 30.5	235 / 107 / 407 / 18 / 385
2	0.4 / 2.1 / 6.4 / 23.0	803 / 115 / 255 / 9 / 541
3	0.5 / 9.8 / 32.0	663 / 349 / 12 / 679
4	0.4 / 7.1 / 80.9	2538 / 338 / 27 / 13012
5	0.5 / 7.1 / 32.6	1263 / 207 / 9 / 4972
6	0.4 / 5.7 / 59.5	2897 / 385 / 25 / 2183
7	0.6 / 5.7 / 17.6	1287 / 314 / 19 / 1732
8	0.5 / 5.3 / 36.7	301 / 507 / 26 / 5185
9	1.0 / 5.8 / 24.6	1474 / 353 / 23 / 3627
10	0.8 / 7.7 / 50.5	1124 / 633 / 96 / 388

2005 and Kellet and Maris, 2005.

The present study considers the use of combined geophysical methods of magnetic and electrical resistivity (VES and dipole – dipole) as tools to establish the stratigraphic profiles across the study area, map possible structures and determine the depth, thickness and extent of its tar sand.

Geologic Setting of the Study Area

The study area is located within the geographical grids of latitude $6^{\circ} 35' 16.3''\text{N}$ and $6^{\circ} 37' 13.9''\text{N}$ and longitudes $4^{\circ} 49' 29.0''\text{E}$ and $4^{\circ} 50' 20.7''\text{E}$ in Ondo State. It falls within the sedimentary terrain in the Dahomey basin of southwestern, Nigeria.

The Dahomey basin is an Atlantic margin basin containing Mesozoic-Cenozoic sedimentary succession reaching a thickness of over 3000m. It extends from southeastern Ghana to the western flank of the Niger Delta. Its stratigraphy is classified by various authors into Abeokuta Group, Imo Group, Oshosun Formation, Ilaro Formation and Coastal Plain sands and Alluvium (Jones and Hockey, 1964; Omatsola and Adegoke, 1981 and Agagu, 1985). The Agbabu area is underlain by the sediments of the Imo Group (Figure1).

Geophysical Method of Investigation

Geophysical methods of magnetic and electrical resistivity involving the use of vertical electrical sounding (VES) technique and dipole-dipole array were carried out for the tar sand investigation. The magnetic measurements were acquired at station interval of 20m along three established traverses which run in a SW – NE and SE – NW direction (Figure 2), while the electrical resistivity data were acquired along two of the traverses namely TR1 and TR2.

The Electrical Method

The electrical resistivity method involves the determination of subsurface resistivity distribution by taking ground surface measurements. This requires passing electrical current (I) into the ground by means of two electrodes and the potential difference (ΔV) is measured between another pair of electrodes. Its apparent resistivity is represented by equation (1) (Telford et al, 1990):

$$\rho_a = \frac{\Delta V}{I} G \quad (1)$$

Where ρ_a is apparent resistivity and G is the geometric factor which value depends on the electrode array's geometric spread. For vertical electrical sounding (VES) technique involving the Schlumberger array with a four-electrode configuration, the apparent resistivity value is calculated using the equation (2).

$$\rho_a = \frac{\pi R (AB/2)^2}{MN} \quad (2)$$

Where AB is current electrode spacing, MN is potential electrode spacing, R is electrical resistance and π is a constant equal to 3.142; from the expression in equation (2) i.e. for Schlumberger array, the distance between the potential electrodes is small compared to the distance between the current electrodes.

In the case of dipole – dipole array which is also referred to as combined HP + VES; its apparent resistivity is given by the equation (3):

$$\rho_a = -\pi R n a (n + 1) (n + 2) \quad (3)$$

Where n is the expansion factor, R is electrical resistance and π is a constant equal to 3.142

Electrical Data Acquisition in the Study Area

Ten vertical electrical sounding (VES) points using Schlumberger array with maximum half way spread length ($AB/2$) of 225m were acquired along two traverses namely TR1 and TR2 (Figure 2). A resistivity meter (OMEGA) was used for taking the resistivity

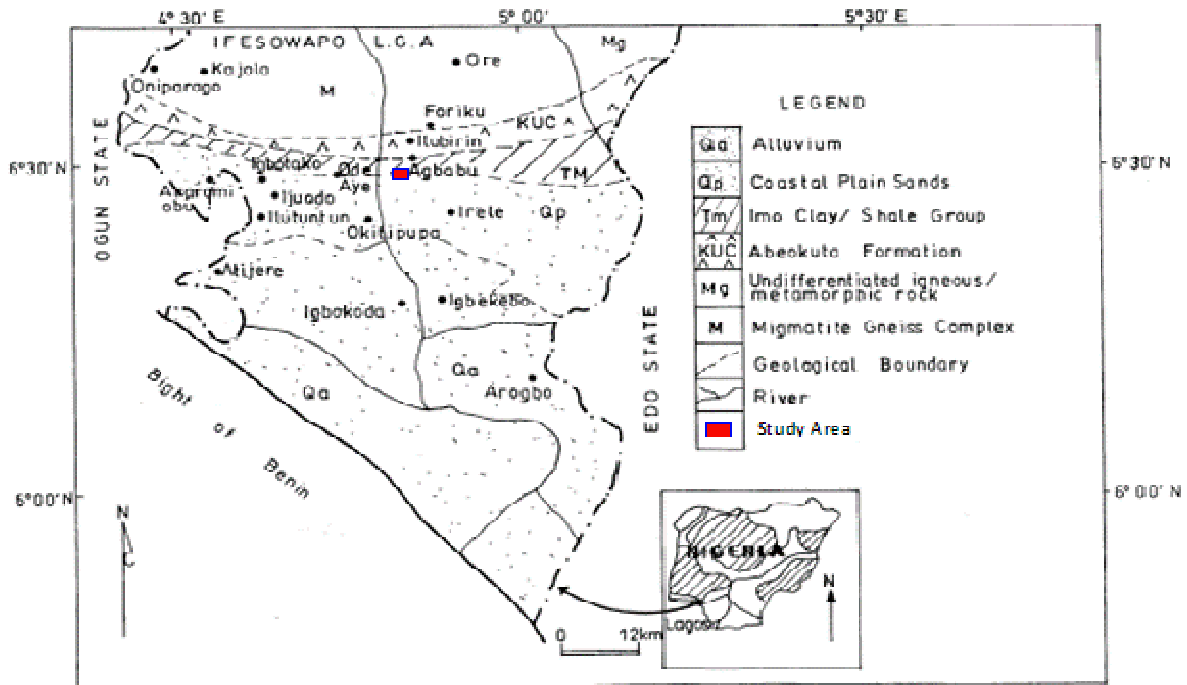


Figure 1. Geological Map of Southern part of Ondo State showing the Study Area (Modified after PTF, 1997).

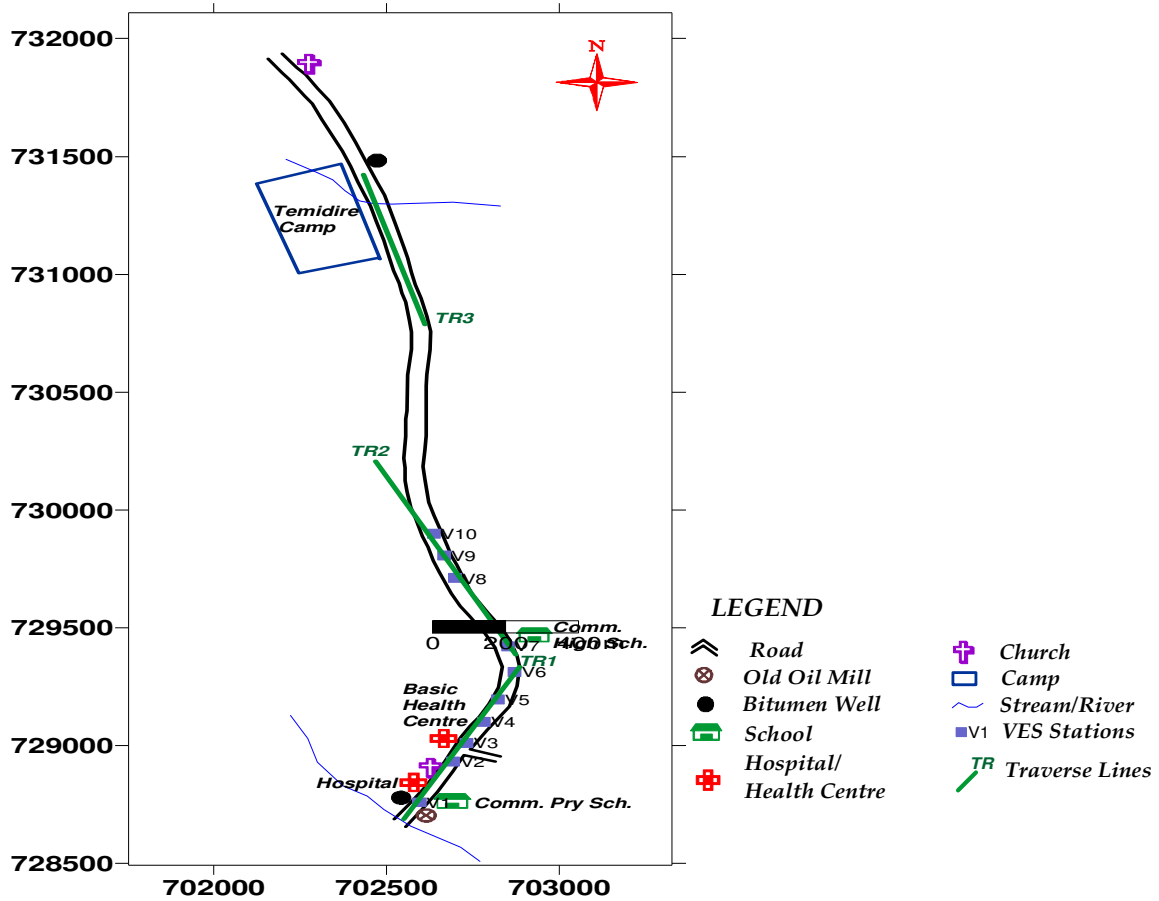


Figure 2. Data Acquisition Map of the Study Area

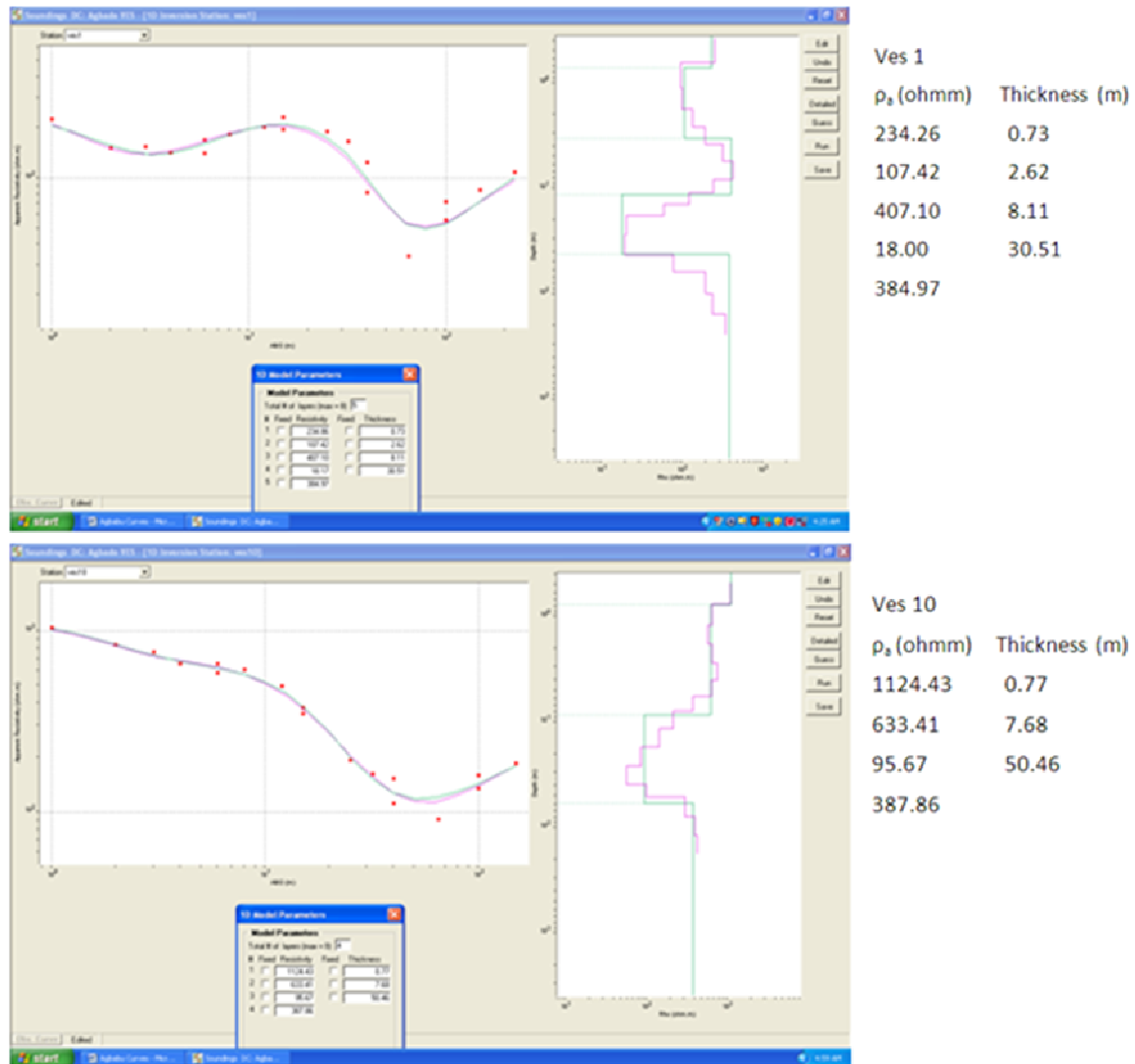


Figure 3. Typical Resistivity Curves of the Study Area and Interpreted geoelectrical Model

measurements. After the initial partial curve matching, the VES data were inverted to a true geological model (Figure 3) of the subsurface using WingLink software (Matias *et al.*, 1994). The VES results' interpretation was used for creating the geoelectric sections in Figure 4

The resistivity measurement for dipole - dipole array was conducted along traverse TR1 and TR2 with a potential spacing of 50m while a separation factors of $n=1$ to 5 were used. Its electrodes spacing are increased in a way that measurements are taken both laterally and vertically. The Inversion Program (DIPRO for window) developed by Jung-Ho Kim, KIGAM that adopts a unique regularization algorithm based on the model parameter resolution analysis (Yi and Kim, 1998) was used for analyzing the dipole - dipole resistivity data in this study. The Interpreted depth section maps in Figures 5 and 6 represent the cross sectional distribution of the

apparent resistivities.

The Magnetic Method

Magnetic method is the oldest geophysical exploration method used in prospecting. It measures variation in the Earth's magnetic field caused by changes in the subsurface's geological structure or the differences in near-surface rocks' magnetic properties. A significant formula that shows the relations between the fields and the magnetization within materials (Telford, 1990) is expressed by equation (4):

$$B = \mu_0 (H + M) \quad (4)$$

Where B, the magnetic induction is the total flux of magnetic field lines through a cross-sectional area of a material, μ_0 is the permeability of free space ($4\pi \times 10^{-7}$

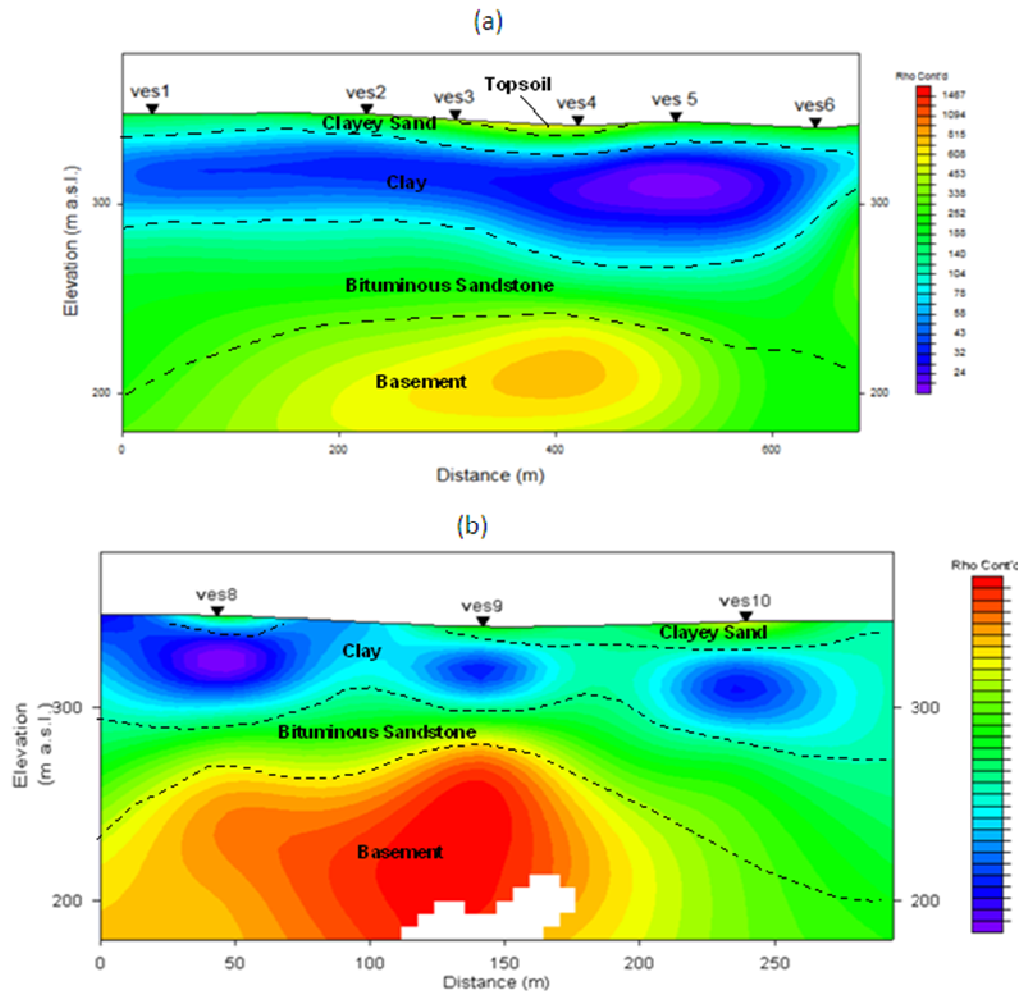


Figure 4a and b. Geolectric Sections along Traverse 1 and 2 respectively.

Wb/Am^{-1}), H is the magnetic field applied to the material and M is magnetization or response of the material to the applied magnetic field. Magnetic susceptibility (k) is another important parameter, the relationship between magnetic induction B , magnetizing force H and susceptibility k (Reynolds, 1997) is given as:

$$B = \mu_0 H (1 + k) \quad (5)$$

Where B is in tesla, μ_0 is free space permeability, H is given in amperes/metres and k is dimensionless in SI units.

Magnetic Data Acquisition in the Study Area.

The magnetic data in the study area are acquired along three established traverses TR1, Tr2 and TR3. These traverses run in the SW-NE and SE-NW direction (Figure 2). The magnetic measurements were made with a GEM systems GSM-19 Proton Precession magnetometer at a

nominal station spacing of 20m. This instrument measures the Earth's total magnetic field in gamma (nanotesla). Sixty three magnetic stations were occupied along the three traverses. The changes in magnetometer reading with time caused by the time-dependent variation of diurnal variation were taken care of. A base station established at the start of the magnetic survey was re-occupied at regular time interval of 2 hours to monitor the drift (diurnal variation) and carry out the drift correction.

Afterward the removal of the International Geomagnetic Reference Field (IGRF) from the corrected magnetic data, a horizontal derivative filter i.e. horizontal gradient was applied to the residual magnetic data to improve the data quality for better understanding of the subsurface geology of the tar sand deposit. According to Hansen *et al.*, 2005, this filter is normally calculated as the root-sum-square of magnetic anomaly data x and y derivative components i.e. for a total magnetic field $T(x, y)$ and its horizontal derivatives $\partial T/\partial x$ and ∂T

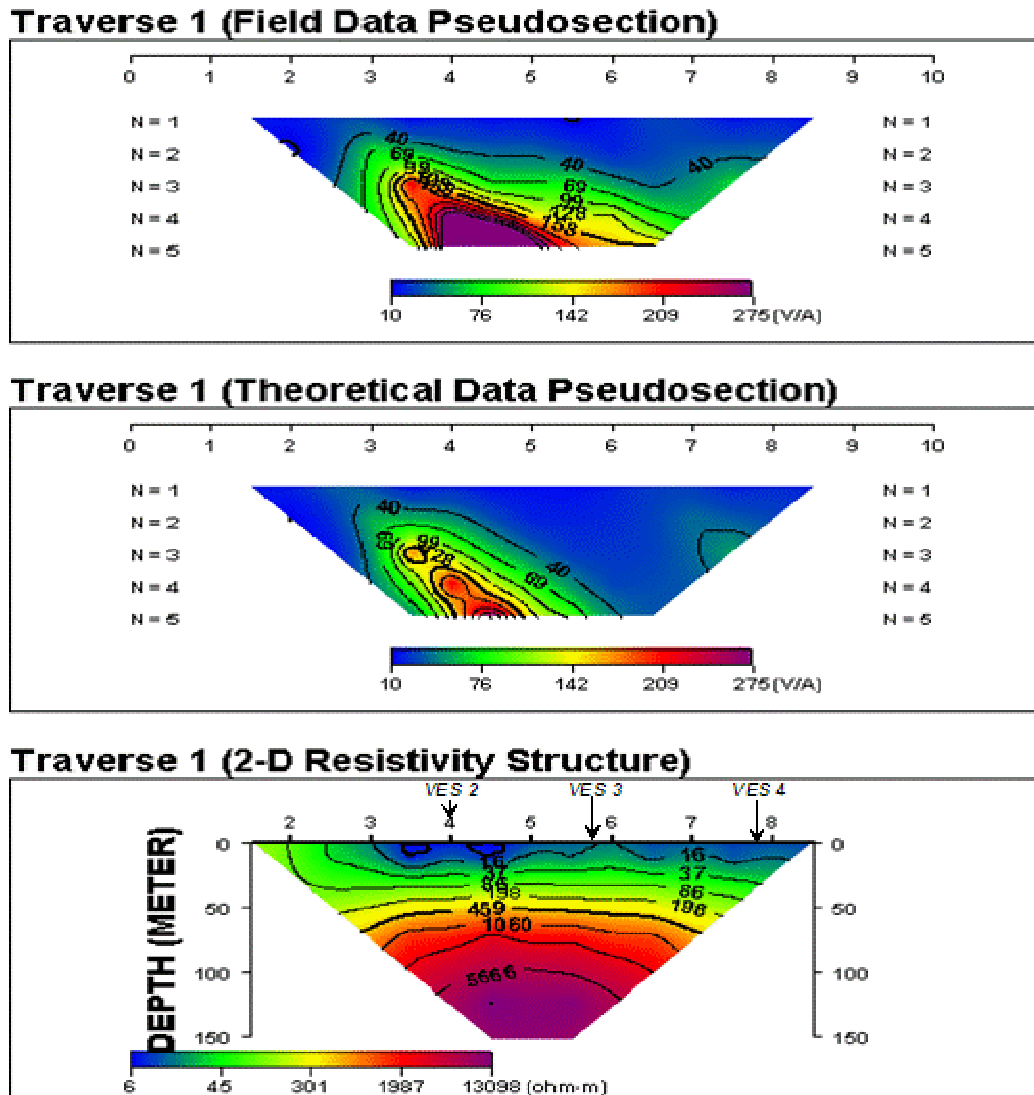


Figure 5. 2D Dipole-Dipole Pseudosection beneath Traverse 1 showing VES 2, 3 and 4

The horizontal gradient $Z(x, y)$ is given by the equation:

$$Z(x, y) = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2} \quad (6)$$

This enhancement filter enables easier identification of fault and contact features (Hood and Teskey, 1989; Aboud *et al.*, 2005; Falebita *et al.*, 2011)

RESULTS AND DISCUSSION

The resistivity and magnetic data from this survey are displayed in several formats i.e. as profiles, depth sounding curves, pseudosection, geo-electric sections and depth sections. They are all registered to the Minna - Nigeria, Zone 32N UTM grid coordinate system.

Geoelectric Interpretation

The successful application of geo-electric techniques in tar sands exploration is based upon the existence of measurable physical contrast associated with tar and the host geology. The various products of petroleum such as oil, gas and bitumen have very high electrical resistivity. The tar (bitumen) and tar-bearing sands in formations are known to be characterized by high resistivity (Eke, 2005). The interpretation results of the VES and dipole – dipole data measured in the study area are presented as geoelectric sections in Figures 4a-b and pseudo sections in Figures 5 and 6 respectively. The Figures 4a and 4b describe the 2-D geoelectric sections along Traverse Tr1 and Tr2, with the section on Tr1 oriented in a SW – NE direction and that of Tr2 in a SE – NW direction.

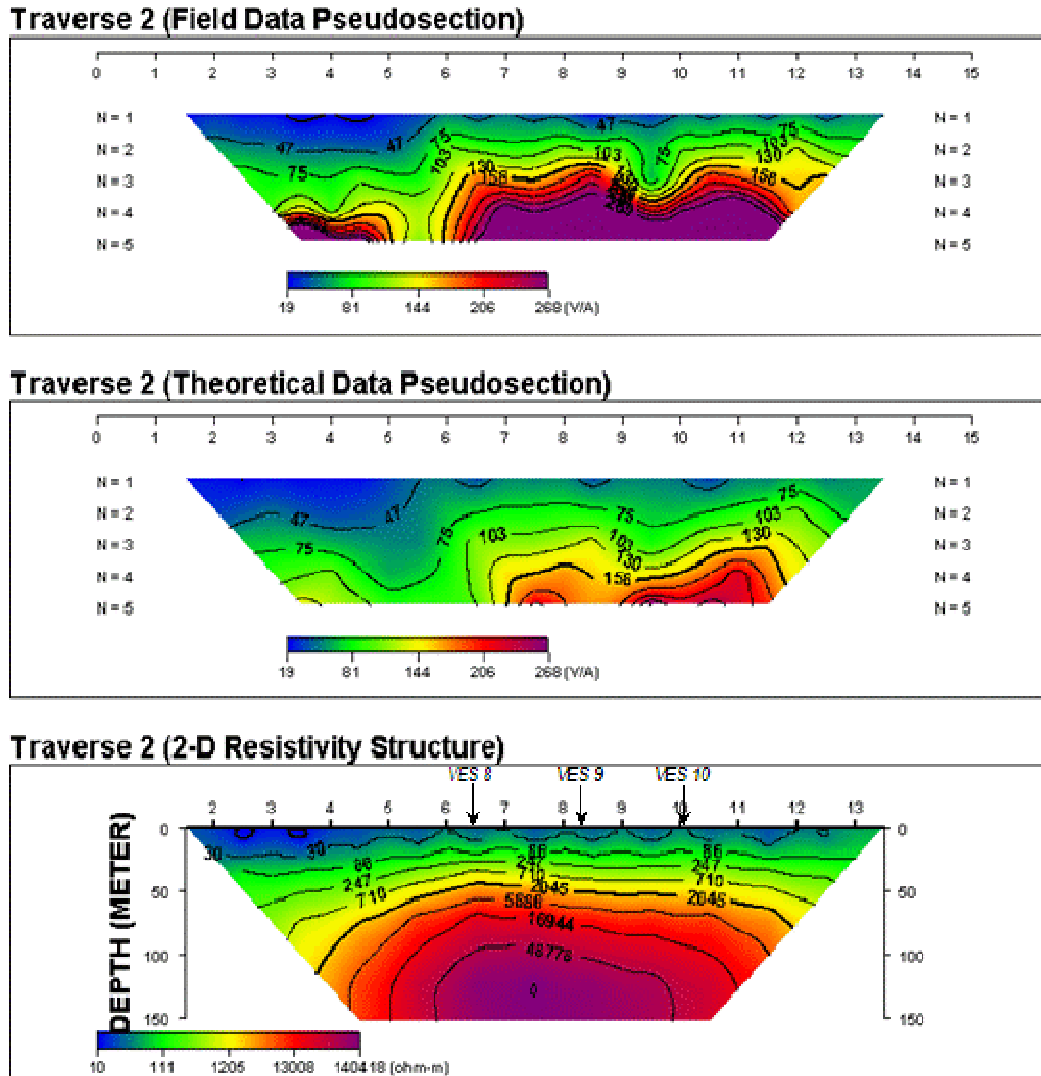


Figure 6. 2D Dipole-Dipole Pseudosection beneath Traverse 1 showing VES 8, 9 and 10

Four to five subsurface geoelectric layers are shown beneath these traverses. These include the topsoil, clayey sand, clay, bituminous sandstone and the basement rock. The topsoil resistivity varies from 453 to 608 Ωm with thickness range of between 0.3 and 2.6 m. It is composed of sand and lateritic soil. The second layer comprising clayey sand has resistivity range of between 104 and 453 Ωm . Its thickness varies between 5.6 and 14.8 m. The third layer is clay and range in resistivity from 16 to 165 Ωm with thickness varying between 27.8 and 62.9 m. The fourth layer is the bituminous sandstone; it ranges in resistivity between 122 and 530 Ωm . This layer is considered the formation hosting the tar (bitumen) in the study area and its thickness varies between 22.2 m and 73.7 m. The fifth layer is the basement rock with resistivity range of 608 to 1467 Ωm ; this layer is assumed to be infinitely thick. Again, this

interpretation is corroborated by boreholes BH21B, BH11 and BH 20 in Figure 7 of an earlier work by the Geological Consultancy Unit of the University of Ile – Ife.

In Figures 5 and 6, the 2-D dipole – dipole inversion depth sections of Traverse Tr1 and Tr2 respectively shows a top layer with low resistivity which varies between 6 and 45 ohm-m with a thickness of about 20 m. The low resistivity response (blue to bluish green colour) indicates a clayey sand / clay layer. The region between the depths 20 m – 80 m with relative high resistivity response (green to yellowish colour) give strong indication of bituminous sandstone layer. This anomaly occurs as a continuous body and thus suggests that the bituminous sandstone is characterized by good lateral continuity. The reddish / purple colour band beneath the bituminous sandstone layer i.e. having resistivity greater than 1000 Ωm is the basement. The comparison of the

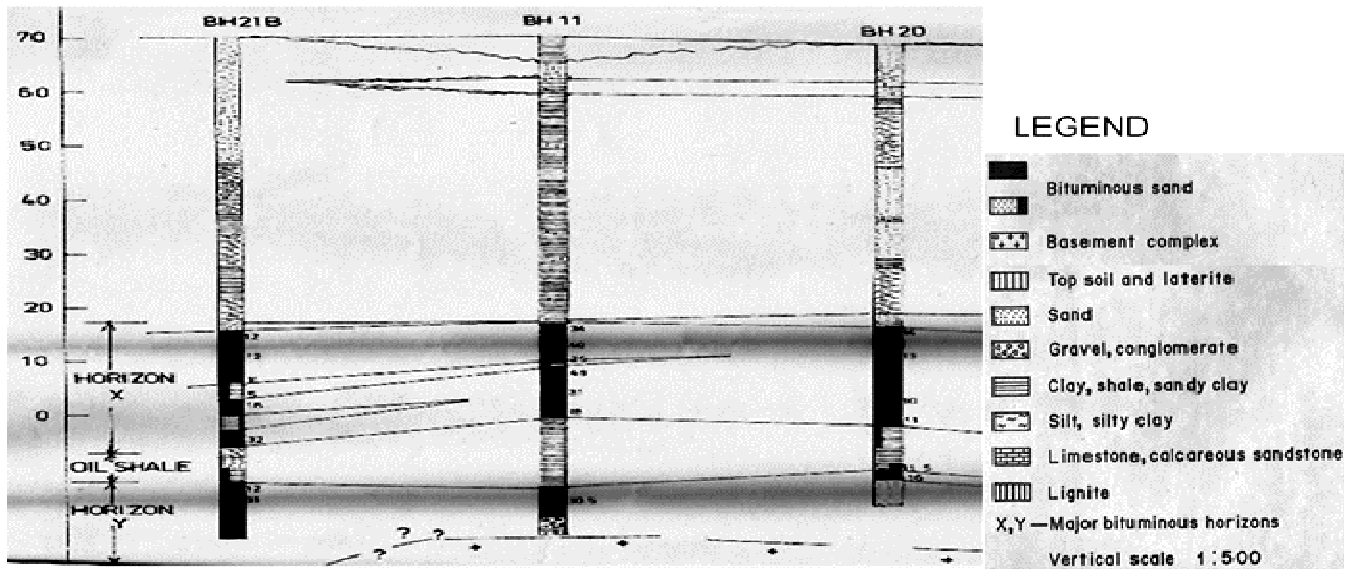


Figure 7. Lithofacies / Bitumen Saturation Correlation Panel of the Study Area (Modified after GCU, Uni. of Ile-Ife, 1980)

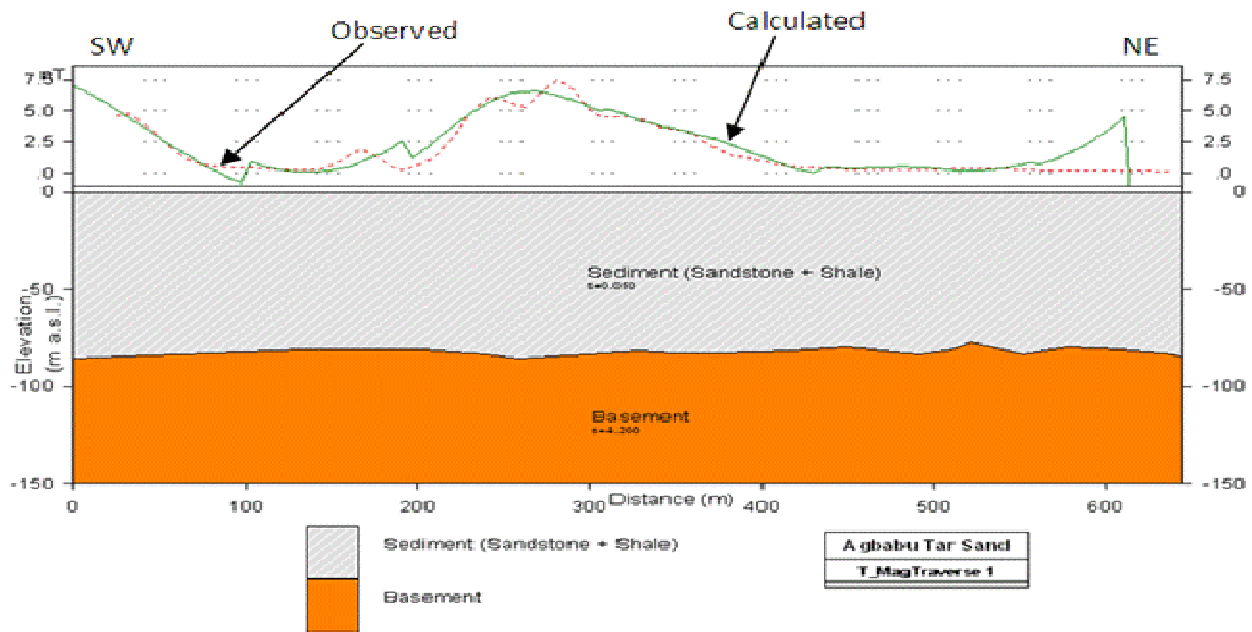


Figure 8. Observed and Calculated Magnetic Data along Profile Tr1 and their Corresponding Subsurface Model of Agbabu Tar Deposit Area.

VES and dipole – dipole inversion results shows they have a good correlation.

Magnetic Interpretation

The main use of any magnetic profiles or maps and their

derivative in mineral prospecting is to make geological deduction from them. From the range of magnetic intensity values of these data, information on subsurface lithology, trend and geological structures can be obtained (Dobrin and Savit, 1988).

In this study, the quantitative interpretation of the magnetic profiles (Figures 8, 9 and 10) using WINGLINK

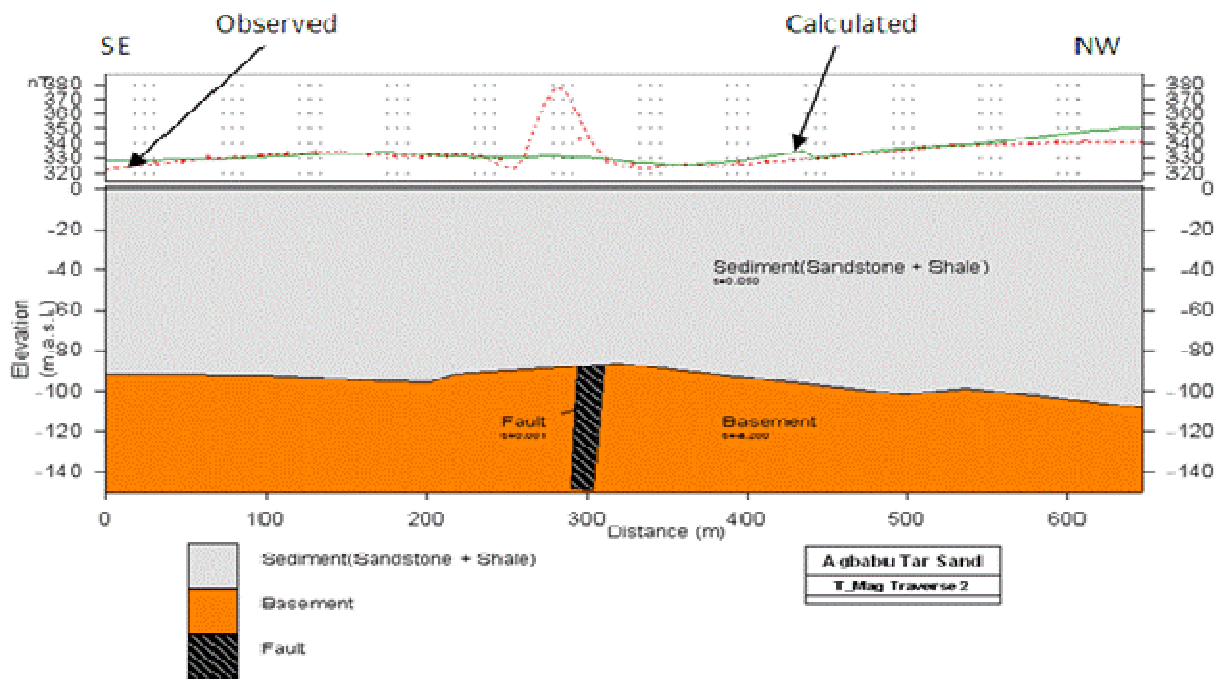


Figure 9. Observed and Calculated Magnetic Data along Profile Tr2 and their Corresponding Subsurface Model of Agbabu Tar Deposit Area.

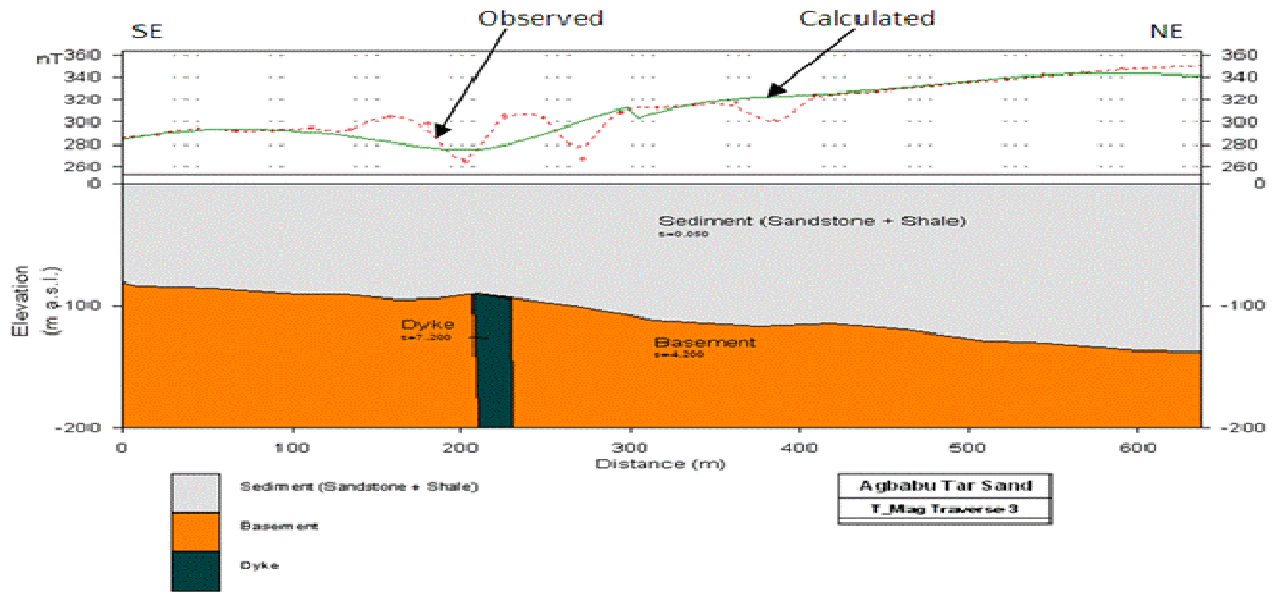


Figure 10. Observed and Calculated Magnetic Data along Profile Tr3 and their Corresponding Subsurface Model of Agbabu Tar Deposit Area.

modeling software enables the calculation of their magnetic response from a geological model. The modeling utilizes as backdrop the geo-electric sections in Figure 4a-b and geologic information from boreholes in

the study area (Figure 7). Sedimentary rocks are known to have low magnetic susceptibility values, hence magnetic anomalies observed in the study area were assumed to have resulted from the basement as well as

magnetic materials contained within the fractured /faulted zones relative to the fresh massive bedrock. For the modeling, magnetic susceptibility value of 0.0063×10^1 SI and 5.278×10^1 SI were adopted for the sediments and basement respectively. The models shows very good fit between the observed and calculated magnetic profiles.

Modeled Profile Tr1

The profile Tr1 (approximately 650m in length) traversed in a SW – NE direction. In Figure 8 the magnetic profile Tr1 was model using two polygons. The upper polygon represents the sedimentary block comprising shale (clay) and bituminous sandstone that are situated above the basement block. The sedimentary block along this direction has an average thickness of about 80 m and occurs as a continuous body. And this could suggest that the oil sand is characterized by good lateral continuity.

Modeled Profile Tr2

The Magnetic profile Tr2 (Figure 9) is about 630m long and oriented in a SE –NW direction. The profile Tr2 was model using three polygons as shown in the figure. The third polygon represents a fault which is located in the area between the distances 280m – 310 m on profile Tr2. Generally faults have a significant role as either barrier or conduit for bitumen in tar sand deposit (Akinmosin et al, 2011). The sedimentary block along this traverse line has an average thickness of about 100 m with its sedimentation increasing towards the northwestern direction.

Modeled Profile Tr3

The magnetic profile Tr3 oriented in a SE – NW direction was modeled using three polygons (Figure 10), with the third polygon denoting possibly a thin vertical dyke at distance 220 m along the traverse 3. The dyke block has a rectangular shape and occurs within the basement rock at a depth of about 85 m beneath the tar sand. The occurrence of the dyke structure will act as a control for the distribution of the oil sand (bitumen) in the study area. On this profile, the basement is seen to thin towards the northwestern direction hence more sedimentation occurs along this direction.

CONCLUSION

This study has shown the successful application of integrated geophysical methods of magnetic, vertical electrical sounding and dipole - dipole in the exploration

of Agbabu tar sand. The inversion of the geoelectric parameters of both the VES and dipole - dipole indicate the possible presence of tar (bitumen) in the bituminous sandstone layer located at a mean depth of 60m. The modeling of the ground magnetic data have shown the nature of the basement topography and the evidence of possible thin vertical dyke and fault which possibly act as control for the distribution of the bitumen in the study area. The results have also indicated that the tar sand layer is characterized by good lateral continuity and is sufficiently thick for commercial exploitation (i.e. average thickness of 80 m).

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