Geophysical and sedimentological studies for reservoir characterization of some tar sands deposits in southwest Nigeria

Geofizikalne in sedimentološke preiskave za opredelitev rezervoarnih lastnosti nekaterih nahajališč naftnega peska v jugozahodni Nigeriji

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Abstract: Electrical resistivity tomography for 2-d subsurface imaging has been integrated with sedimentological and petrophysical analyses for detailed mapping and reservoir characterization of some Nigerian tar sands deposits in southwestern Nigeria with a view to generate a spatial distribution and reservoir quality description as well as compare the result with already characterized deposits in other parts of the Nigeria tar sands belt.

Electrical resistivity survey delineated a relatively thick (average thickness of 50 m) high resistivity tar impregnated sand layer with resistivity value range of 1519 Ω m to 5772 Ω m, which is located about 10 m below the ground surface. Granulometric analyses of eight samples of the tar sands deposit indicate fairly well distributed reservoir sand with grain size distribution range between ϕ = 0.03–0.55 mm with up to 3 % fines. The reservoir sands is poor to moderately well sorted (ϕ = 0.94–1.63 mm), the measure of skewness indicates a strongly coarse to strongly fine skewed (–0.–0.47) reservoir sands. Petrophysical analyses such as porosity and permeability range from 16–24 % and 143–887 mD, respectively. The tar sands deposit was also analyzed to have between 60–90 % hydrocarbon impregnation, while bitumen saturation of the mass fractions 18–30 % was recorded. The viscosity of the impregnated

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heavy oil with API gravity less than 20° and a specific gravity value range of 0.95 g/cm^3 to 1.27 g/cm^3 was determined to range between 1.080 Pa s to 1.360 Pa s. The results obtained agreed with borehole information and earlier published geophysical and petrophysical results of the tar sands deposits located in other parts of the Nigerian tar sands belt.

Izvleček: Električna upornostna tomografija s podzemnim 2-d-prikazom v povezavi s sedimentološkimi in petrofizikalnimi analizami je bila uporabljena za detajlno kartiranje in rezervoarno opredelitev nekaterih nahajališč naftnih peskov v jugozahodni Nigeriji z namenom ugotoviti prostorski razpored, opredeliti rezervoarne lastnosti in izvesti primerjavo z že raziskanimi nahajališči v drugih delih nigerijskega pasu naftnih peskov.

Z električno upornostjo je bilo mogoče omejiti razmeroma debelo (povprečne debeline 50 m) visoko uporno (v razponu 1519–5772 Ω m) plast peska, prepojenega z bitumnom in ležečega okoli 10 m pod površjem. Granulometrična preiskava osmih vzorcev iz nahajališča naftnega peska nakazuje razmeroma enakomerno porazdelitev rezervoarnega peska z zrnavostjo med ϕ = 0,03 mm in 0,55 mm in z do 3 % fine frakcije. Rezervoarni pesek je slabo do srednje dobro sortiran (ϕ = 0.94–1.63 mm), ugotovljena asimetričnost pa nakazuje zelo debelozrnato do zelo drobnozrnato asimetrične (–0.58 to 0.47) rezervoarne peske. Rezultati preiskave poroznosti in prepustnosti so v razponih od 16 % do 24 % in ustrezno 143 mD do 887 mD. Stopnja impregniranosti z ogljikovodiki se giblje med 60 % in 90 % in stopnja nasičenosti z bitumnom med masnima deležima 18 % in 30 %. Viskoznost impregnirane težke nafte, ki ima relativno gostoto pod 20° API in specifično maso med 0.95 g/cm^3 in 1.27 g/cm^3, se giblje med 1.080 Pa s in 1.360 Pa s. Dobljeni rezultati ustrezajo meritvam v vrtinah in objavljenim geofizikalnim in petrofizikalnim podatkom z nahajališč peskov v drugih območjih nigerijskega pasu naftnih peskov.

Key words: tomography, reservoir characterization, tar sands, porosity, permeability

Ključne besede: tomografija, rezervoarna opredelitev, naftni peski, poroznost, prepustnost

Introduction

Asphalt-impregnated sandstones otherwise referred to as oil sands (tar sands) and active oil-seepages occur in southwestern Nigeria within the marginal pull-apart or margin-sag Dahomey (Benin) basin. The oil sands outcrop in an E-W belt, approximately 140 km long and 4–6 km wide, extending from Edo, Ondo and Ogun State in southwest Nigeria. Bituminous sands are composed of sand, heavy oil and clay that are rich in minerals and water. The heavy oil in the bituminous sand is commonly called bitumen, which is a very dark coloured, sticky and viscous substance. Total reserve of the heavy oil is estimated to exceed 30 billion barrels (Adegoke et al, 1980).

The petroleum habitat is almost exclusively the Afowo Formation, a member of the Abeokuta Group. This litho-unit is of Turonian - Maastrichtian age and consists of interbeds of coarse-medium grained sandstones, siltstones and shale deposited in a transitional to marginal marine environment (Omatsola & Adegoke, 1981). The oil is found in the coarse grained clastics within the formation in two discrete bands (the X and Y horizons), each 30–40 m thick and separated by 6–15 m carbonaceous shales with a thin band of lignite (Ako et al., 1983) and overburden thickness in excess of 50 m at Agbabu, Ondo State, south western Nigeria (Enu, 1985).

This research utilizes electrical resistivity studies, sedimentological and petrophysical studies to characterize the reservoir sands of the tar sand deposits in Gbegude area; a continuum of the tar sand belt of North-Eastern Dahomey basin, South Western Nigeria. The study is aimed at delineating the subsurface distribution and occurrence of the deposits as well as determining the reservoir characteristics of the tar sand deposits in the study area.

Geological setting

The study area is situated in the eastern part of Dahomey basin and located within longitude 4°22ʾE to 4° 30ʾE and latitude 6° 40ʾN to 6° 43ʾ N (Figure 1). The Dahomey Basin constitutes part of the system of West African pericratonic (margin sag) basin (Klemme 1975; Kingston et al 1983) developed during the commencement of the rifting and associated with the opening of the Gulf of Guinea, in the Late Jurassic to Early Cretaceous (Burke et al, 1972; Whiteman, 1982). The crustal separation, typically preceded by crustal thinning, was accompanied by an extended period of thermally induced basin subsidence through the Middle – Upper Cretaceous to Tertiary times as the South American and the African plates entered a drift phase to accommodate the emerging Atlantic Ocean (Mpanda, 1997).

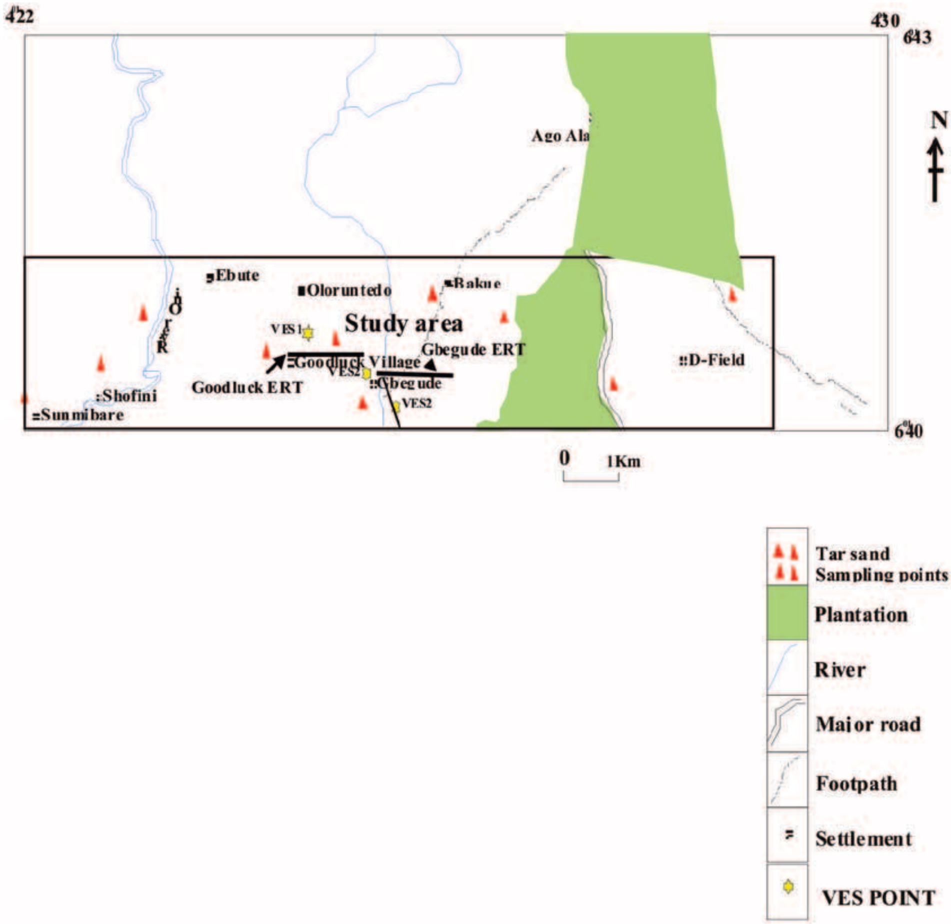


Figure 1. Location map of the study area showing sampling and VES points.

The basin is bounded in the west by the Ghana Ridge which is presumably an offset extension of the Romanche Fracture Zone while the Benin hinge line, a basement escarpment which separates the Okitipupa Structure from the Niger Delta basin and a continental extension of the Chain Fracture, bounds it in the east (Figure 2). The onshore part of the basin covers a broad arc-shaped profile of about 600 km^2 in extent and attains a maximum width, along its N-S axis, some 130 km around the Nigerian – Republic of Benin border. The basin narrows to about 50 km on the eastern side where the basement assumes a convex upwards outline with concomitant thinning of sediments. Along the northeastern fringe of the basin where it rims the Okitipupa high is a band of tar (oil) sands and bitumen seepages (Nwachukwu & Ekweozor, 1989).

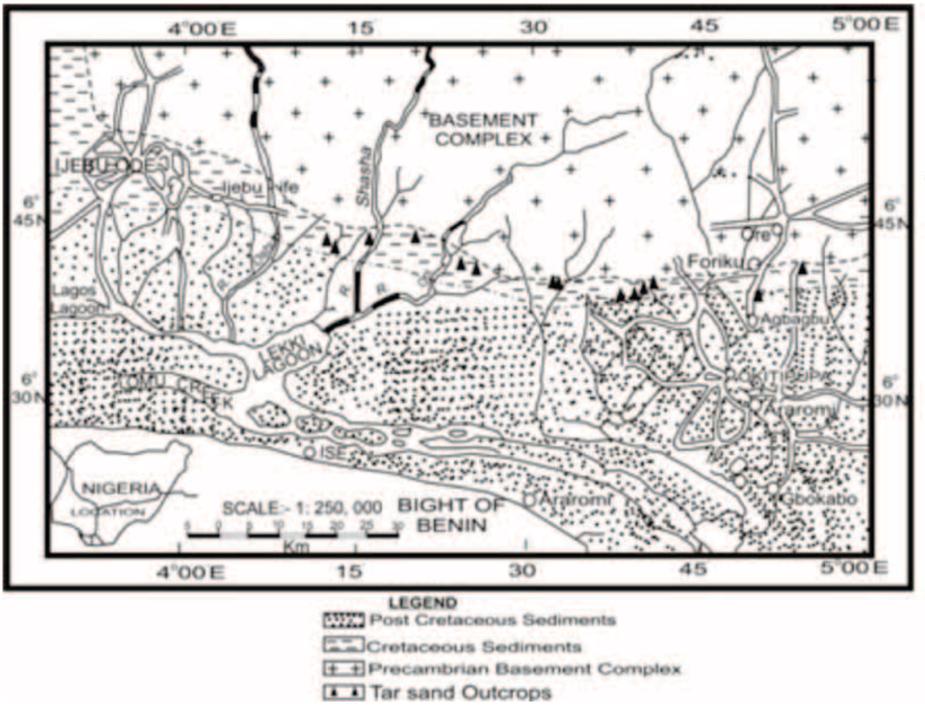


Figure 2. Generalized geological map of the Eastern Dahomey Basin showing area extent of the tar sand deposits (Modified after ENU, 1985).

Table 1. Regional Stratigraphic Setting of the Eastern Dahomey Basin (After IDOWU et al., 1993)

	AGE	FORMATION			LITHOLOGY
		Ako et al. 1980	Omatsola and Adegoke 1981		Sandstone
TERTIARY	EOCENE	Ilaro formation	Ilaro formation		Shale
		Oshosun formation	Oshosun formation,		
	PALEOCENE	Ewekoro formation	Ewekoro formation		Limestone
CRETACEOUS	MASSSTRICHTIAN TURONIAN BERREMIAN	ABEOKUTA FORMATION	ABEOKUTA GROUP	Araromi	Shale
				Afowo	Sandstone and Shale
				Ise	Sandstone
PRECAMBRIAN		BASEMENT COMPLEX			

The lithostratigraphic units of the Cretaceous to Tertiary sedimentary sequence of eastern margin of Dahomey basin according to Idowu et al (1993) is summarized in Table 1.

Materials and methods

Geophysical, sedimentological and petrophysical investigation techniques were integrated in this study which required both field and laboratory measurements. Electrical resistivity data acquisition involved setting out Schlumberger and Wenner electrode configurations for Vertical Electrical Soundings (VES) and Electrical Resistivity Tomography (ERT), respectively. Zero/low frequency (no inductance) current was injected into the ground via two current electrodes, the injected current flow through the earth and generates potential difference across two potential electrodes. The generated potential difference was measured with the aid of ABEM 4000 SAS resistivity meter. High integrity data (r.m.s. < 5 %) which approximate the apparent resistivity of the subsurface layers were obtained by integrating the geometric factor of the electrode configuration used. Vertical Electrical Sounding enables 1-dimension measurement of variation in subsurface electrical properties with depth by systematically increasing the separation between the two current electrodes about a symmetrical center. Two dimensional ERT measurements was performed using Wenner electrode configuration which allows determination of apparent resistivity values in the horizontal direction and variation in resistivity value with depth by increasing the electrode spacing. VES and ERT gave insight into the electrical property distribution of the earth's subsurface. Figure 1 presents the location map of the study area showing ERT profiles and VES locations.

Data Processing

Data processing involved data quality check for spurious and erroneous data which may constitute noise. VES data were plotted on bi-log paper for partial curve matching using standard two layer curves and auxiliary Cagniard Graph (Koefoed, 1979). This compares the observed data curves with theoretically generated standard curves and gave some electrical parameters such as thickness and resistivity values of each layer. The obtained layer parameters served as starting model for inversion of the field data using WinRESIST version 1.0 software. This helped to generate sets of earth models that represent the electrical properties distribution of the subsurface. Electrical resistivity subsurface model with high geological significance as well as least misfit between the measured and generated data was accepted. ERT data were also inverted using RES2DINV, version 3.4 developed by Loke, 1999b.

The inversion software is based on the Least Squared Inversion algorithm which performs smoothness constrained by Least Squared Inversion based on finite element modeling.

Sedimentological and Petrophysical Analyses

Tar sands samples recovered from borehole drilled to the deposit were analyzed in the laboratory for various granulometric and petrophysical analyses. Mechanical sieving was carried out using set of sieve size range from 75 µm to 4760 µm. The results of the various fractions were also employed to determine the sorting and skewness of the reservoir sands. The effective porosity of the tar sands was determined using a solid density test (displacement method). The core sample was immersed in water for ten minutes to allow for initial absorption in a measuring cylinder. The specimen was then transferred to a displacement vessel where it displaced a certain volume of liquid (bulk volume of specimen). The same sample after drying to a constant weight was pulverized in mortar and the resulting powder was carefully transferred into a half filled measuring cylinder with liquid. Rodding was then done at interval, to displace any air that may be trapped in it. Afterwards, the reading of the final level of the liquid in the cylinder was noted. The porosity of the tar sand specimen was determined using the mathematical relation below.

Porosity/% = Bulk volume – solid volume/bulk volume × 100

The permeability of the tar sand specimen was also carried out using the Falling Head Permeability Apparatus set. This method measures the hydraulic gradient and quantity of water flow into the sample, using a varying head of water during the test.

Permeability is obtained from the formula

$K/(\mathrm{cm/s}) = 2.3026\, a\, L/A(\lg H_1 - \lg H_2)/(t_2 - t_1)$

Where K is the coefficient of permeability is obtained from the formula

a - cross-sectional area of the standpipe

L - length of soil sample in permeameter

A - cross-sectional area of the permeameter

H_1 & H_2 - the heads between which the permeability is determined.

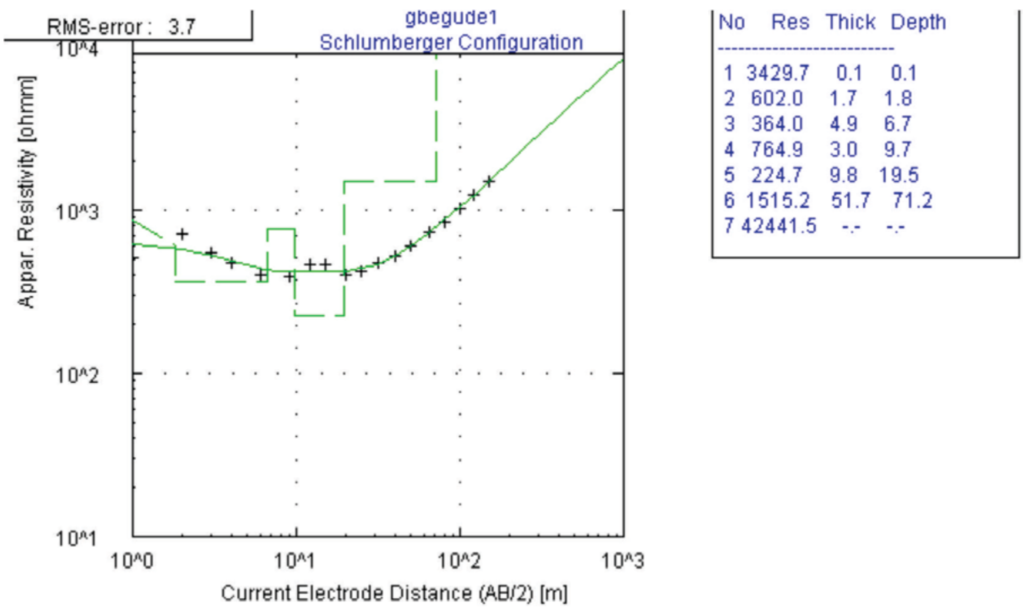
t_1 - time when water in the standpipe is at H_1

t_2 - time when water in the standpipe is at H_2

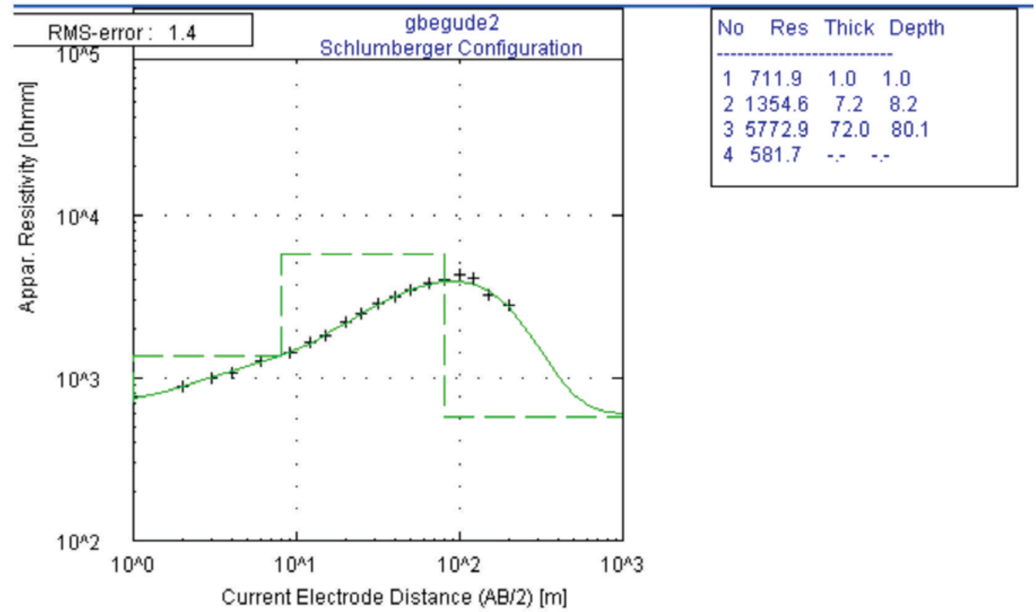
The specific gravity and API gravity of the extracted oil was obtained by measuring displacement in water. The viscosity of tar extract was also done using a cone plate viscometer. The tar extraction was done using the Soxhlet extractor. This was achieved by placing the tar sands in the thimble made from thick filter papers loaded in the main chamber of the apparatus and placed on a flask containing the extraction solvent. The solvent is heated to reflux, releasing its vapour to travel up the distillation arm. A condenser ensures that the solvent vapour cools and drips back into the chamber housing the tar materials. The chamber containing the solid material is slowly filled with the warm solvent. When the Soxhlet chamber is almost filled, it is automatically emptied by siphon side arm with the solvent running down into the distillation flask. This cycle is allowed to repeat many times, over hours or days.

RESULTS AND DISCUSSION

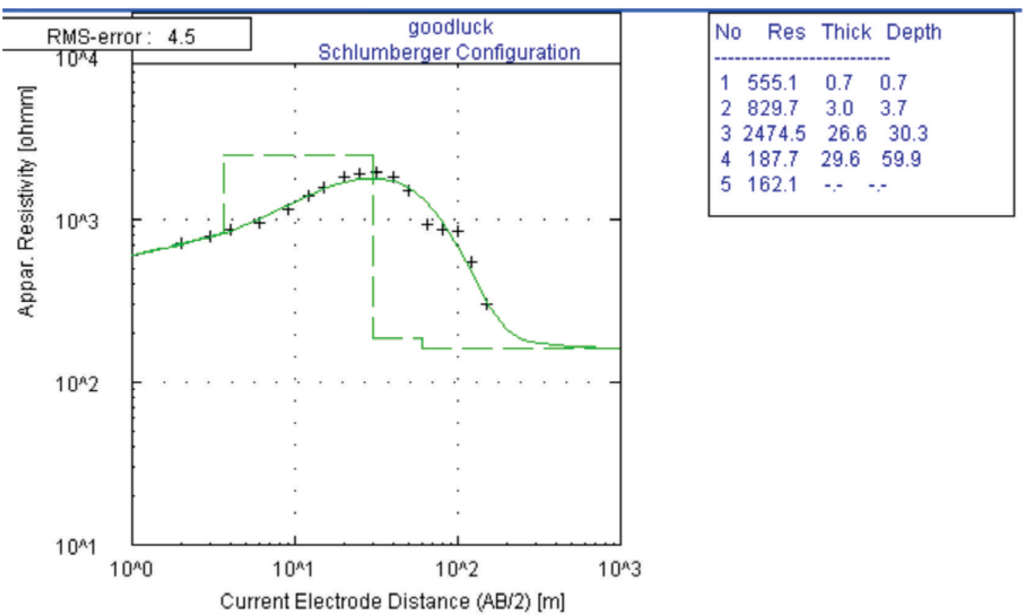
Electrical resistivity method has found wide and successful application both in surface and borehole measurements to differentiate hydrocarbon saturated region from saline water saturated sand on the account of very high resistivity signature of hydrocarbon pore fluids that are incapable of ionic conduction (WINSAUER et al, 1952). Representative resistivity VES curves obtained after 1-d inversion of the field data are presented in figure 3 (a–c). The interpretation of the resistivity layered parameters was constrained by core and drill cuttings information from a drilled borehole from where samples were



a)



b)



c)

Figure 3. VES Curves obtained from the Study Area

recovered for laboratory studies. The layer with the highest resistivity value corresponds to the section in the borehole with tar impregnated sand. The tar sands layers delineated from resistivity investigation range in thickness from 17–72 m with resistivity values of 1515–5773 Ω m. The obtained results indicate a general reduction trend toward the west, in the tar sands layer thickness and resistivity. High resistivity values of the tar impregnated layer

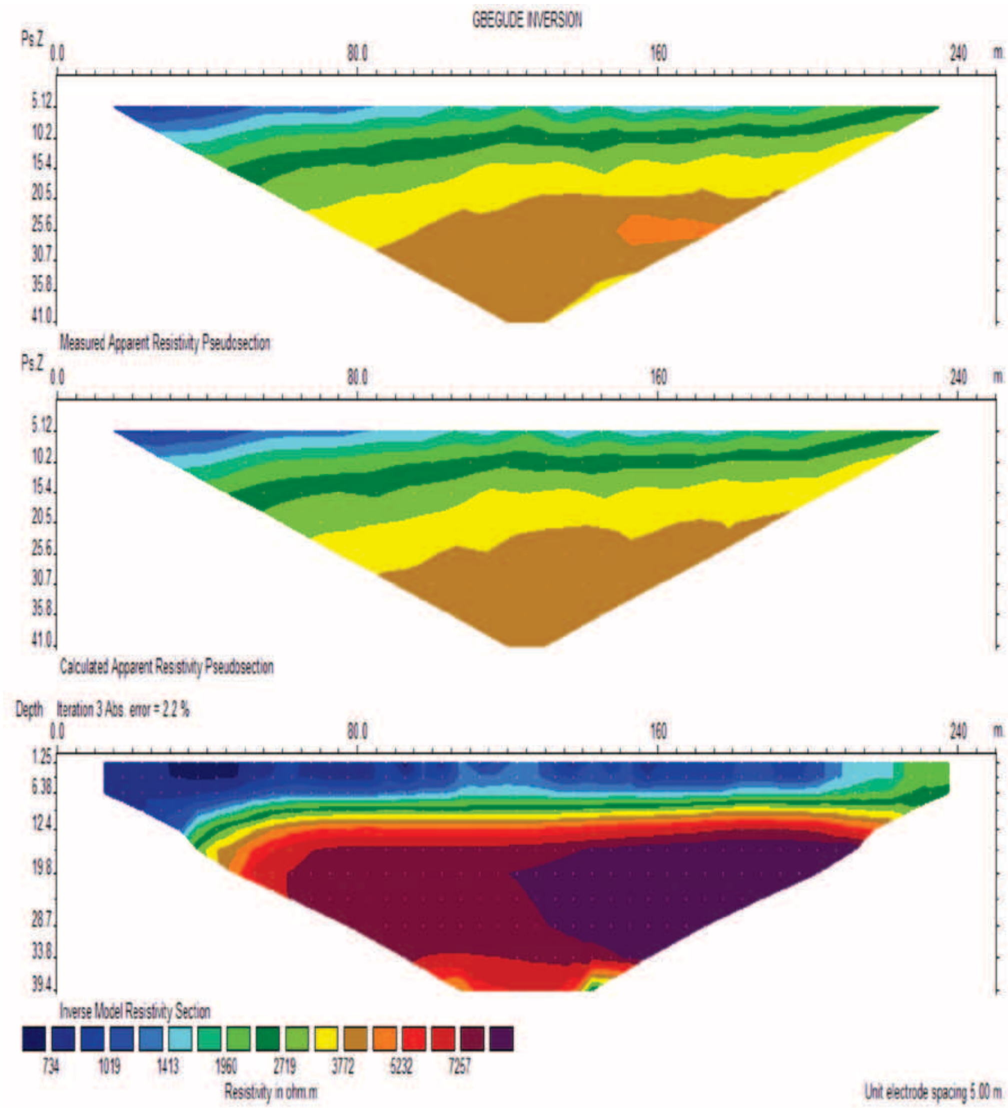


Figure 4. Raw data, pseudosection and 2-d resistivity inverted section across Gbegude II profile.

were recorded; this is likely due to the fact that the heavy hydrocarbon oils which fill the pore spaces are molecular compounds which are poor conductor of electricity. However, low resistivity tar sands deposits are also commonly encountered in the southern part of the Nigerian tar sand belt. This is probably because the tar sands in this region are water wet (ADEGOKE et. al, 1981), where the incorporated/impregnated saline water enables ionic conducion.

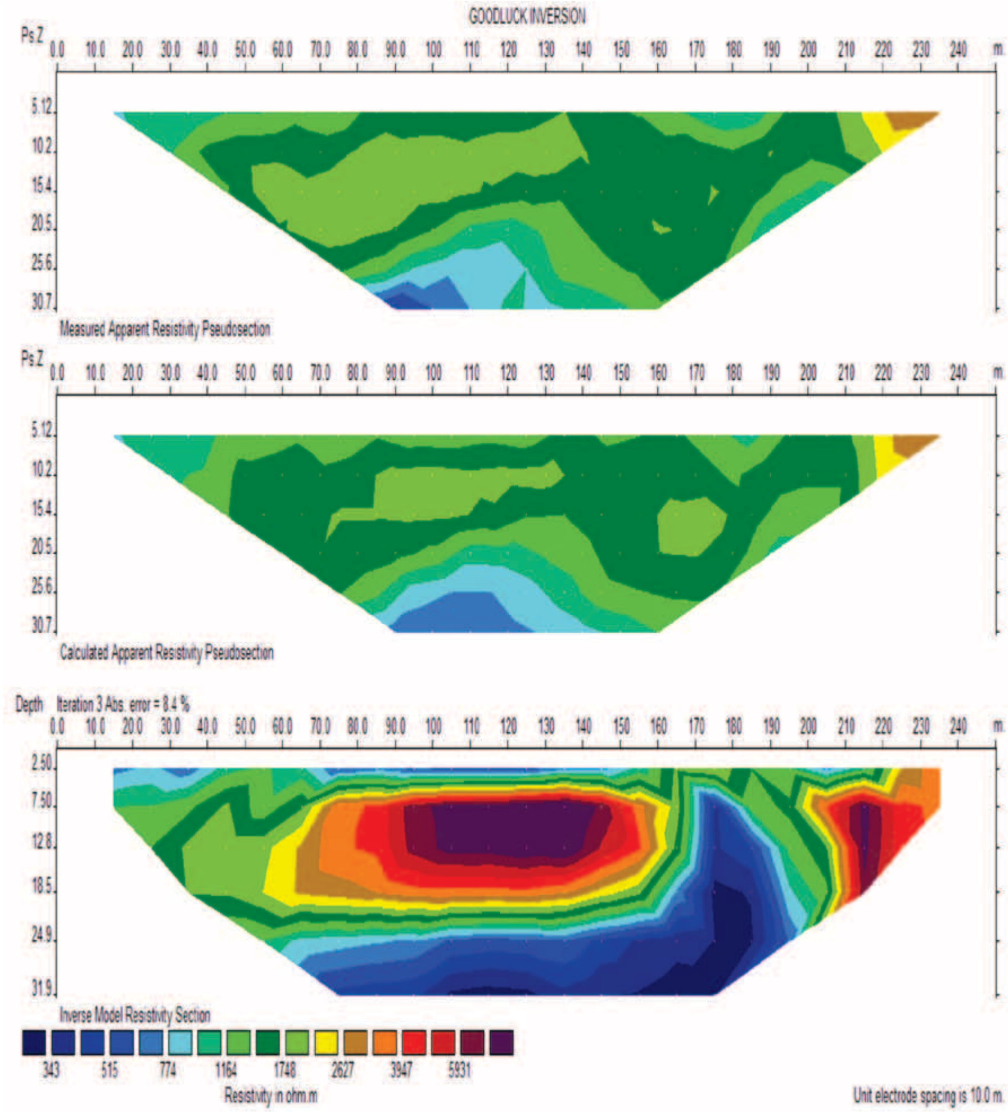


Figure 5. Raw data, pseudosection and 2d resistivity inverted section across Goodluck profile.

Figures 4 and 5 present the ERT raw data, calculated pseudosection and 2-d inverted resistivity data across the field along the E-W profile. The plot also delineates the high resistivity layer to be tar impregnated. This agrees with VES results and borehole information.

Sedimentological Analyses Results

The mechanical sieve analysis gave an average grain size distribution of the reservoir sand to range from ϕ = 0.03–0.55 mm, which indicates a medium to coarse sands. The skewness of the reservoir sand was determined to ranges from –0.58–0.47, indicating strongly coarse to strongly fine skewed according (Folk, 1974). This result defines a high energy of deposition at Ebute, Shofini and Bakue, but lower at Gbegude, thus accounting for the 2.5 % of fines in its composition. The sorting of the reservoir sands ranges in values from ϕ = 0.82 mm (moderately sorted) to ϕ = 1.63 mm (poorly sorted) according to Folks`1974 classification, while the percentage of fines collected were composed of silt and kaolinitic clays in the range of 1–3 %. The summary of the granulometric analyses results is presented in table 2.

Depth of occurrence of the tar sand deposits affects the volume of voids as well as the precipitation of bitumen during migration by fines due to geopetal accumulation (Lomando, 1986 and 1992; Dutton & Finley, 1988) which has the tendency to result in a reduction of pore throats and porosity. The moderate to high porosity values obtained for the reservoir sands, which range from 16–24 %, (Cole & Christopher, 1992; Wallace & John, 1992, Lomando, 1992). The interconnectivity of pore spaces to transmit fluid is however obstructed by the precipitation of fines from migrating fluids which reduced the pore throats. In addition, the degree of sorting as well as the measure of skewness also affects the degree of reservoir's permeability. This is because a strongly coarse skewed reservoir sands is expected to have larger pore throats, which if interconnected is expected to be highly permeable. The permeability may be reduced however where the pore throats are blocked by fines in case of poorly sorted reservoir sands. Most of the reservoir sands are moderately sorted, which is a good reservoir quality. Permeability is also dependent on the effective grain size of the reservoir sand (Schlumberger, 1989). It can be stated from this study that the larger the effective grain size, the greater the permeability as evident in Table 3. More so, the presence or abundance of fines in a reservoir reduces the permeability of the reservoir. This was observed in the analyzed samples. It was observed that the poorly sorted reservoir sand at Gbegude with about 2.5 % of fines record the lowest permeability value of 143 mD. While the reservoir at Ebute

Table 2. Summary of the result of granulometric analyses of the tar sands deposit.

Sample	Mean ϕ/mm	Sorting ϕ/mm	Remark: Folk,1974	Skewness	Remark: Folk, 1974
Gbegude 3	0.033	1.5	Poorly sorted	0.34	strongly fine skewed
Shofini 12	0.55	0.82	Moderately sorted	–0.58	strongly coarse skewed
Shofini 13	0.26	1.63	Poorly sorted	0.47	strongly fine skewed
Ebute 14	0.53	0.93	Moderately sorted	–0.32	strongly coarse skewed
Bakue 18	0.52	0.94	Moderately sorted	–0.43	strongly coarse skewed

Table 3. Relationship between Reservoir Grain Size, Porosity and Permeability.

Sample	D10(mm)	Porosity (%)	Perm. k. (mD)
AB1	0.51	23.08	3053.8
B18	0.43	23.72	215.4
G1	0.87	20.78	887.53
G3	0.35	16.22	143.03
E14	0.45	23.36	236.44
SH12	0.47	21.9	257.9
SH13	0.42	23.32	210
M5	0.57	22.37	3826.74

Table 4. API gravity values of oil grades (USGS, 2000).

Light Oil 22.3^0
21.6^0 Heavy Oil 10.0^0
6.5^0 Extra Heavy Oil 0.1^0

and Shofini were moderately sorted with amount of fines less than 2 % and permeability values greater than 215 mD. Finally, from the study, the permeability values are found to be moderate to very high (Cole & Christopher, 1992).

The API gravity values obtained in the area are all below 20°, this indicates that the tar sands are composed of Heavy and Extra Heavy Oils according to the USGS scale of oil grades (USGS, 2000), (Table 4). This implies that extracted bitumen is moderately biodegraded and contains good proportion of Asphaltene and Heavy Oil which are responsible for the high resistivity values of the tar sand obtained from the resistivity survey. The bitumen in this area is highly viscous with viscosity of 1080 cP and 1360 cP in Gbegude and Ago – Alaaye respectively. The bitumen content of the tar sand samples analyzed ranged from mass fractions 18 % to 30 %.

Conclusion

The high porosity and permeability values obtained and the degree of sorting of the reservoir sands are indications of a good reservoir quality in the study area. Also, the viscosity and specific gravity values obtained from the analyses indicate highly viscous and low specific gravity oil. These, coupled with high asphaltene content are an indication of severe biodegradation. Moreover, result of API gravity equally showed that the deposits belong to the class of heavy oil. The biodegraded, low viscous low API gravity of the tar which impregnated the sands explains the high resistivity value of the tar sands deposit around the study area in addition to the fact that molecular compounds (hydrocarbons) are incapable of ionic conduction.

The reservoir characteristics of the tar sands in Gbegude area are similar to those earlier studied by other researchers, in that porosity values obtained fall between 16–24 %; percentage of fines ranges from 1–7 %, and are mainly composed of kaolinitic clay and silt; depth of burial ranges from 0 m to >50 m; tar sand reservoir is about 18–72 m thick.

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