Geology, Geophysics & Environment 2021, vol. 47 (4): 217–226

Frequency domain electromagnetic and electrical resistivity geophysical investigation of tar sands deposits in the Ijebu Waterside area, Eastern Dahomey Basin, southwestern Nigeria

Olawale Olakunle Osinowo[1], Ifeayinchukwu Okechukwu[2]

[1] *University of Ibadan, Department of Geology, Ibadan, Nigeria, e-mail: wale.osinowo@ui.edu.ng, olawale.osinowo13@alumni.imperial.ac.uk (correspondence author), ORCID ID: 0000-0002-0436-3461*
[2] *University of Ibadan, Department of Geology, Ibadan, Nigeria*

Received: 21 September 2021; accepted: 8 December 2021; first published online: 30 December 2021

Abstract: The use of electromagnetic conductivity and electrical resistivity geophysical techniques has been employed in this study to investigate the occurrence, thickness, and spatial distribution of bitumen deposit around Makun-Omi in the Ijebu Waterside area of southwestern Nigeria. Subsurface apparent conductivity distribution data obtained using Geonic 34-3 equipment along fifteen traverses which sounded from different depths of 7.5, 15, 30 and 60 m at inter-coil separation of 10, 20 and 40 m in vertical and horizontal coupling modes and ground resistivity distribution measurements, obtained using Geopulse Tiger Allied resistivity meter at fourteen Vertical Electrical Sounding (VES) stations, were processed and employed to characterize the subsurface in terms of tar sands distribution. The conductivity and resistivity distribution in the form of a 3D earth model, iso-depth maps, 2D sections generated from the processed conductivity and resistivity data indicate relatively low conductivity <20 mS/m and high resistivity >1300 Ωm values around tar/bitumen impregnated sands which mostly occurred in the southern part of the study area. Clearly defined conductivity and resistivity anomalies which delineate the lateral and vertical occurrence of tar impregnated sands underscore the efficacy of integrating electromagnetic and electrical resistivity geophysical techniques to identify occurrence of economic deposits of tar sands in parts of southwestern Nigeria.

Keywords: frequency domain electromagnetic survey, conductivity, electrical resistivity, tar sands

---

INTRODUCTION

In Nigeria, hydrocarbons are one of the main energy resources and major income generators. Conventional crude oil has been greatly explored, and exploitation is still ongoing. In recent years, however, the need for an alternative or additional energy source has arisen amid declining hydrocarbon reserves. Nigeria has the second largest reserve of bitumen, after Alberta in Canada, projected to have between 30 to 40 million barrels of heavy oil in place with prospect recovery as high as 3,654 × 10^6 billion barrels (Adegoke et al. 1981). Bitumen deposits is a useful mineral resource in road construction. It comprises sand, clay and asphalt, which fill the pore spaces between the grains. Nigerian tar sand deposits, first discovered through field mapping in 1900, has been reported to occur

https://doi.org/10.7494/geol.2021.47.4.217 ISSN 2299-8004 | e-ISSN 2353-0790 | Wydawnictwa AGH

along a belt that stretches about 120 km in length and 4 km wide from Epe through Ijebu Ode to Okitipupa, Benin and Lagos, within the Nigerian sector of the Dahomey Basin in southwestern Nigeria (Enu 1985). The nature and the occurrence of the Nigerian tar sands have been well described by Enu (1985, 1990) to contain up 84, 17, 4 and 2% of sand, bitumen, water and mineral clay, respectively. Tar sands or bituminous sand deposits have been reported to result from biodegradation of crude oil at low temperature. The process concentrates high molecular weight hydrocarbons as well as hetero-atomic compounds of resins and asphaltenes (Whiteman 1982). Omatsola & Adegoke (1981) reported that the deposits mostly occur at the edge, especially the shallow layers within the Dahomey Basin.

In this study, we employed the combined subsurface illuminating strength of frequency domain electromagnetic (FDEM) and electrical resistivity (ER) geophysical techniques and most especially employed the discriminating ability of subsurface conductivity/resistivity distribution to delineate zones of tar impregnated sands which often present characteristically low conductivity/high resistivity signatures. Soil resistivity directly relates to various geological parameters, such as the mineral composition of the rock matrix, fluid type, concentration and saturation, as well as the soil porosity and permeability. Direct Current electrical resistivity (DC-R) investigation involves the injection of artificially generated electric current into the ground via two current electrodes. In comparison, the potential difference generated between the current electrodes is measured through two potential electrodes. Ground resistivity distribution, which reflects the degree of ground resistance to the flow of electric current within the subsurface, is determined by incorporating the geometric factor of the electrode configuration used during measurement to the measured ground resistance. The distribution of ground resistivity is not homogenous due to the occurrence of anomalous zones, which may result due to variations in lithological composition, structures, fluid concentration/saturation, impregnation with hydrocarbon, among others. The electrical resistivity method has found useful applications for mapping the spatial distribution, depth of occurrence as well as thickness of tar sands deposits.

GEOLOGY OF THE STUDY AREA

The study was carried out within the Dahomey Basin in southwest Nigeria (Fig. 1). The basin is a marginal pull-apart basin (Klemme 1975) formed during the Early Cretaceous tectonic event when South American plate separates from African plates (Ogbe 1972, Whiteman 1982). The Dahomey Basin is an extensive sedimentary wedge basin consisting of over 3000 m Cretaceous sediments which thickens from onshore (at less than 200 m) seaward (offshore at >3000 m) (Okosun 1990). The basin is bounded and separated from the Niger Delta Basin by the Okitipupa ridge/Benin hinge line while in the west it is bound by the Romanche Fracture zone (RFZ) and associated structures (Omatsola & Adegoke 1980). The basin consists of Cretaceous to Tertiary sedimentary sequences and forms an arcuate belt which runs roughly parallel to the ancient coastline (Fig. 2) (Adegoke et al. 1976b, Whiteman 1982). The Nigerian tar sands deposits which occur within the Nigerian bitumen belt that stretches about 120 km in length and 40 km in width occur predominantly in loosely consolidated Createaceous Afowo sand units which itself is capped by the Maastrichtian Shales of the Araromi Formation (Enu 1985). The bitumen impregnated sand units occur in two main horizons. The upper horizon, commonly referred to as X horizon is a sandstone with interbeds of shales and siltstone that ranges in thickness from 10–22 m. The lower (Y) horizon, which is separated from the upper unit by 8 m thick oil shales unit (may be unsaturated with hydrocarbon), is a predominantly quartz grain, upwardly fining sequence that ranges in thickness between 3–26 m. The units have been recorded to have a mean hydrocarbon saturation of 12% in the two horizons (Enu 1985, 1990). A number of wells constructed by the consultant unit of the then University of Ile-Ife, now Obafemi Awolowo University (OAU) indicate that the two tar sands horizons are overlain by variably thick overburden which ranges in thickness from 3 m in the north to about 50–80 m in the south. The overburden is mainly comprised of shales, siltstones, interbedded limestones and lateritic top soil which often vary in thickness (Adegoke et al. 1976a, 1976b, Enu 1985). Figure 3 presents a representative borehole lithofacies and hydrocarbon/bitumen saturation logs drilled within the Nigerian Bitumen Belt.

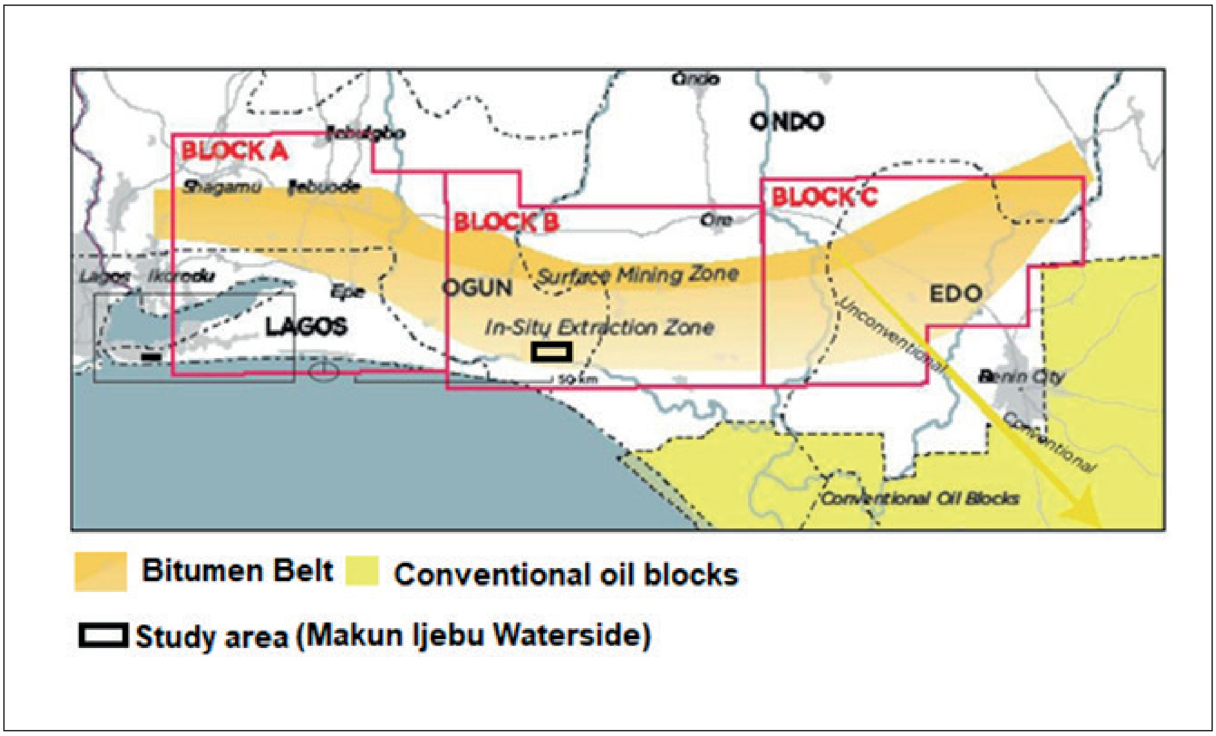

Fig. 1. *Map of the Dahomey Basin showing the Nigerian bitumen belt, some bitumen blocks and the study area in Makun in Ijebu Waterside (Milos 2015)*

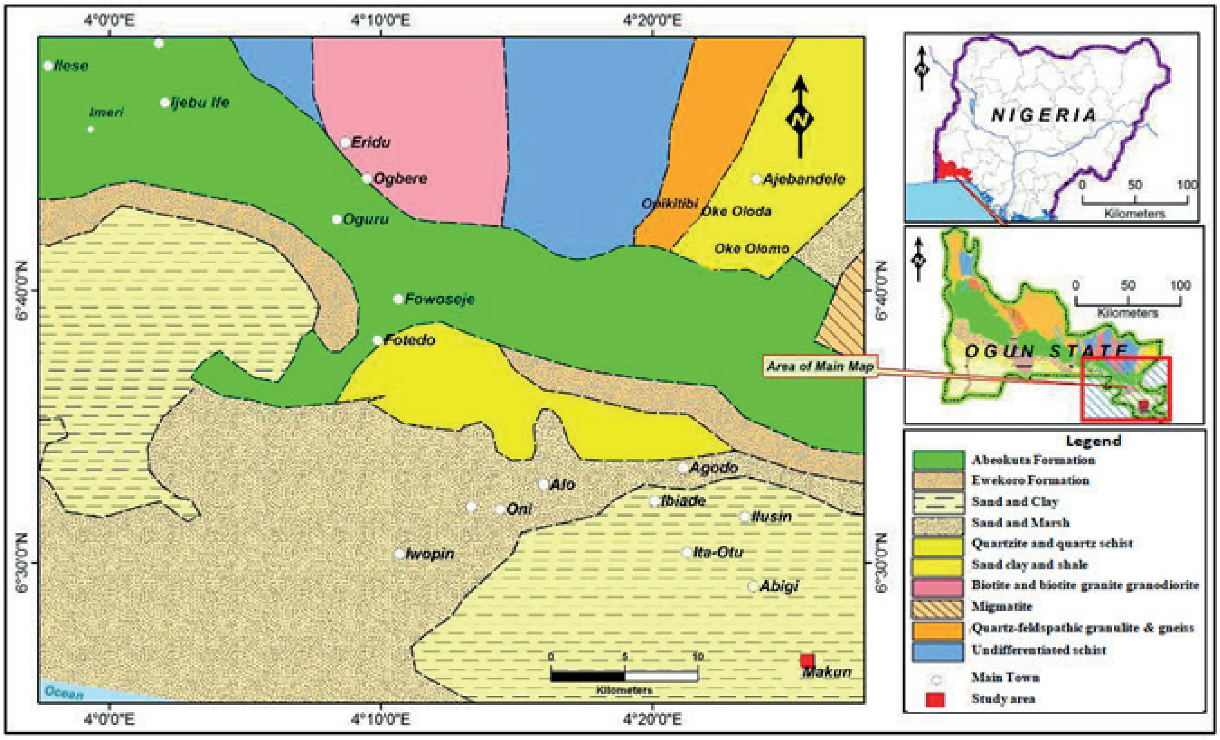

Fig. 2. *Geological framework of the eastern Dahomey Basin (NGSA 2009). Inserts are: the map of Nigeria and the geological map of Ogun State, southwestern Nigeria*

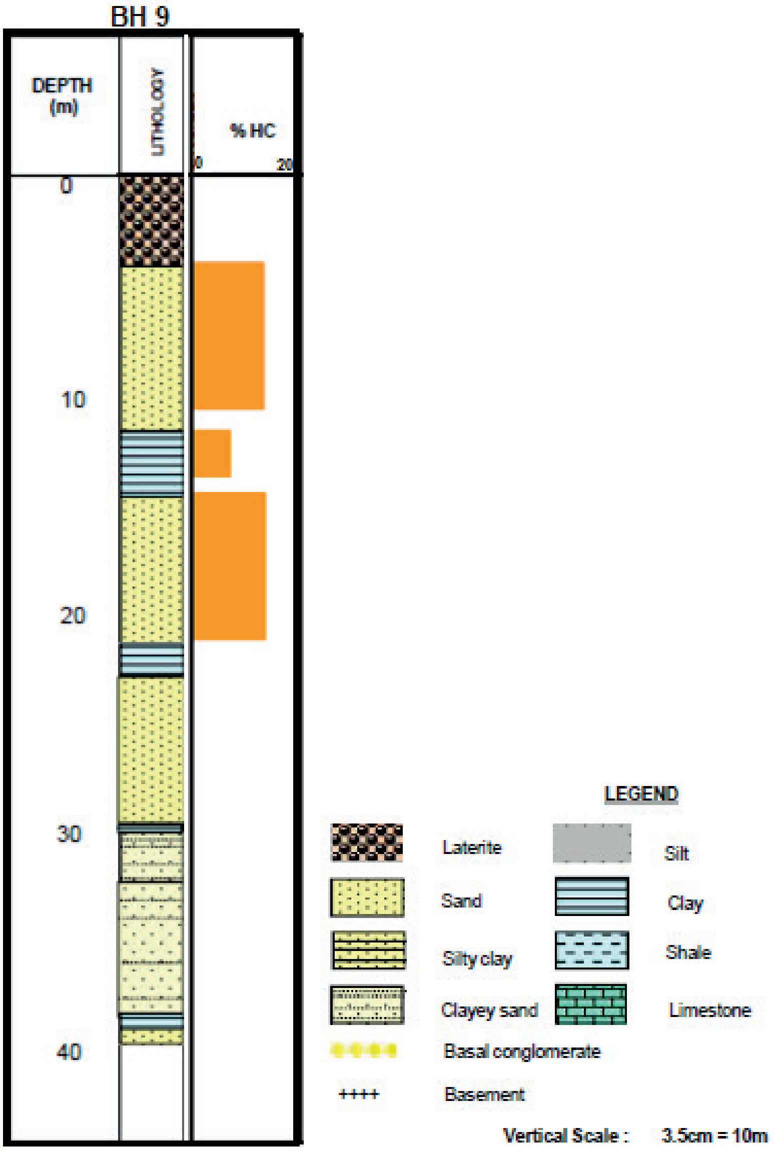

Fig. 3. Lithofacies (LITHOLOGY) and bitumen saturation (%HC) borehole log of a well drilled within the Bitumen Belt of southwestern Nigeria (modified after Geological Consulting Unit (GCU) of OAU Ile-Ife, Adegoke et al. 1976a)

MATERIALS AND METHODS

The study began with a reconnaissance and geological field mapping exercise which includes setting up the area to be surveyed, observing the geological and hydrological features within the area and planning out the layout and traverses for geophysical survey. Two geophysical investigation techniques, electromagnetic and electrical resistivity traversing, were integrated to better delineate and satisfactorily resolve the spatial distribution of the tar sand deposit within the study area. The two techniques complement each other. While the ER evaluated the upper 25 m of the subsurface, the FDEM was able to probe up to 60 m depth across the study area.

Frequency domain electromagnetic (FDEM) survey

The Geonics EM 34-3 used in this study is a portable device, usually operated by two people. The device consists of two circular coils which are connected to the transmitter (T_x) and receiver (R_x) consoles of the device via flexible cables (Fig. 4A, B). Ground conductivity measurement is possible in both horizontal dipole (HD) and vertical dipole (VD) modes, by aligning both the transmitter and the receivers' coils in vertical or horizontal positions, respectively (Fig. 4C). Intercoil spacing of 10, 20, or 40 m enabled progressive apparent conductivity measurements with depth at 7.5, 15, 30 and 60 m in horizontal and vertical dipole coupling modes, respectively (Tab. 1) with the point of observation located at the midpoint between the transmitter and the receiver. The instrument is calibrated to read terrain conductivity in millisiemens per metre (mS/m). In vertical orientation, the instrument is most responsible to material at the surface and at depths down to one half the coil spacing. However, in the horizontal orientation, the instrument is most responsive to materials at depths of one- quarter and three quarters of the coil spacing (McNeil 1990). Increasing coil separation proportionately increases the depth of penetration of the instrument in both coil coupling modes. Fifteen EM traverses which range in length from 180 to 500 m were occupied along NE-SW direction with the traverses running perpendicular to the general geological strike of the study area.

Table 1
Investigation depth of Geonics EM 34-3

Intercoil spacing [m]	Explored depth [m]		Frequency [Hz]
	HD	VD	
10	7.5	15	6.4
20	15	30	1.6
40	30	60	0.4

Fig. 4. *FDEM and ER geophysical investigation equipment and field operations: A) transmitter module, coil and connecting cable; B) receiver module and coil; C) geophysical crew carrying out FDEM survey using Geonics EM 34-3; D) Campus Ohmega resistivity meter, stainless electrodes and reels of flexible cables*

Electrical Resistivity (ER) survey

Ground resistivity measurement was achieved by injecting an appropriate amount of current (I) into the subsurface via two current electrodes of distance AB, using Geopulse Tigre resistivity meter. The potential difference (dV) generated by the flow of injected current (I) within the subsurface is measured via two potential electrodes to determine the resistance of the earth material to flow of electric current (Fig. 4D). Apparent ground resistivity (ρ_a) is subsequently determined by incorporating the geometric factor (K) of Schlumberger electrode configuration, employed in this study:

$$\rho_a = \frac{KV}{I} \tag{1}$$

Vertical electrical sounding (VES) measurement technique was employed to determine variation in ground resistivity distribution with depth. Fourteen VES stations with current electrode separation (AB) from 1 to 100 m enabled the measurement of ground apparent resistivity from very close to the surface and progressively deeper as AB increases. The base map showing the survey layout is presented in Figure 5.

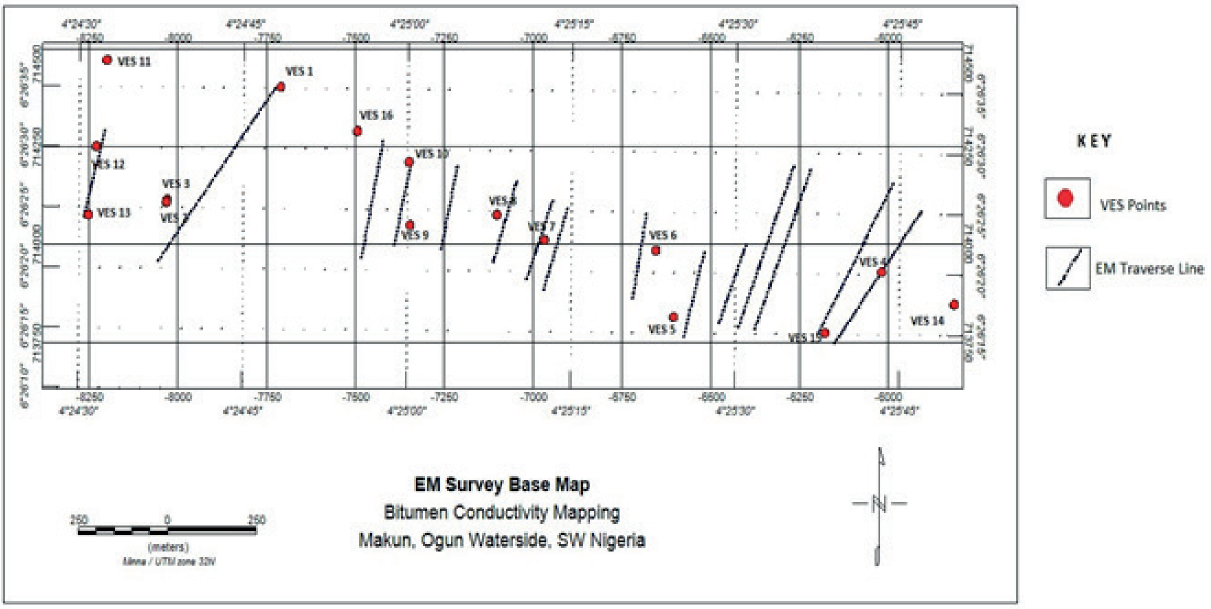

Fig. 5. Location map of the study area showing the FDEM profiles and VES data points

Data processing

Data quality check (QC), the first data processing step carried on both the electromagnetic and the ER data, involves checking the two geophysical data sets for accuracy and consistency. Isolated spurious and outranged data, especially those without geological significance, were filtered. The measured apparent conductivity data from the Geonics EM-34-3 were filtered to reduce noise to the barest minimum (thus increasing signal to noise ratio (S/N)), and inverted to generate ground conductivity values at the measurement stations. Individual ground conductivity data were integrated using the GPS readings recorded at each station during field measurement. The resultant data were visualized using Geosoft Oasis Montaj application software. The VES data were also QC and subsequently plotted on log-log paper for partial curve matching using standard two-layer curves and auxiliary Cagniard Graph (Koefoed 1979). The plotted VES data curves were compared with standard curves and thus determined geo-electrical parameters (thickness and resistivity values) of each layer. The resultant layer parameters served as starting models for inversion of the field data using the model inversion software WinRESIST (Vender Velpen 1988) and WingLink geophysical application algorithms, developed based on the modified Marquardt–Levenberg inversion algorithm (Marquardt 1963, Ghosh 1971, Vender Velpen 1988).

RESULTS AND INTERPRETATION

The results obtained from the FDEM survey are presented in the form of cross-section of 1D resistivity profiles, 2D conductivity distribution sections, iso-depth subsurface conductivity distribution maps and 3D subsurface conductivity model across the study area. The iso-depth subsurface conductivity distribution maps, which show variations in layer conductivity distribution with depth, delineated three distinct conductivity distribution domains (Fig. 6). The first is the relatively high conductivity distribution pattern (30–35 mS/m) that characterizes the north-central part of the study area. The north central high conductivity pattern is largely consistent with depth, though slightly decreases in extent at depth. The second is the relatively low conductivity distribution pattern (20–24 mS/m) that dominates the southern part of the study area. The eastern and the western flanks displayed conductivity distributions that vary with depth. The western flank displayed relatively low conductivity values that gradually increase with depth while high conductivity distribution in the eastern flank gradually decreases along the southern direction (Fig. 6).

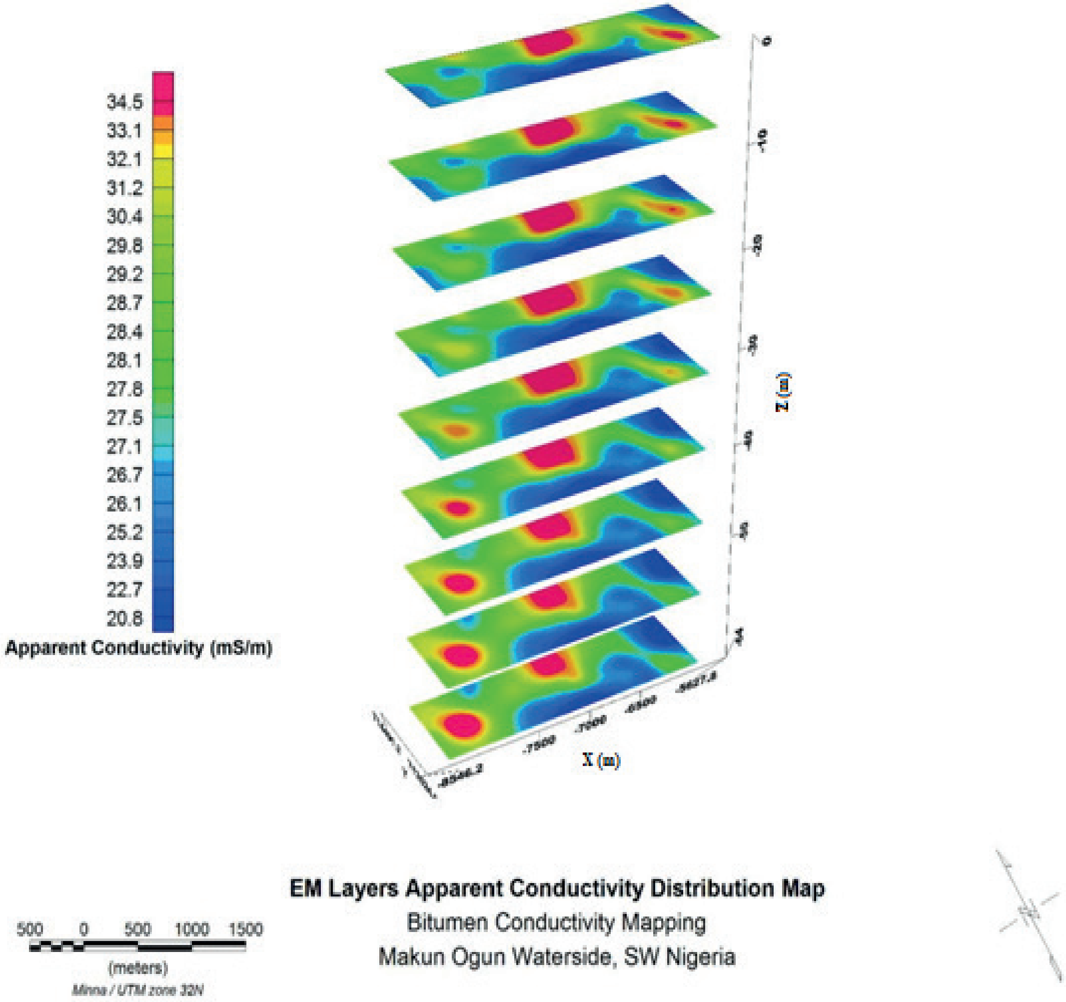

Fig. 6. *Orthomaps of conductivity distribution at different depths from FDEM*

The three-dimensional (3D) model was generated by combining all the filtered conductivity values of different georeferenced FDEM stations, including at different layers/depths, displayed conductivity distribution across the study area from −7.5 to −60 m below the earth's surface (Fig. 7). The model generally indicates that the study area is characterized by a relatively high apparent conductivity distribution that ranges in value from 20 to 34 mS/m with an average background value of 25 mS/m. Isolated regions of higher conductivity value (30–34 mS/m), higher than background value, occurred in the north and southeastern parts of the study area. The southern end of the study area, especially at the south-central part present relatively low conductivity values (20–23 mS/m). The low conductivity distribution region coincides with part of the study area where tar sands outcrops were observed to be exposed in the surface (Fig. 8).

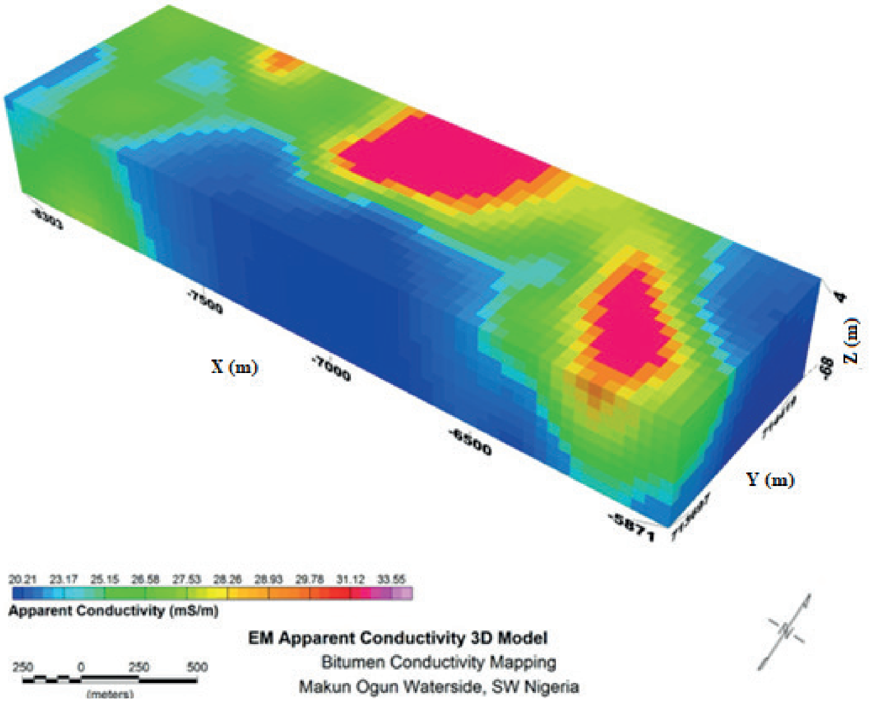

Fig. 7. *3D conductivity distribution model across the study area generated from FDEM method*

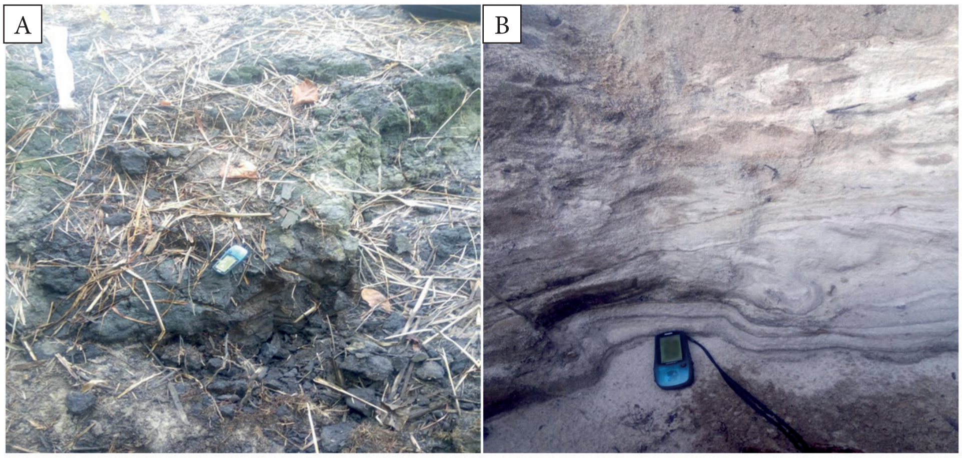

Fig. 8. *Bitumen/tar sands deposit outcrop (A) and asphalt oozing out from bitumen outcrop around the study area (B)*

The VES survey defined a three layered geoelectric earth based on a vertical and lateral subsurface resistivity distribution model obtained from the inversion of the measured resistivity data. The resistivity method resolves the subsurface up to 24.1 m depth with resistivity values that generally range from 51 to 7844 Ωm. A 2D NW-SE trending resistivity profile/section reveals the topsoil, second/middle and the third/lower layers. The first layer (topsoil) is relatively thin (usually less than 2 m thick) and presents characteristic heterogeneous resistivity distribution that range in value from 204 to 3759 Ωm. The middle layer can be subdivided into low resistive (61–688 Ωm) brackish water-saturated sands or tar sands, and high resistivity (1435–7843 Ωm) tar/bitumen saturated sands. The third/lower layer presents background resistivity values. Figure 9 presents the subsurface resistivity distribution model generated by combining the fourteen resistivity logs, indicating the variation in the resistivity distribution with depth. The 2D resistivity section indicates low resistivity second/middle layer encountered at VES 13, 12, 11, and three stations, having resistivity distribution that range in value from 52 to 688.6 Ωm. On the other hand, a high resistivity value (1363–7844 Ωm) characterizes the middle/second layer at VES 16, 10, 9, 8, 6, 5, 4 and 14 stations. The low resistivity VES stations appeared to be restricted to the southwestern part of the study area while the high resistivity ones occur in the northwest. Field observation indicates tar sands deposit exposed at VES station 4 (Fig. 9) with a characteristic high resistivity value (as high as 7843 Ωm). The low resistivity region in the eastern part of the field is close to the lagoons and hence usually flooded with brackish water during the rainy season. The high resistivity values towards the southern part of the study area can be attributed to bitumen impregnation of the sand unit within the study area. The thickness of the high resistivity bitumen impregnated layer ranges from less than 2 m to as much as 10 m within the study area.

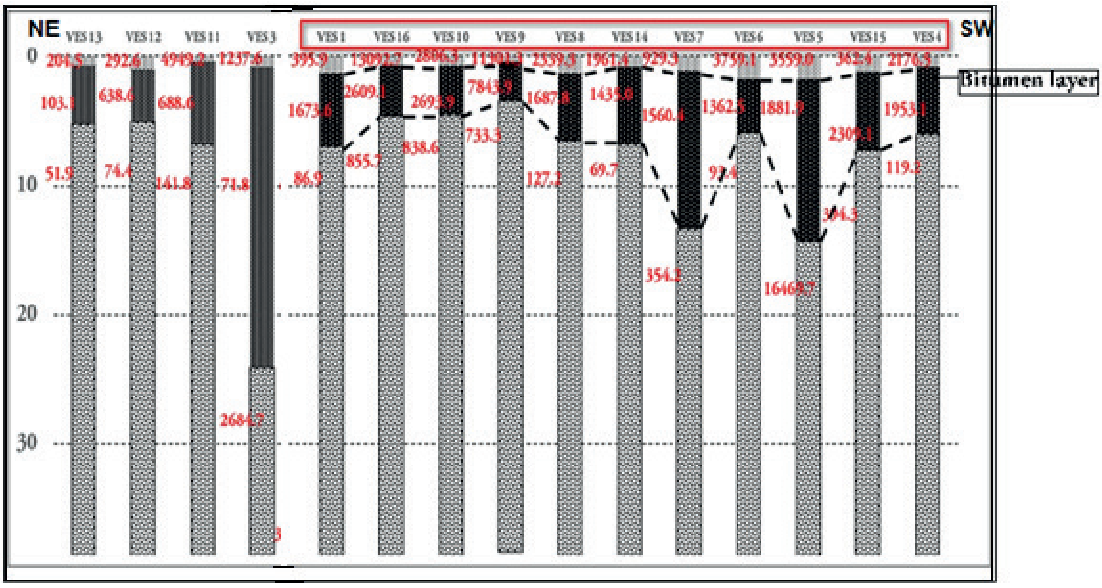

Fig. 9. *Resistivity distribution section generated from VES data points aligned along NE-SW*

CONCLUSION

Combining frequency domain electromagnetic terrain conductivity and electrical resistivity distribution data has proved potent to illuminate the subsurface and delineate the spatial distribution and thickness of bitumen saturated deposits around Makun Omi in the Ijebu Waterside area of southwestern Nigeria. The orthomaps (iso-depth) conductivity distribution maps and 3D conductivity earth model generated from the EM survey indicate low conductive regions attributed to the occurrence of bitumen impregnated sands/tar sands in the south-central part of the study area while relatively high conductivity values characterize the fresh/brackish water-saturated sands in the north central part of the study area. The resistivity distribution pattern complements and corroborates the electromagnetic survey results as it delineates three resistivity layers, with the middle layer saturated with bitumen.

REFERENCES

Adegoke O.S., Ako B.D., Enu E.I., Petters S.W., Adegoke A.C.W., Odebode M.O. & Emofurieta W.O., 1976a. *Tar Sand Project Phase II. Estimation of reserves, materials, testing and chemical analyses*. Geological Consultancy Unit, Department of Geology, University of Ire, Ile-Ife [unpublished report].

Adegoke O.S., Petters S.W., Enu E.I., Ako B.D., Adegoke-Anthony C.W., Odebode M.O. & Emofurieta W.O., 1976b. The bituminous sands of Ondo and Ogun states of Nigeria. [in:] Adegoke O.S. (ed.), *Geological Guide to Some Nigerian Cretaceous-Recent Localities*, Nigerian Mining and Geosciences Society Special Publication.

Adegoke O.S., Enu E.I., Ajayi T.R., Ako B.D., Omatsola M.E. & Afonja A.A., 1981. Tar sands – a new energy raw material in Nigeria. [in:] *Proceedings of Symposium on New Energy Raw Material, Karlovy Vary, Czechoslovakia*, 17–22.

Enu E.I., 1985. Textural characteristics of the Nigerian tar sands. *Sedimentary Geology*, 44(1–2), 65–81. https://doi.org/10.1016/0037-0738(85)90032-6.

Enu E.I., 1990. Textural and occurrence of tar sands in Nigeria. [in:] Ako B.D. & Enu E.I. (eds.), *Occurrence, utilization and economics of Nigerian tar sands: A workshop held in Ogun State University Ago-Iwoye, Nigeria on 29–31 May, 1990*, Nigerian Mining and Geoscience Society, 11–16.

Ghosh D.P., 1971. The Application of Linear Filter Theory to the direct interpretation of geoelectrical resistivity sounding measurements. *Geophysical Prospecting*, 19(2), 192–217. https://doi.org/10.1111/j.1365-2478.1971.tb00593.x.

Klemme H.D., 1975. Geothermal gradients, heat flow and hydrocarbon recovery. [in:] Fischer A.G. & Judson S. (eds.), *Petroleum and Global Tectonics*, Princeton University Press, Princeton, 251–304.

Koefoed O., 1979. *Geosounding Principles 1: Resistivity Sounding Measurements*. Elsevier Science Publishing Company, Amsterdam.

Marquardt D.W., 1963. An Algorithm for Least-Squares Estimation of Nonlinear Parameters. *Journal of the Society for Industrial and Applied Mathematics*, 11(2), 431–441.

McNeil J.D., 1990. Use of electromagnetic methods for groundwater studies. [in:] Ward S.H. (ed.), *Geotechnical and Environmental Geophysics: Review and Tutorial*, Society of Exploration Geophysicists, Tulsa, 191–218.

Milos C., 2015. *Bitumen in Nigeria: Weighing the True Cost of Extraction*. Abeysteph, Abuja. https://ng.boell.org/sites/default/files/bitumen_in_nigeria.pdf.

Nigerian Geological Survey Agency (NGSA), 2009. *Geological Map of Southwestern Nigeria*.

Ogbe F.G.A., 1972. Stratigraphy of Strata Exposed in Ewekoro Quarry, Southwestern Nigeria. [in:] Dessauvagie T.F.J. & Whiteman A.J. (eds.), *African Geology*, University of Ibadan Press, Ibadan, 305–322.

Okosun E.A., 1990. A review of the Cretaceous stratigraphy of the Dahomey embayment. *West Africa: Cretaceous Research*, 11, 17–27. https://doi.org/10.1016/S0195-6671(05)80040-0.

Omatsola M.E. & Adegoke O.S., 1980. Tectonic evolution of the Dahomey Basin (West Africa) and its implication on the opening of the North and South Atlantic. [in:] *26th International Geological Congress, Paris, July 7–17, 1980*, International Union of Geological Sciences.

Omatsola M.A. & Adegoke O.S., 1981. Tectonic evolution and Cretaceous stratigraphy of the Dahomey Basin. *Journal of Mining and Geology*, 18(1), 130–137.

Vender Velpen B.P.A., 1988. *A computer processing package for DC. Resistivity interpretation for IBM compatibles*. ITC Delft, Delft, The Netherlands.

Whiteman A.J., 1982. *Nigeria: Its Petroleum Geology, Resources and Potential. Volume 2*. Graham and Trotman, London.