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Integration of Seismic and Well Log Data for Reservoir Characterization in Offshore Niger Delta, Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Author IAA did the supervised and wrote the Manuscript. Author AOA performed methodology and analysis of the manuscript. Both authors read and approved the final manuscript.

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ABSTRACT

The demand for fossil fuels is continually increasing due to the growing global population and industrialization. It is thus necessary to find hydrocarbon prospects in new fields and those that have previously been classified as marginal fields in order to maximize production. An integrated approach is required to effectively characterize hydrocarbon reservoirs and assess their ability to store and produce hydrocarbons. 3D seismic reflection data and well log data were combined to quantitatively estimate hydrocarbon reserves in a field, offshore Niger delta, Nigeria. The reservoirs were delineated on the gamma ray and resistivity logs which penetrate four wells selected from the field. The petrophysical analysis provided information about the net-to-gross thickness ratio, porosity, shale volume and water saturation of the reservoirs, deduced from well log suites comprising gamma, resistivity, density and neutron-porosity logs through four wells. The seismic

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interpretation involved mapping of horizons and faults across the wells on the seismic section. Check shot data were used to tie the seismic data to the well log data to generate the synthetic seismogram. The time structural and depth structural maps were generated. The volumetric analysis entailed derivation of the Gross rock volume from the depth structural map, and estimation of the Stock Tank Oil Initially In Place (STOIIP). Four reservoirs were delineated in each of the four wells. The average thickness of the reservoirs ranges from 56.6 m to 232.7 m while the water saturation varies from 0.29% to 0.57%. The average porosities of the reservoirs ranges from 0.18% to 0.22%. The structural interpretation of the eight faults mapped reveals synthetic and antithetic faults, and rollover anticlines. The time- and depth structural maps generated from the mapped horizons show that the reservoirs are penetrated by the different faults. The Stock Tank Oil Initially In Place (STOIIP) of the reservoirs range from 25 MMstb to 468 MMstb. The study shows that the integration of 3D reflection data and well log data can be used effectively to estimate hydrocarbon reserves. The results of the study are expected to contribute to the development of new exploration and production strategies in the Niger delta basin and similar sedimentary environments.

Keywords: Reservoir characterization; well log data; seismic reflection data; hydrocarbon reserves; Niger delta.

1. INTRODUCTION

The discovery and extraction of hydrocarbons are essential to meet global energy demand that is continually increasing. Reservoir characterization involves a multidisciplinary approach, integrating well log data, core data, and seismic reflection data to gain a comprehensive understanding of subsurface reservoirs [1-5]. It is critical for hydrocarbon reserve estimation which will help to reduce exploration risks, optimize hydrocarbon production, and consequently maximize economic benefits. The integration of well log and seismic reflection data has proven to be an effective approach to enhancing reservoir characterization [6-8].

Well log data are essential for creating a geological model, quantifying important petrophysical properties and improving drilling operations in subsurface reservoir [9]. They are measurements taken within a borehole or well that provide information about the physical properties of the rock formations present. These measurements may include electrical resistivity, gamma ray emission, sonic velocity, and density, among others. By analyzing these measurements, geoscientists can determine the lithology, porosity, permeability, and fluid content of the rocks, which can help in the characterization of reservoirs for oil, gas, or water.

Seismic data can provide information about the structure and composition of the subsurface, including the depth, thickness, and orientation of rock layers, as well as the presence of faults and other geological features [10-12]. Analysis of time and amplitude of seismic wave reflections can provide definitive images of the subsurface, quantify important petrophysical properties and identify fluid-filled reservoir zones [13,14].

Integrating well log and seismic reflection data will enhance the generation of detailed model of the subsurface, which would produce better overall interpretation results. This enhancement would guide reservoir management decision to optimize oil and gas production, and ultimately maximize economic benefits [15,16].

Geoscientists today must put in much more efforts to find economic reservoirs, as they frequently search for subtle stratigraphic and structural traps while examining mature zones for undiscovered hydrocarbons. An integrated approach is required to effectively characterize reservoirs, as the use of well log data alone may not sufficiently delineate the reservoir characteristics capable of assessing the ability to store and produce hydrocarbons. This study therefore uses a combination of seismic and well log data to characterize reservoirs in an offshore field (named ATAGA) in the Niger Delta, for enhanced reserve estimation. The objectives are to map the seismic horizons and faults in the study area, delineate the petrophysical characteristics of hydrocarbon-bearing sands in the reservoirs across the wells, to determine the reservoirs' Net to Gross ratio (NTG), volume of shale (V_{sh}), and porosity, and estimate the hydrocarbon productivity of the reservoir.

The Niger Delta is located in the south-south region of Nigeria within Longitude 3º E - 9º E and

Latitude 4º 30′ N – 5º 20′ N (Fig. 1). It is bounded to the east by the Calabar flank, to the west by the Benin flank, to the south by the Gulf of Guinea, and to the north by older tectonic elements such as the Anambra Basin, Abakaliki Anticlinorium, and Afikpo Syncline [17,18]. It is a vast sedimentary basin covering an area of approximately 75,000 km2 [19-21] and a major hydrocarbon-bearing province accounting for over 90% of Nigeria's oil and gas reserves [22]. The precise location of the study area could not be disclosed here due the proprietary nature of the data.

The delta has prograded southwestward from the Eocene to the present, forming depobelts that represent the most active portion of the delta at each stage of its development. These depobelts are among the largest regressive deltas in the world, covering an area of approximately 300,000 km^2, with a sediment volume of 500,000 km^3 and a sediment thickness of over 10 km in the basin depocenter [23].

The Niger Delta is divided into three formations, each of which represents a prograding depositional facies distinguishable mainly based on sand-shale ratio. The formations, in descending order, are the Benin, Agbada, and Akata formations (Fig 2). The Benin formation is the topmost and mainly composed of sandstones with shale intercalations. It has very little hydrocarbon accumulation. The Agbada formation is the most widespread and major hydrocarbon-bearing unit comprising mainly a sequence of interbedded sandstones and organically-rich shales. The reservoir rocks are capable of storing large volumes of oil and gas. It is the main target for oil

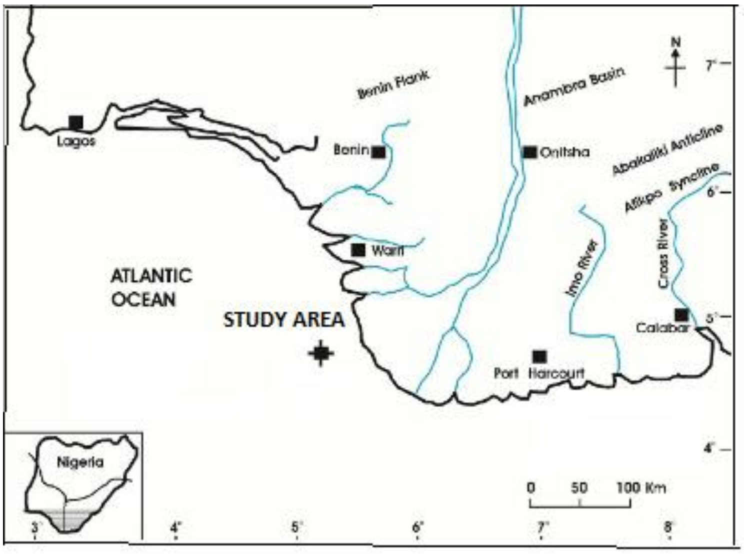

Fig. 1. Location map showing the study area

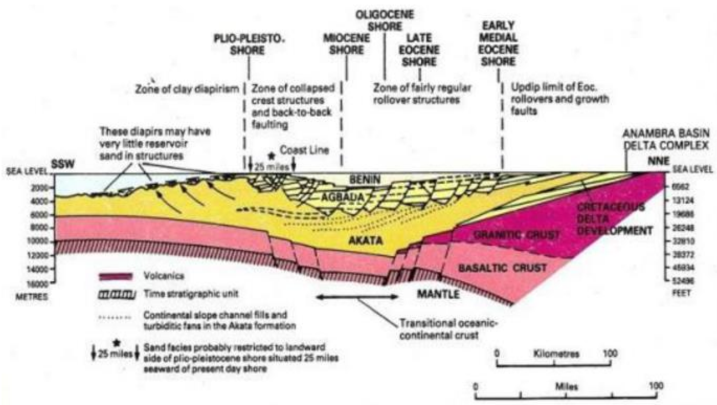

Fig. 2. Niger delta stratigraphy sequence

and gas exploration and development in the Niger delta region. The Akata Formation is a uniform shale development comprising sandy, silty shale with plant remains at the top. The shale sequences of the formation are the primary source rocks for the hydrocarbons found in the Niger Delta, as they contain high concentrations of organic matter that have been subjected to high pressure and heat for a very long time [24].

2. METHODOLOGY

The study employed a combination of processed 3D seismic data and well log data from four wells named ATAGA 10, ATAGA 5, ATAGA 7, and ATAGA 11. The well data, acquired in LAS format, were quality checked and imported into Petrel software to generate continuous logs for each of the selected wells. The hydrocarbon-bearing sands were correlated across the wells and the petrophysical parameters were computed for the identified hydrocarbon sands. The seismic data were imported into the Petrel software and used to conduct structural interpretation which involves mapping of faults and horizons on the seismic sections, and the synthetic seismograms were generated to tie the wells to the seismic data using check shot data. Time structure and depth structure maps were generated and used for volumetric analysis to determine the hydrocarbon-in place volumes in terms of Stock Tank Oil Initially In Place (STOIIP).

The gamma ray (GR) logs were used to identify and distinguish the different types of rock formations in the wells. Low GR values were used to indicate the presence of sands, while high GR values were used to indicate the presence of shales. The resistivity logs were used to differentiate between zones that were hydrocarbon bearing and those that were water bearing.

The petrophysical analysis involved computer-assisted analysis of well log responses by Techlog Schlumberger software, to determine the net thickness to gross thickness ratio, porosity, water saturation, and volume of shale for the reservoirs, using the inputs of depth to reservoir tops and bases obtained from the log suites comprising gamma, resistivity, neutron and density logs. These physical properties were used to infer the presence and location of hydrocarbons within the reservoirs, and evaluate the potential productivity of the wells.

The total (Φt) porosity was computed using the formula:

$$\Phi t = \frac{\rho ma - \rho b}{\rho ma - \rho fluid} \quad (1)$$

where

ρma = rock matrix density, ρ_b = measured density, Water (1 g/cm^3), oil (0.87 g/cm^3), gas (0.65 g/cm^3),
ρ_{fluid} = fluid density. Water saturation ($S_w{}^n$) was computed using Archies equation [25]:

$$S_w{}^n = \frac{R_w}{(\Phi^m \times R_t)} \quad (2)$$

where

R_w = formation water resistivity at formation temperature, R_t = true resistivity of the formation (corrected for invasion, borehole, thin bed, and other effects), Φ = porosity,
m = cementation exponent, which varies from 1.7 to 3.0 but normally is 2.0, n = saturation exponent, which varies from 1.8 to 4.0 but normally is 2.0
The volume of shale was calculated using the Larionov Tertiary equation [26]:

$$V_{ah} = 0.083(2^{3.7.IGR}-1) \quad (3)$$

where V_{sh} = Volume of shale and IGR = Gamma ray index (calculated by dividing the gamma ray log value at a point by the gamma log value at the shale baseline).
The hydrocarbon-in-place volume (STOIIP) for each reservoir was estimated by using the equation:

$$\text{STOIIP} = \frac{6.29 \times GRV(m^3) \times \frac{N}{G} \times \Phi \times (1-Sw)}{B_o} \quad (4)$$

where B_o = Oil Formation Volume Factor, S_w = Water Saturation and N/G= Net to Gross ratio.

3. RESULTS AND DISCUSSION

The reservoirs were identified on the gamma ray logs. The correlation of the well logs shows that the reservoirs selected (A6, A7, A8, and A9) appear across the four wells (Fig. 3). The results of the petrophysical analysis conducted on samples obtained from the reservoirs penetrated by the wells revealed that the depth to the top and bottom intervals of reservoir A6 are 3522 m – 3541 m in ATAGA-5, 3471 m -3497 m in ATAGA-7, 3522 m – 3541 m in ATAGA-10 and

3500 m – 3519 m in ATAGA-11, representing gross thickness ranging from 19.81 m to 26.52 m. (Table 1) The net thickness, which is the thickness of the hydrocarbon bearing sand, ranges from 5.6 m to 21.2 m. The Net-to-Gross ratio and Shale Volume ranges from 0.28 to 0.91 and 0.11 to 0.34 respectively while the porosity of the reservoir ranges from 0.12 to 0.22. The water saturation ranges from 0.37 to 0.97. Typical Pickett plots showing the degree of water saturation in the reservoirs is shown in Fig. 4.

Reservoir A6 consists of sandstone in ATAGA-10 and ATAGA-11, while ATAGA-5 and ATAGA-7 consist of dolomite and limestone respectively (Fig. 5). The depth intervals of reservoir A7 are 3578 m – 3677 m, 3536 m -3663 m, 3587 m – 3677 m in and 3554 m – 3706 m in ATAGA-5, ATAGA-7, ATAGA-10 and ATAGA-11 respectively, which represent gross thickness ranging from 99.67 m – 151.64 m. The net thickness varies from 73.5 m to 147.1 m. The Net-to-Gross ratio and Shale Volume ranges from 0.74 – 0.97 and 0.12 – 0.25 respectively. The Porosity of the reservoir ranges from 0.1 – 0.18 while the water saturation ranges from 0.33 – 0.50. The lithology of the reservoirs is predominantly sandstone in ATAGA-7, ATAGA-10 and ATAGA-11 with only ATAGA-5 consisting of limestone.

Reservoir A8 lies within the depth intervals 3757 m – 3860 m in ATAGA-5, 3796 m -3853 m in ATAGA-7, 3757 m – 3850 m in ATAGA-10 and 3836 m – 3904 m in ATAGA-11. The gross thickness varies from 57.15 m to 102.41 m. The net thickness ranges from 56.09 m – 89.46 m. The Net-to-Gross ratio ranges from 0.87 to 0.98 while the Shale Volume ranges from 0.07 to 0.18. The porosity and water saturation of the reservoir ranges from 0.17 to 0.22 and 0.17 to 0.45 respectively. The lithology of this reservoir in all the wells is sandstone.

The depth to the top and bottom intervals of reservoir A9 are 3890 m – 3934 m in ATAGA-5, 3923 m -3974 m in ATAGA-7, 3890 m – 3934 m in ATAGA-10 and 3940 m – 3981 m in ATAGA-11, representing gross thickness ranging from 40.54 m – 51.5 m. The net thickness ranges from 28.2 m to 49.7 m. The Net-to-Gross ratio and Shale Volume ranges from 0.65 to 0.98 and 0.11 to 0.80 respectively. The porosity of the reservoir ranges from 0.13 to 0.20 while the water saturation ranges from 0.17 to 0.45. The reservoirs consist of limestone in ATAGA-5 and ATAGA-7 while those in ATAGA-10 and ATAGA-11 consist of sandstone.

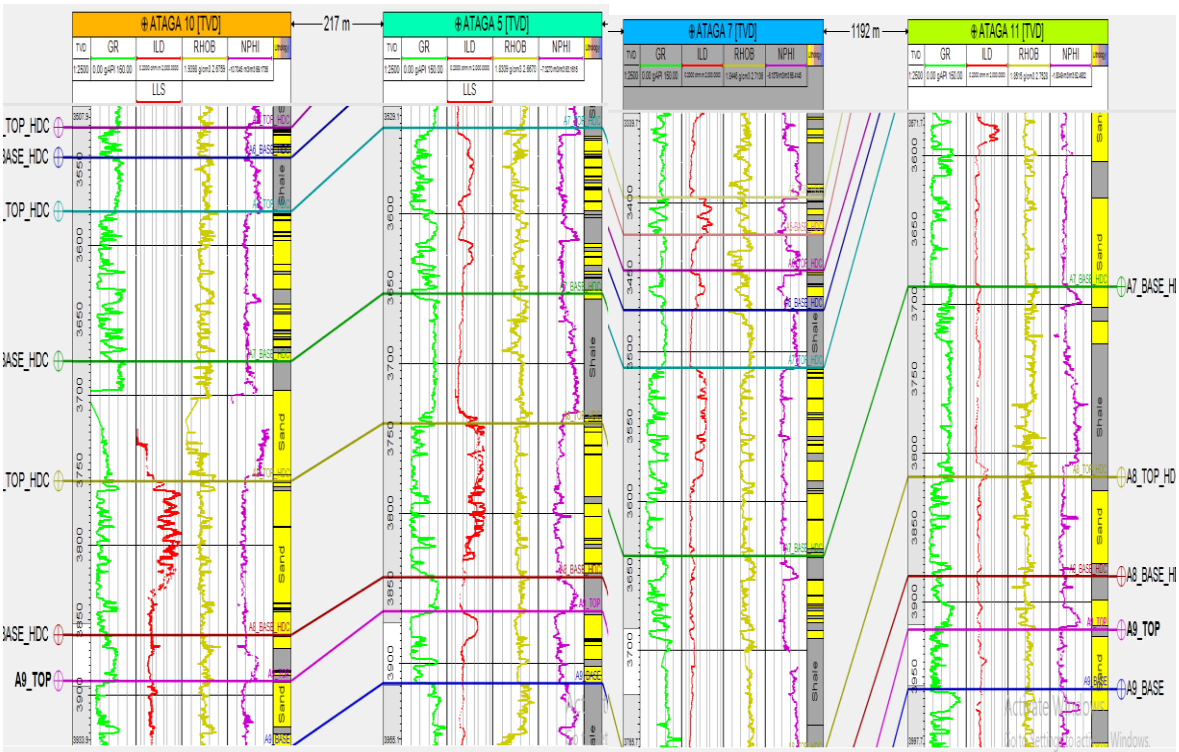

Fig. 3. Correlation of reservoirs across the wells

Table 1. Petrophysical parameters of Reservoirs A7-A9 across the wells

	Depth to Top (m)	Depth to Bottom (m)	Gross Thickness (m)	Net Thickness (m)	Net to Gross ratio	Shale Volume (V_{shale})	Porosity	Water Saturation	Inferred lithology
Reservoir Ataga-5	3522.11	3541.93	19.81	5.60	0.28	0.11	0.12	0.97	Dolomite
Ataga-7	3471.38	3497.89	26.52	21.21	0.8	0.34	0.19	0.43	limestone
Ataga-10	3523.11	3548.93	19.81	17.39	0.88	0.18	0.22	-	sandstone
Ataga-11	3500.48	3519.22	18.75	17.08	0.91	0.28	0.19	0.37	Sandstone
Reservoir A7									
Ataga-5	3578	3678	99.76	73.50	0.74 0.18	0.210	0.34		Limestone
Ataga-7	3537	3663	126.64	114.32	0.90 0.12	0.220	0.40		Sandstone
Ataga10	3578	3677	99.67	94.95	0.95 0.14	0.210	-		Sandstone
Ataga11	3555	3706	151.64	147.07	0.97 0.11	0.220	0.50		Sandstone
Reservoir A8									
Ataga-5	3758	3860	102.41	89.46	0.870	0.077	0.208	0.179	Sandstone
Ataga-7	3797	3854	57.15	56.09	0.980	0.167	0.175	0.335	Sandstone
Ataga-10	3758	3860	102.41	98.76	0.960	0.087	0.217	0.207	Sandstone
Ataga-11	3837	3904	67.67	66.14	0.980	0.1207	0.227	0.448	Sandstone
Reservoir A9									
Ataga-5	3891	3935	43.74	28.22	0.65	0.101	0.187	0.427	Limestone
Ataga-7	3923	3975	51.51	49.69	0.97	0.086	0.132	0.771	Limestone
Ataga-10	3891	3935	43.74	39.34	0.90	0.081	0.206	0.456	Sandstone
Ataga-11	3940	3982	40.54	39.78	0.98	0.118	0.201	0.423	Sandstone

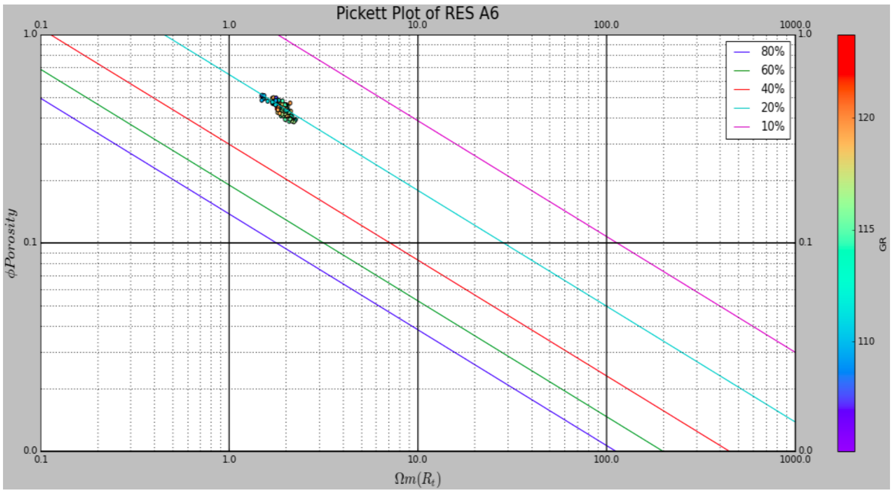

Fig. 4. Typical Pickett plot showing the degree of water saturation in reservoir A6 in ATAGA-5

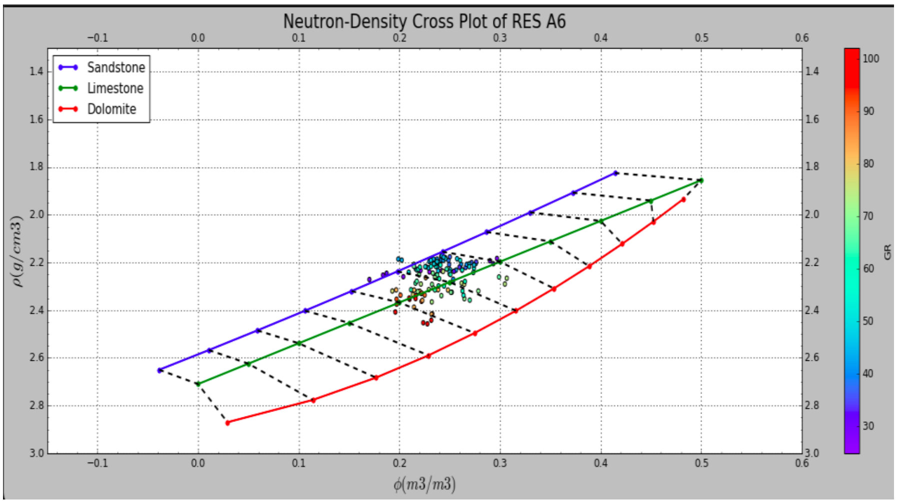

Fig. 5. Typical Neutron–Density cross plot showing sandstone composition of reservoir A6 in ATAGA-10

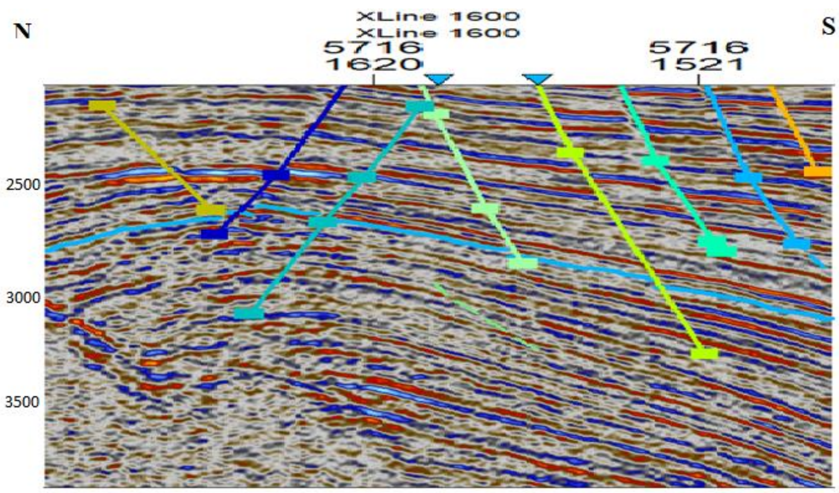

Fig. 6. N-S Seismic line showing the faults cutting through the different Seismic reflectors

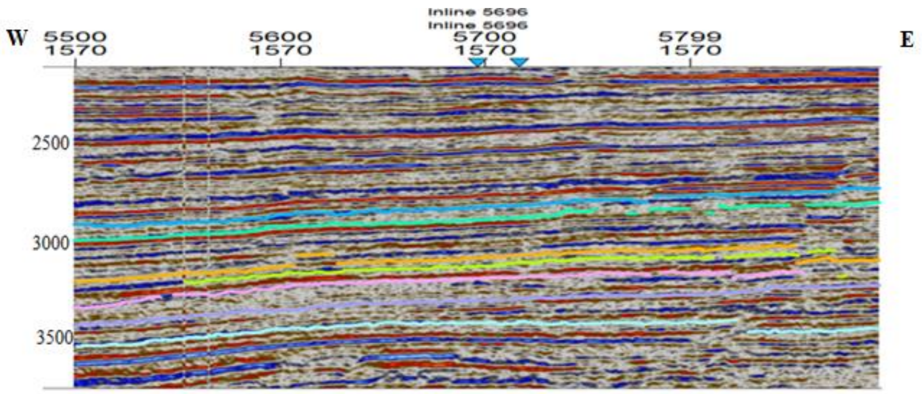

Fig. 7. E-W Seismic line showing the different Seismic Horizons

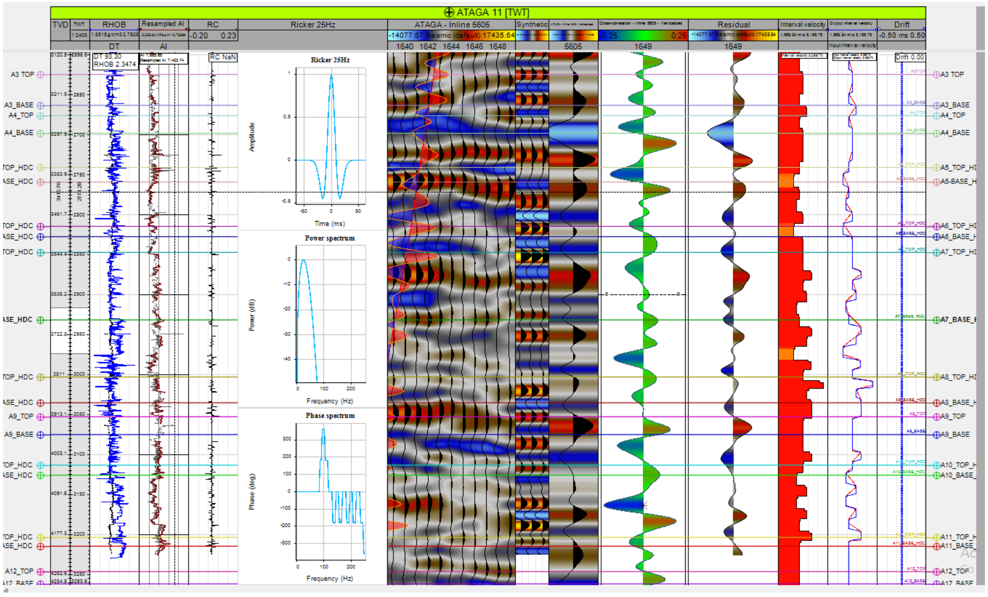

Fig. 8. Synthetic Seismosgram showing correlation of the well log and seismic reflection data

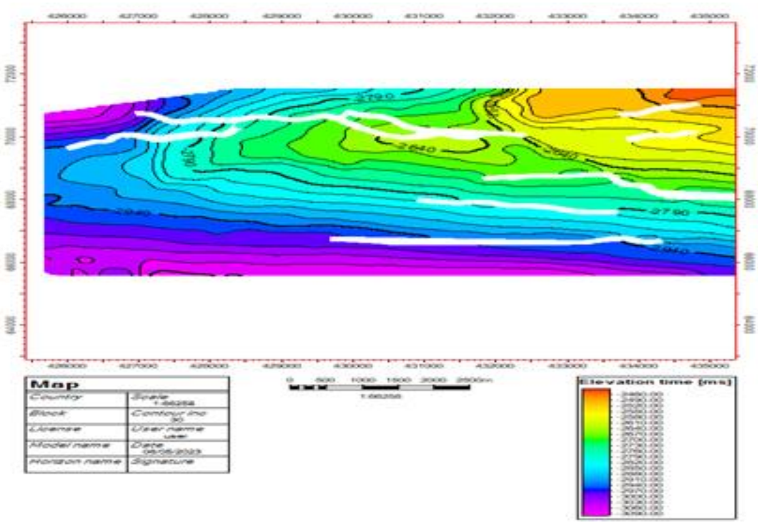

Fig. 9. Typical Time structural map for Reservoir across the wells in the study area

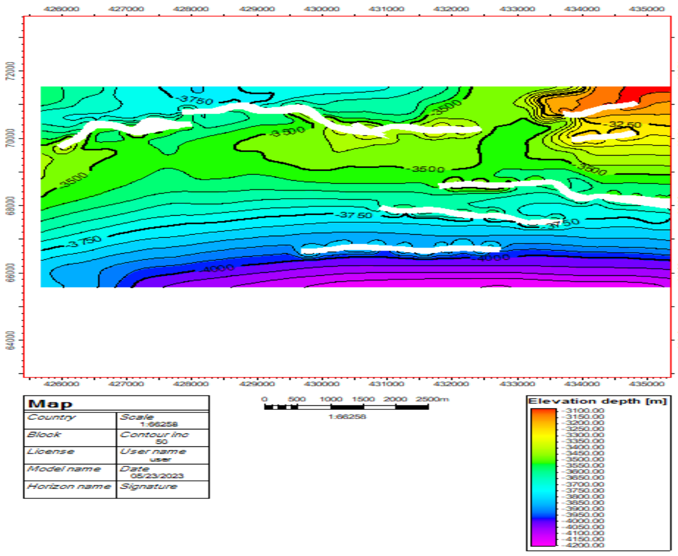

Fig. 10. The Depth structure map of reservoir in the study area.

The average porosity values of the reservoirs across the wells range from 0.18 to 0.22 while the average volume of shale and water saturation ranges from 0.11 to 0.23 and 0.29 to 0.57 respectively.

3.2 Faults and Horizons Interpretation

Eight faults were observed on the seismic section (Fig. 6). The ATAGA field is marked by several synthetic and antithetic normal growth faults typical of the Niger Delta Basin faulting system. Eight horizons were also delineated on the seismic section, and designated as Sand A6_Top_HDC, Sand A7_Top_Hdc, Sand A8_Top_HDC, Sand A9_Top_HDC, Sand A10_Top_HDC, Sand A11_Top_HDC and Sand A13 Top HDC (Fig. 7) These mapped intervals are characterized by high amplitude with moderate-to-good continuity reflections, mostly disrupted by some truncations, which are fault-related.

3.3 Seismic to Well Tie

The synthetic seismogram panel (Fig. 8) shows the correlation of the well log data and the seismic reflection data. The wells picked are in sync with high reflections of the seismic data.

3.4 Time and Depth Structure Map

The time structural maps show the two way-travel time of the mapped horizons and highlight the geometry of the reflector (Fig. 9). The time range of the horizons is between 2500 ms and 3500 ms. The time structural maps of horizons reveal the presence of anticlinal structures which close on the major faults across the field.

The depth structural maps depict areas with structural highs. The depth range of the horizons is between 3100 m and 4700 m (Fig. 10). Reservoir A6 shows multiple faults that penetrate the reservoir. Close examination of these maps reveals the presence of growth faults and anticlines that can possibly harbour hydrocarbon in the study area. The trapping mechanisms in ATAGA field as observed in both time and depth structural maps are anticlines and fault assisted closures.

3.5 Hydrocarbon-in-Place Volume

The type of hydrocarbon present in the reservoirs is oil. The estimated reserves are 25 million, 384 million, 468 million, and 95 Million stock tank barrels (MMstb) for Reservoir A6, Reservoir A7, Reservoir A8, and Reservoir A9 respectively. The total estimated reserves, which is the sum for all the reservoirs is therefore 972 MMstb.

4. CONCLUSIONS

The subsurface geology and prospect areas of ATAGA field offshore Niger Delta were studied using 3D seismic, composite well logs, and check shot data. Four hydrocarbon-bearing sands were identified based on the log curve signatures of the gamma ray, neutron, density, and resistivity logs. Lithological panels derived from well log data show that the study area is characterized by sand-shale interbeds. The hydrocarbon reservoir sands were correlated across the wells and hydrocarbon intervals in the field were mapped onto the seismic section using time-depth data.

These sand units have porosity ranging from 0.12 to 0.23 characteristic of hydrocarbon reservoirs, and the water saturation is typically less than 0.5. The fluid type is oil. The eight faults mapped across the intervals show that the field is highly faulted as typical of the tectonic setting of the Niger Delta.

The seven horizons interpreted along the inline and crossline correlated with the reservoirs picked on the well logs. The depth maps indicated the reservoirs as fault-assisted closures and characterized by rollover anticlinal structure. The value of the reserves (STOIIP) ranges from 25 MMstb, in reservoir A6, to 468 MMstb in reservoir A8, while it varies from 384 MMstb to 95 MMstb in reservoirs A7 and A9 respectively. The integration of 3D seismic data and well logs has helped in identifying probable zones of hydrocarbon accumulation and characterizing the delineated reservoirs. The findings of the study are expected to contribute to the development of new exploration and production strategies in the Niger delta basin and similar sedimentary environments.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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