



Hydrocarbon reservoir characterization of “Otan-Ile” field, Niger Delta

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Abstract

Otan-Ile field, located in the transition zone Niger Delta, is characterized by complex structural deformation and faulting which lead to high uncertainties of reservoir properties. These high uncertainties greatly affect the exploration and development of the Otan-Ile field, and thus require proper characterization. Reservoir characterization requires integration of different data such as seismic and well log data, which are used to develop proper reservoir model. Therefore, the objective of this study is to characterize the reservoir sand bodies across the Otan-Ile field and to evaluate the petrophysical parameters using 3-dimension seismic and well log data from four wells. Reservoir sands were delineated using combination of resistivity and gamma ray logs. The estimation of reservoir properties, such as gross thickness, net thickness, volume of shale, porosity, water saturation and hydrocarbon saturation, were done using standard equations. Two horizons (*T* and *U*) as well as major and minor faults were mapped across the ‘Otan-Ile’ field. The results show that the average net thickness, volume of shale, porosity, hydrocarbon saturation and permeability across the field are 28.19 m, 15%, 37%, 71% and 26,740.24 md respectively. Two major faults (*F*₁ and *F*₅) dipping in northeastern and northwestern direction were identified. The horizons were characterized by structural closures which can accommodate hydrocarbon were identified. Amplitude maps superimposed on depth-structure map also validate the hydrocarbon potential of the closures on it. This study shows that the integration of 3D seismic and well log data with seismic attribute is a good tool for proper hydrocarbon reservoir characterization.

Keywords Niger Delta · Well logs · Seismic · Reservoir characterization · Seismic attributes

Introduction

Niger Delta basin is ranked among the most prolific basins in the world and its productivity has made it to be the fulcrum of Nigeria economy. The ‘Otan-Ile’ field, located in the transition zone Niger Delta (Fig. 1). The basin is often characterized by complex structural deformation and faulting which could lead to high uncertainties in the reservoir properties (Doust and Omatsola 1990). These high uncertainties greatly affect the exploration and development of fields within the basin such as ‘Otan-Ile’ field. Improper interpretation of reservoir properties heterogeneity in the field has led to poor performance of reservoir during hydrocarbon production. Nonlinearity, natural heterogeneity and uncertainty of reservoir parameters make problems related to hydrocarbon characterization difficult (Koneshloo et al. 2018). Thus, it is problematic to clearly quantify spatial relationships of variable properties of reservoir. In resolving this problem, well logs and seismic data can be used to generate useful petrophysical parameters, maps and seismic attributes

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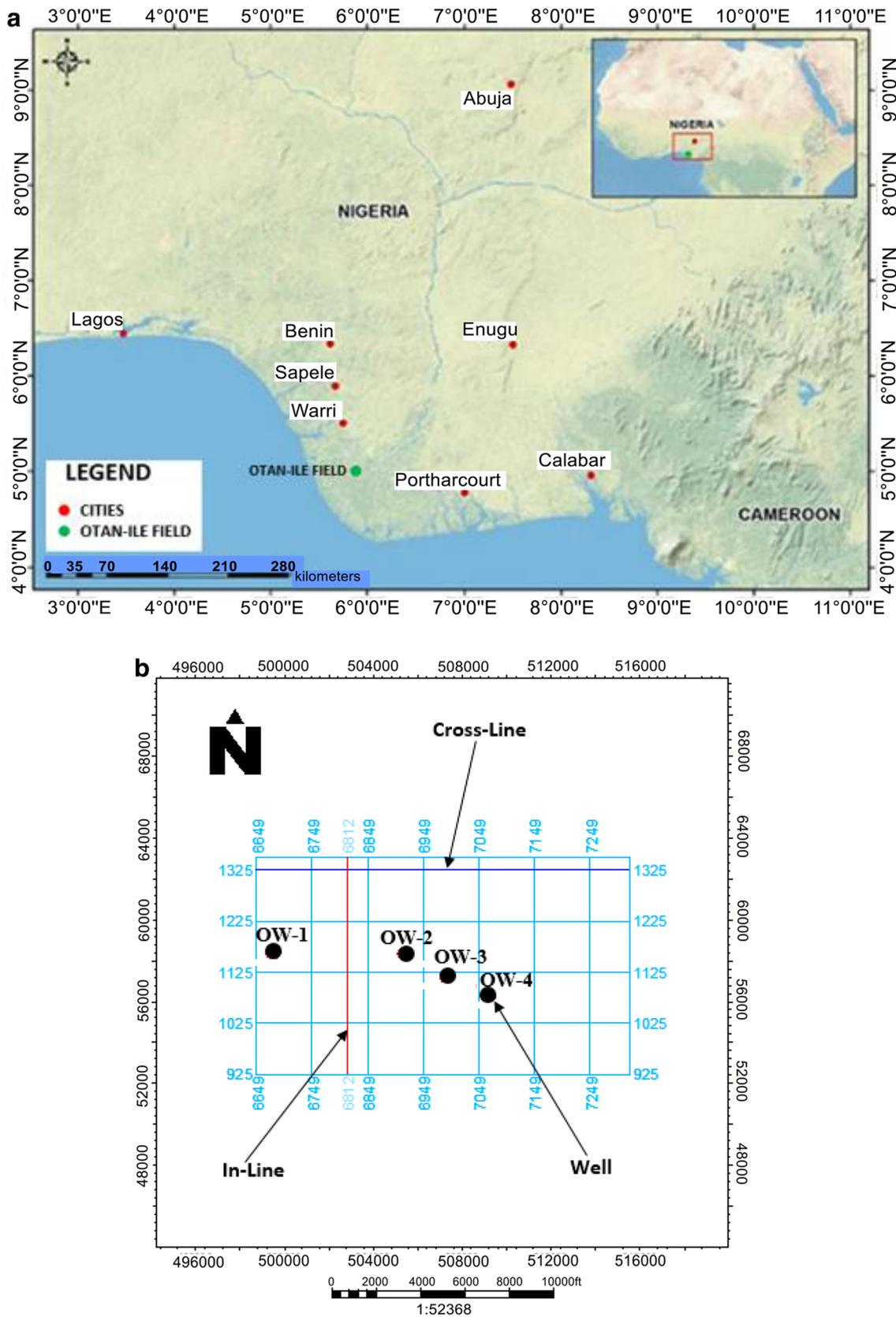


Fig. 1 a The Niger Delta Provinces (modified Edigbue et al. 2015). b Base Map of “Otan-Ile” Field

which could provide detail description of reservoir properties and assist in optimal well placement. Concise geometric description of stratigraphic and structural aspects of a reservoir can be well achieved using well log and seismic data (Adelu et al. 2016; Sanuade et al. 2018; Akanji et al. 2018).

Several studies have been carried out in the Niger Delta Basin using 3D seismic and well log data to properly characterize hydrocarbon reservoirs (Sanuade et al. 2018; Ibe and Ezekiel 2019), for stratigraphical analysis (Emujakporue and Eyo 2019; Dim et al. 2019), volumetric analysis (Adelu et al. 2016; Akanji et al. 2016; Okpogo et al. 2018; Ukuedojor and Maju-Oyovwikowhe 2019), pore pressure prediction (Chiazor and Beka 2019; Tanko et al. 2019; Umoren et al. 2019) and structural analysis (Sanuade et al. 2018; Akanji et al. 2018; Adeoti et al. 2014; Ibe and Ezekiel 2018; Soneye and Osinowo 2019). Furthermore, seismic attributes (measure of seismic data which aids to improve visualize or quantify structures of interpretation concern (Marfurt and Chopra 2007) are very important tools in analyzing and interpreting hydrocarbon reservoir as they provide detailed information. Seismic attribute maps have also been used by several researchers to enhance hydrocarbon characterization (Adelu et al. 2016; Sanuade et al. 2018; Akanji et al. 2018; Ibe and Ezekiel 2019).

Therefore, the objective of this study is to characterize the complex reservoir bodies in the Otan-Ile field and to evaluate the petrophysical parameters so as to provide detailed geological information about the field.

Geology of the study area

Structure and Sedimentology of Niger Delta

The structure of the Niger Delta basin is comparable to a colossal rollover, with paralic shales and sands acting as the principal sediments present. The latter sequence prevails at 1930–2050 m within the subsea (Short and Stauble 1967; Whiteman 1982; Doust and Omatsola 1990).

The three key formations within the Niger Delta basin are the bottom Akata, middle Agbada and topmost Benin Formations (Fig. 2). The first, newest, coastal plain, Miocene to Recent Benin Formation (Short and Stauble 1967; Evamy et al. 1978; Ejedawe 1986; Doust and Omatsola 1990) largely consists of deposits of alluvia and non-marine sandstones, in a continental, yet fluvial setting, encompassing the western flank of the Niger Delta complex to the total basin and the southern region of the shoreline. Bands of gravel lignite, wood fragments, minute intercalations of shales and coarse-grained sandstones are prime deposits observed. It is also primarily linked with infinitesimal accumulation of hydrocarbon (Akanji et al. 2018). The thickness of this Formation varies widely, exceeding 1820 m in some instances.

The underlying lower Agbada Formation, is a chief petroleum-bearing, Eocene to Pliocene Formation, which is situated within varying environments from a coastal brackish and/or marine one to a fluvial one. There are equivalent layers and quantities of sandstone and shale at the basal region

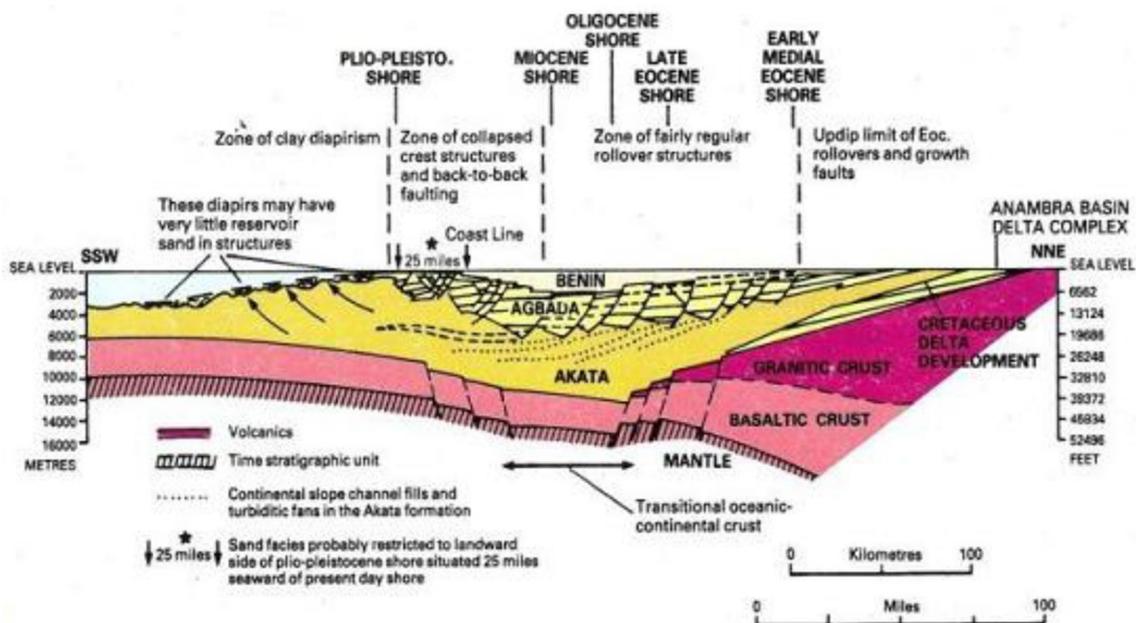


Fig. 2 Structural units of the Niger Delta complex (Short and Stauble 1967)

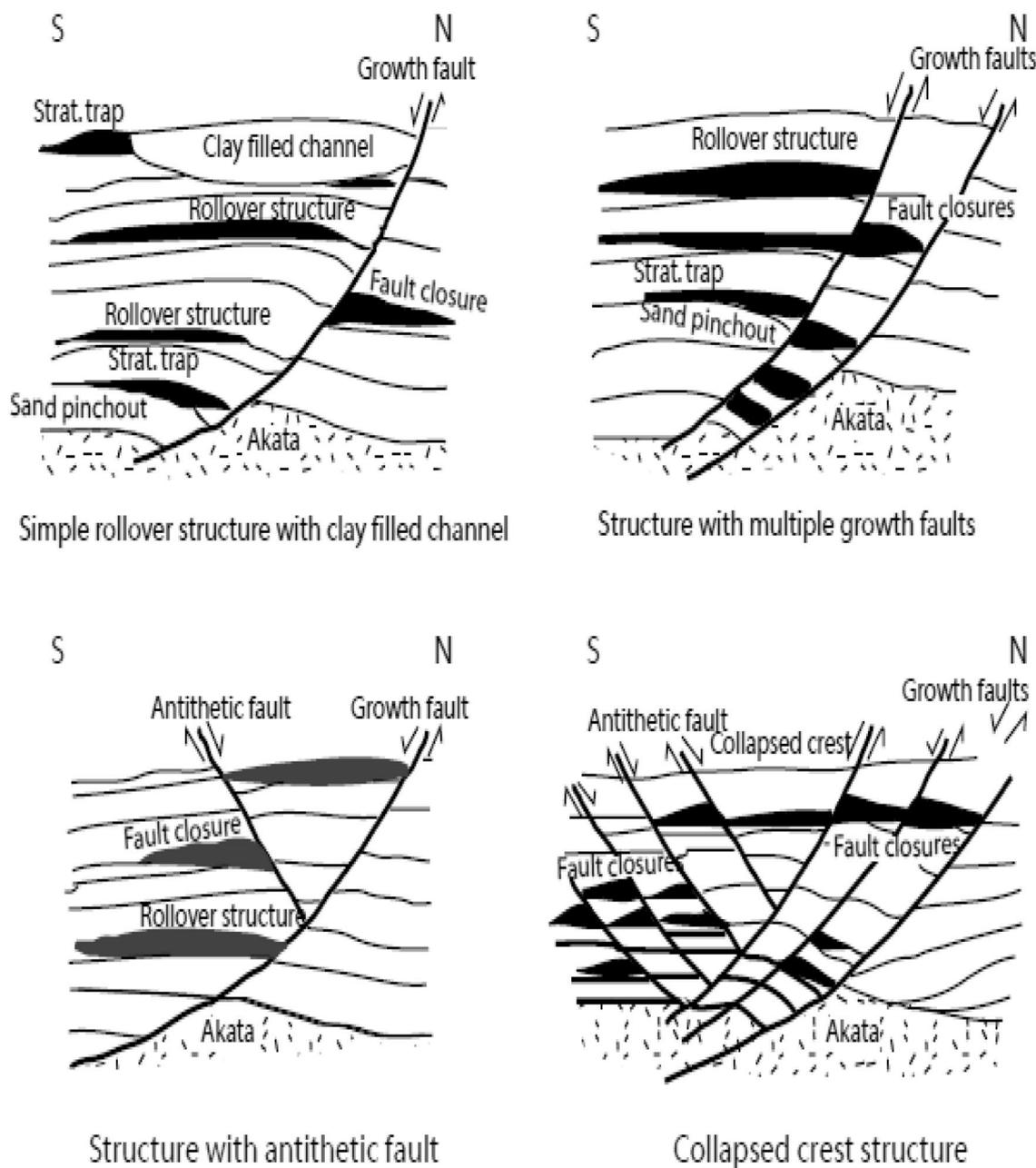


Fig. 3 Example of Niger Delta oil field structures and associated traps types (Doust and Omatsola 1990)

with more sands in the upper layer. Furthermore, in the basal layer, shales result from gradual variation of unconsolidated to marginally consolidated sandstones which are well graded with varying degrees of roundness. The sands host the hydrocarbon, acting as reservoirs with the shales offering effective closures and seals (Bustin 1988; Corredor et al. 2005; and Adeoti et al. 2014). Here, there are several orientations of the belts hosting massive quantities of oil, and a maximum thickness of 4500 m is observed (Evamy et al. 1978; Doust and Omatsola 1990; Dieokuma et al. 2014).

The ancient, bottom, marine Akata Formation is about 7000 m thick, with an age range from Eocene to Recent exhibits signs of excess overburden pressure; and resembles a diapir from the offshore continental slope. It is made up of dense series of the potential hydrocarbon source rock (shale), turbidites and insignificant amounts of clays and silts (Doust and Omatsola 1990). The shales also host local siltstones and sandstones as interbeddings (Haack et al. 2000).

Northwest to southeast and northeast to southwest trending growth faults—antithetic, flank, regional, crestal, structure-building and listric faults; ridges, rollover anticlines and shale diapirs are associated with the Niger Delta basin (Hosper 1971). The Niger Delta comprises depobelts/megaunits which are objects with respect to distribution of hydrocarbon, stratigraphy and structure-building (Evamy et al. 1978). The improvement and style of the discrete megaunits are connected to the equilibrium between the rate of sediment subsidence and supply (Knox and Omatsola 1989). Doust and Omatsola (1990) described a variety of structural trapping elements, including those associated with simple rollover structures; clay filled channels, structures with multiple growth faults, structures with antithetic faults and collapsed crest structures (Fig. 3).

Methodology

Database

The data used for this study include 3D seismic data (covering an area of 51 km²), well log from four wells (sonic, density, gamma ray and resistivity) and checkshot data.

Methodology

Lithology delineation

The methodology used in this study include identifying lithology by using gamma ray log. The lithology was identified by defining the shale base line to be 65 API (American Petroleum Institute) (Asquith and Krygowski 2004) which is a constant line in front of shale Formation across the entire ‘Otan-Ile’ field. A deflection, even slight from the shale base line to the left, indicates a sand Formation. Delineation of petroliferous zones was done by using combination of gamma ray and resistivity logs. When sand Formation correlates with relatively high resistivity response, such is recognized as petroliferous zone.

Petrophysical evaluation

Standard equations were used for the estimation of reservoir properties, which involves calculation of reservoir parameters such as gross thickness, net thickness, volume of shale, porosity, water saturation and hydrocarbon saturation of the field.

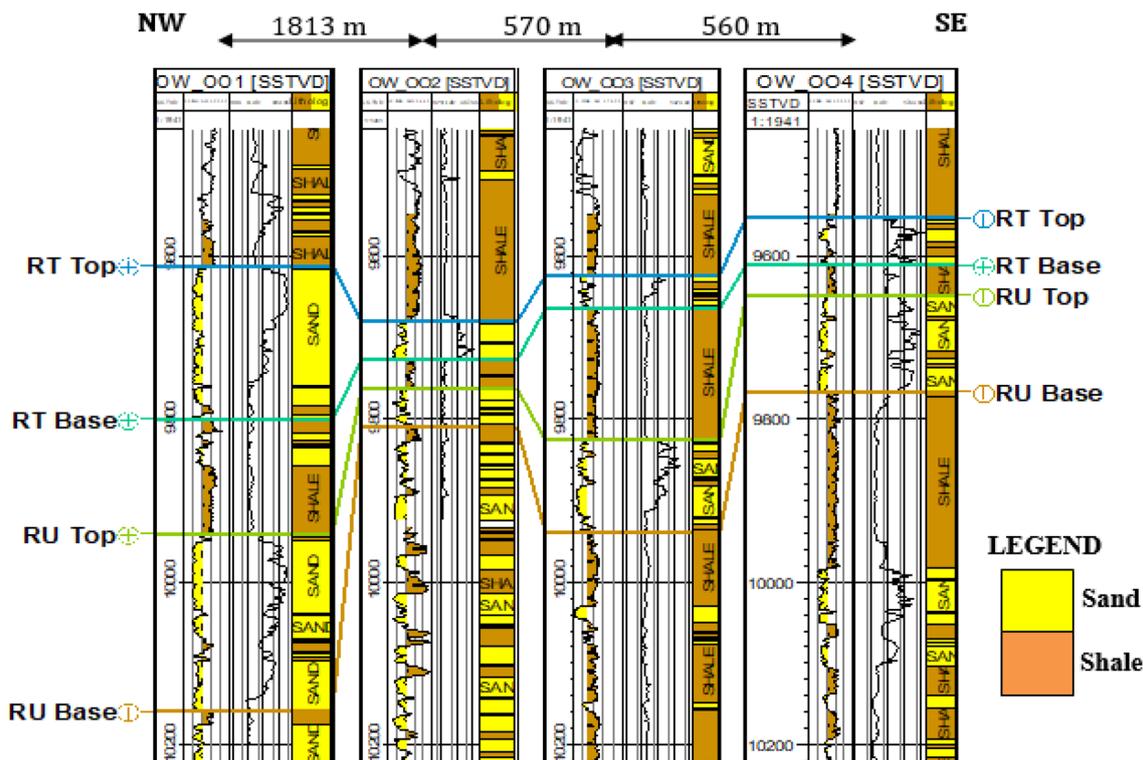


Fig. 4 Lithostratigraphic well correlation of reservoirs T and U along West–East direction

Table 1 Computed petrophysical parameters of the studied wells

Wells	Reservoirs	Gross thick-ness (m)	Net thickness (m)	V_{shale} (%)	Effective poros-ity (%)	Hydrocarbon saturation (%)	Permeability (md)
OW-1	Sand T	57.38	48.20	16	37	68	61,004.57
	Sand U	67.39	55.26	18	32	60	18,684.89
OW-2	Sand T	14.37	7.61	59	20	80	405.43
	Sand U	14.18	12.05	15	29	65	8376.49
OW-3	Sand T	12.27	11.53	6	30	80	11,042.22
	Sand U	34.62	30.82	11	31	66	14,425.01
OW-4	Sand T	17.89	16.64	7	39	80	93,690.35
	Sand U	36.08	32.11	11	28	65	6292.98

Table 2 Porosity and Permeability values for Reservoirs Qualitative Description (Rider 1986)

Qualitative evaluation of porosity		Qualitative evaluation of perme-ability	
Porosity (%)	Qualitative descrip-tion	Average km value (md)	Qualitative description
0.5	Negligible	< 10.5	Poor to fair
5–10	Poor	15–50	Moderate
15–20	Good	50–250	Good
20–30	Very good	250–1000	Very good
> 30	Excellent	> 1000	Excellent

Volume of Shale

The data obtained from gamma ray log was used to achieve this. The volume of shale (V_{sh}) was mathematically computed using Eq. 1 (Asquith and Krygowski 2004):

$$v_{sh} = 0.083(2^{3.7I_{GR}} - 1) \tag{1}$$

where I_{GR} can be estimated using Eq. 2.

$$I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \tag{2}$$

where GR_{max} is gamma ray maximum (shaly sand); GR_{min} is gamma ray minimum from clean sand; GR_{log} is gamma ray log (shaly-sand); I_{GR} is the gamma ray index.

Porosity

The porosity is a measure of the amount of internal space that is capable of holding fluid. It is expressed in percentage (%) (Asquith and Krygowski 2004). Porosity was estimated from the sonic log using Eq. 3:

$$\phi_{sonic} = \left(\frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \right) \tag{3}$$

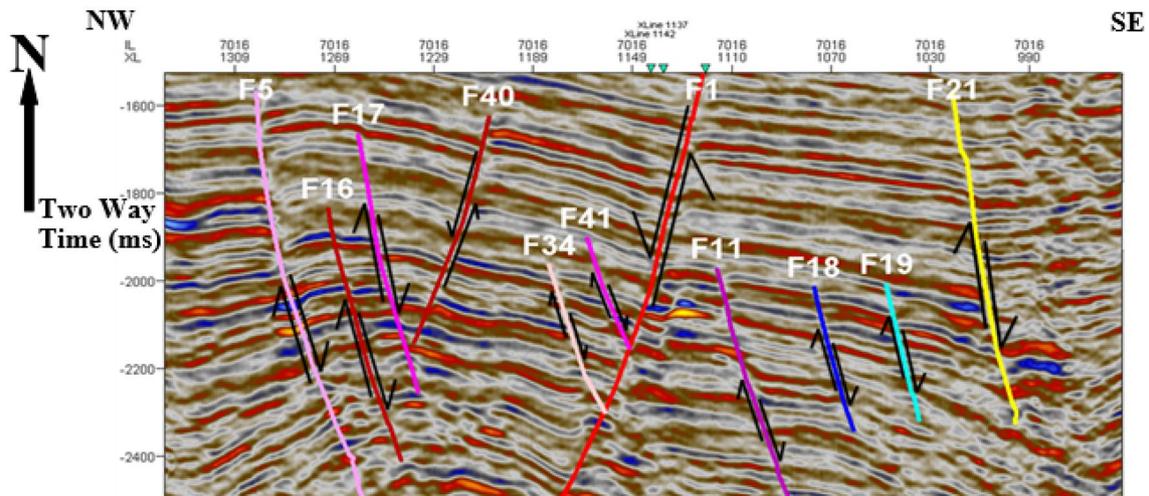


Fig. 5 Some of the faults mapped showing on inline 7016

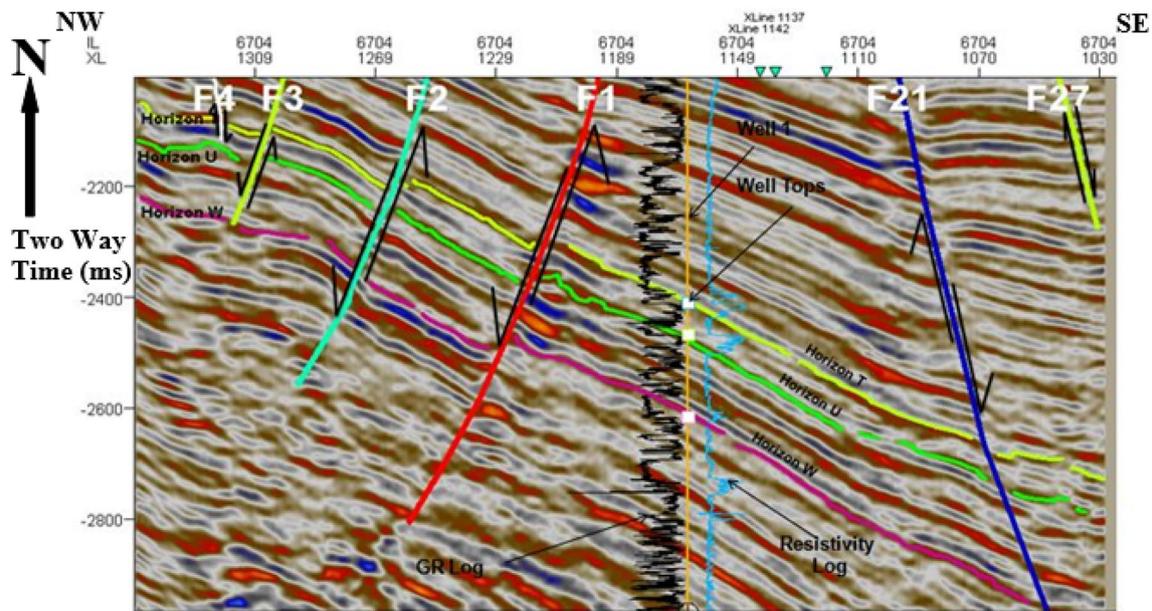


Fig. 6 Inline 6704 displaying horizons mapped, well tops and well log

Table 3 Computed throws of the two major faults F_1 and F_5

Horizon	Fault throw (F_1)		Fault throw (F_5)	
	ft	m	ft	m
T	159.57	48.64	93.73	28.57
U	155.38	47.36	157.06	47.87

where φ_{sonic} = Sonic-derived porosity; Δt_{ma} = Interval transit time of matrix; Δt_{log} = Interval transit time of formation; Δt_f = Interval transit time of the fluid in the well bore (fresh mud = 620 μ s/m salt mud = 607 μ s/m). The sonic log only records matrix porosity rather than fracture or secondary porosity.

Water Saturation (S_w)

Water saturated was estimated using Eqs. 4-6 (Archie 1942).

$$F = \frac{R_o}{R_w} \tag{4}$$

$$S_w^n = \frac{F \cdot R_w}{R_t} \tag{5}$$

$$S_w^2 = \frac{R_o}{R_t} \tag{6}$$

where S_w = water saturation; F = formation Factor; R_w = Formation water resistivity at formation temperature; R_o = Resistivity of formation at 100% water saturation; R_t = True formation resistivity; n Saturation exponent. This is usually two.

Hydrocarbon saturation

Hydrocarbon saturation (S_h) was calculated using Eq. 7

$$S_h = 1 - S_w \tag{7}$$

Permeability

Permeability was estimated using Eqs. 8 (Asquith and Krygowski 2004):

$$K = \left[\frac{250x\Phi^3}{S_{w\text{ irr}}} \right]^2 \tag{8}$$

where K = Permeability; Φ = Porosity; $S_{w\text{ irr}}$ = Irreducible water saturation.

3D seismic interpretation

Fault identification on the seismic section was centered on reflection discontinuity, vertical displacement of reflection, mis-closures in tying reflections around loops, sudden cessation of events and change in shape of events transversely the faults. The tops of petroliferous zones were tied to the

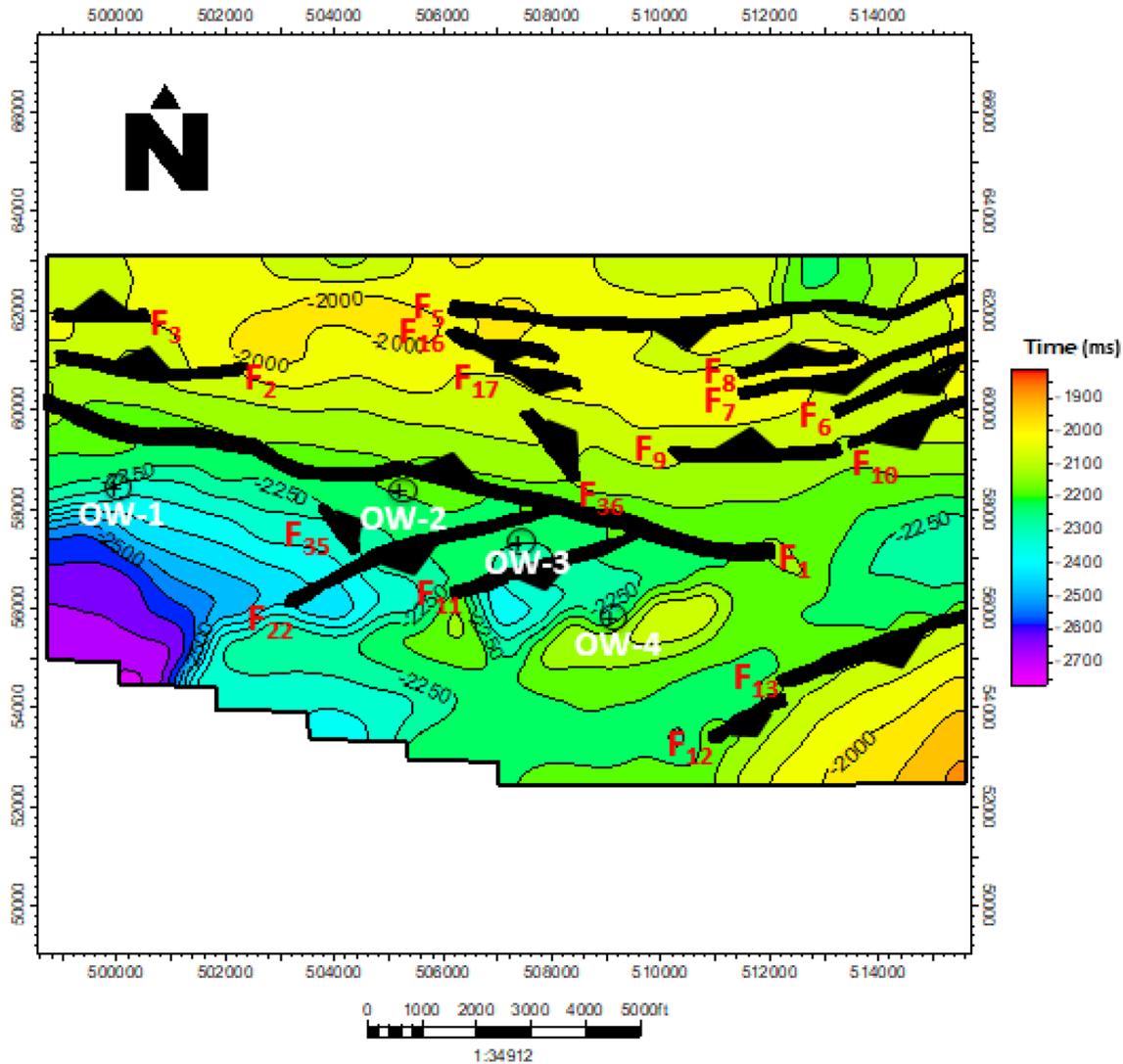


Fig. 7 Map of time-structure of horizon *T*

seismic section to identify two horizons (*T* and *U*) through seismic-to-well tie based on the continuity, event strength, amplitude and coherency and prospectivity. Two horizons were mapped across the 3D seismic volumes; and time, depth and attribute contour maps were generated for the horizons. Seismic attributes gives an idea of the vertical—lateral variations of the reservoirs in the subsurface. Having completed the horizon and fault mapping; an attempt to complement the conventional interpretation was undertaken using attribute analysis. The two attributes utilized were root mean square and maximum amplitudes.

Results and discussion

Well log data interpretation

Two reservoir sand bodies (Sand *T* and *U*) were delineated across the ‘Otan-Ile’ field from four wells: OW-1, OW-2, OW-3 and OW-4 (Fig. 4). The general stratigraphy comprised intercalation of sand and shale layers. The shale strata increase in thickness with respect to depth, while the sand layers decrease in thickness with depth. This is typical of rock sequence within the Agbada Formation (Anthony and Aurelius 2013; Akanji et al. 2018). The sand bodies thinning southeastern direction of ‘Otan-Ile’ field implying the direction of deposition or erosion as highlighted by (Caturanu 2006). The reservoir sand bodies’ gross thickness,

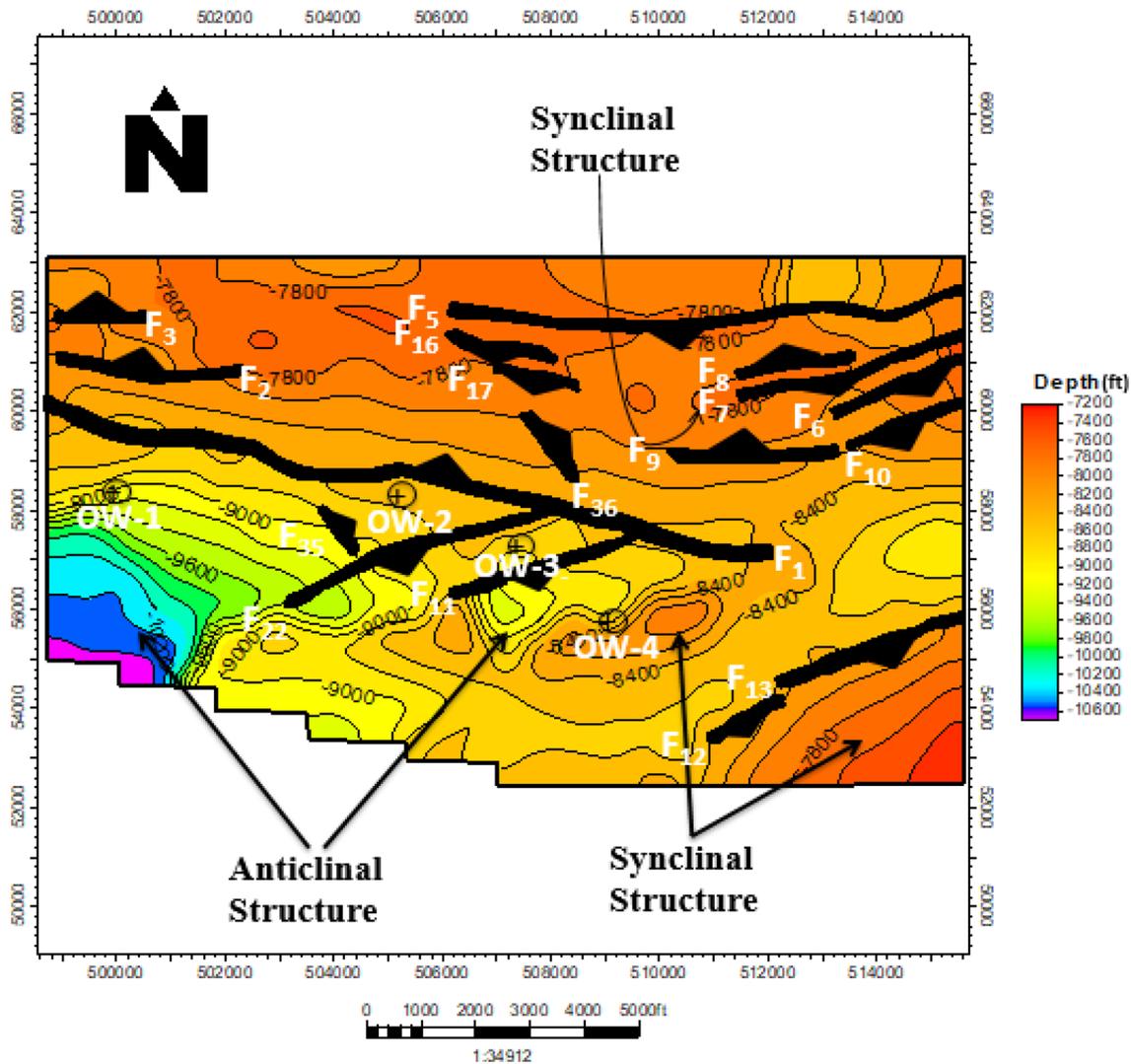


Fig. 8 Map of depth-structure of horizon T

net thickness, volume of shale, effective porosity, hydrocarbon saturation and permeability vary from 12.27–67.39 m, 7.61–55.26 m, 6–59%, 20–39%, 60–80% and 405.43–93, 690.35 md, respectively, across the field (Table 1). The average gross thickness of reservoir sand bodies across the wells is 31.76 m. The average effective porosity (31%) and permeability (26,740.24 md) of the field show it is viable in terms of porosity and permeability (Buller et al. 1970; Ibe and Ezekiel 2019). This plays a vital role in releasing of hydrocarbon

from the reservoir. The petrophysical parameters of this field have similarity with some of the works that had been carried out in Niger Delta (Adeoti et al. 2014; Adelu et al. 2016; Sanuade et al. 2018; Akanji et al. 2018). The porosity and permeability values of the field satisfied the porosity and permeability values for reservoirs qualitative description by Rider (1986) (Table 2). The field varies from very good to excellent in terms of porosity and permeability.

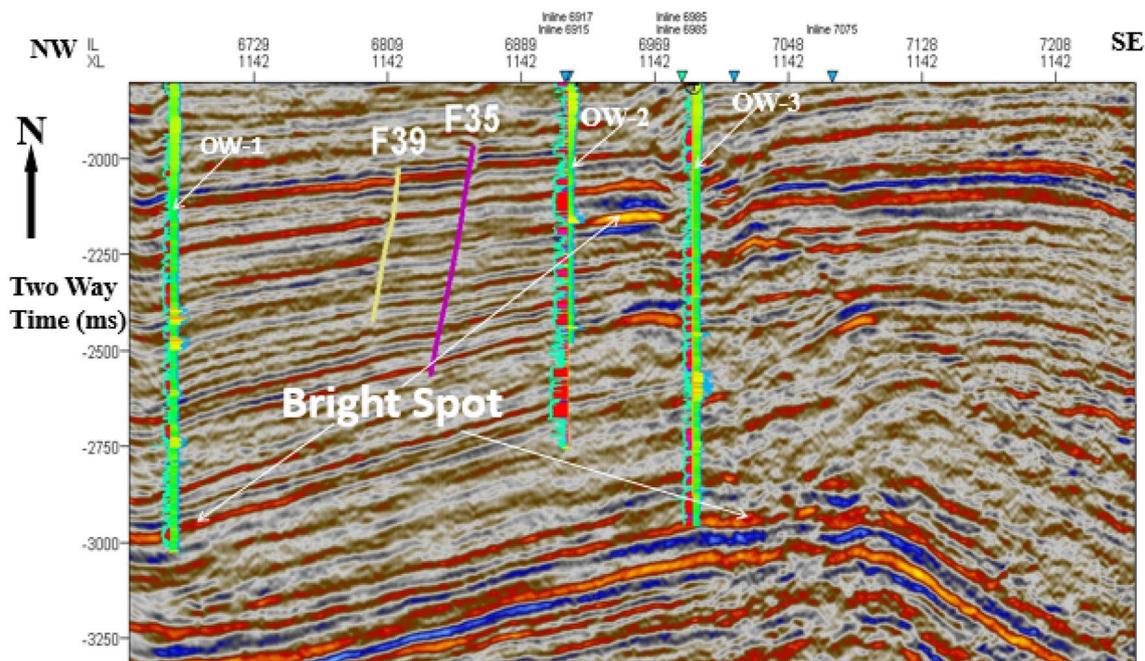


Fig. 9 Relative acoustic impedance attribute displaying the high amplitude (bright spots) as indicator of hydrocarbon

Seismic data interpretation

Faults F_1 , F_2 , F_5 , F_{17} and F_{21} are the major growth faults delineated in the ‘Otan-Ile’ field, while the minor faults are F_3 , F_4 , F_{11} , F_{16} , F_{18} , F_{19} and F_{34} (Fig. 5). Both antithetic (F_{34} and F_{41}) and synthetic (F_1) faults were identified in the field (Fig. 5). The throw of the major faults increases with depth, which may serve as migration path and the minor faults are characterized with small throws, which could be acting as a seal in the field. The faults could serve as trap and most of them form potential sites for thick sediment accumulation in the down thrown region as described by Short and Stauble (1967). Figure 6 has well OW-4 projected on to it, which validates that proper horizon was mapped and the extensiveness of the petroliferous layers.

Primary seal rocks in the Niger Delta are the inter-bedded shale within the Agbada Formation, the juxtaposition of reservoir sands against shale beds due to faulting creates good seal integrity (Doust and Omatsola 1990). The shale provides seals in the form of clay smears along these

syn-sedimentary faults and vertical fault seals in a compressive stress setting (Weber and Daukoru 1975).

The sealing capability of the faults is dependent on the amount of throws and shale/clay smeared along the fault planes (Busch 1975; Weber and Daukoru 1975). According to Weber and Daukoru (1975), faults can be sealing if either the throws are less than 492 ft (150 m), or the amount shale/clay smeared along the fault planes is greater than 25%. The average throws of the major faults F_1 and F_5 calculated are 134.88 ft (41.11 m) and 125.4 ft (38.22 m), respectively (Tables 3). Therefore, based on the amount of throws, faults F_1 and F_5 are sealing which is in agreement with the work by Weber and Daukoru (1975), signifying that in the Niger Delta, the soft and over-pressured Akata Shale, in most cases rise up to fill the fault zones, thus enhancing their sealing capabilities.

The time horizon map of Horizon T in Fig. 7 shows that the anticlinal structure observed on this surface is heavily faulted. Major faults associated with this structure are faults F_1 and F_5 . Faults F_{22} and F_{11} are antithetic to fault F_1 . Minor faults include faults F_2 , F_3 , F_6 , F_7 and F_8 . The

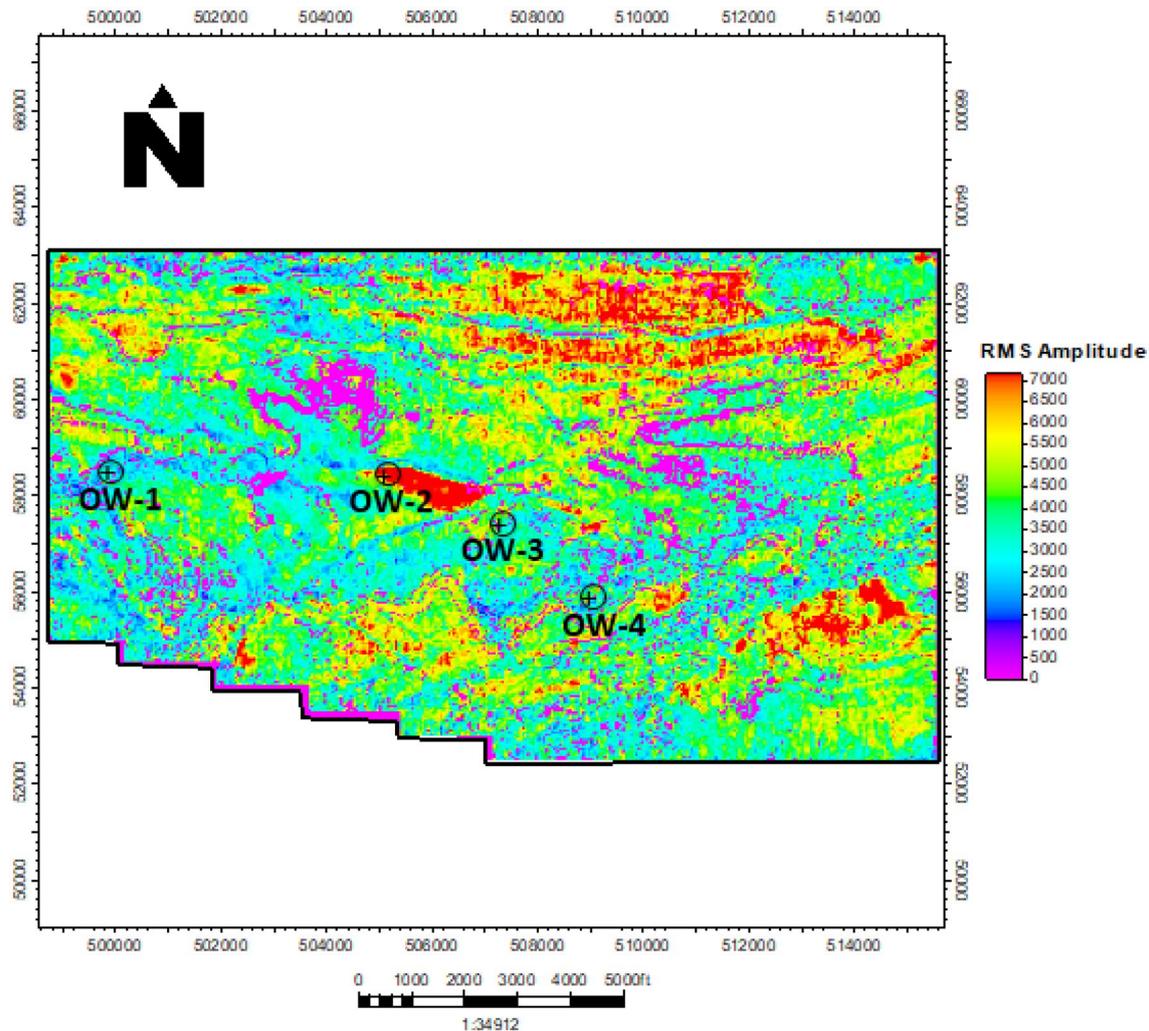


Fig. 10 Map of RMS amplitude attribute of horizon *T*

probable structures accumulating oil and gas in this field are fault-assisted closures. On the depth structural map (Fig. 8), the two major closures identified at southeastern region are structurally controlled, which are four-way closures. These two major structural closures possess efficient traps suitable for hydrocarbon accumulation. The potential of trapping in the “Otan-Ile” field can be attributed to faults and/or anticlines, acting either as fault aided or anticline closures correspondingly or both.

The relative acoustic impedance attribute, which is volume seismic attribute, shows areal range of the bright spots (sweet spots) of several seismic attributes determined for reservoir sand bodies (Fig. 9). The detected sturdy reflection

is a suggestive of reservoir rocks, which may be owing to the manifestation of hydrocarbons in the delineated layers (sands). It is observed here that, the existing wells target the observed bright spots for production, which supports the effectiveness of seismic attributes in optimal well placement.

Figures 10 and 11 show the root mean square (RMS) and maximum amplitude maps. The high amplitude form observed around the exiting well positions on the attribute maps indicate bright spot, which may be produced by a locally greater-than-normal velocity dissimilarity amid two strata or a decrease in the acoustic impedance from the overlying shale to the sand reservoir saturated with hydrocarbon. The high amplitude areas are in patches on the attribute

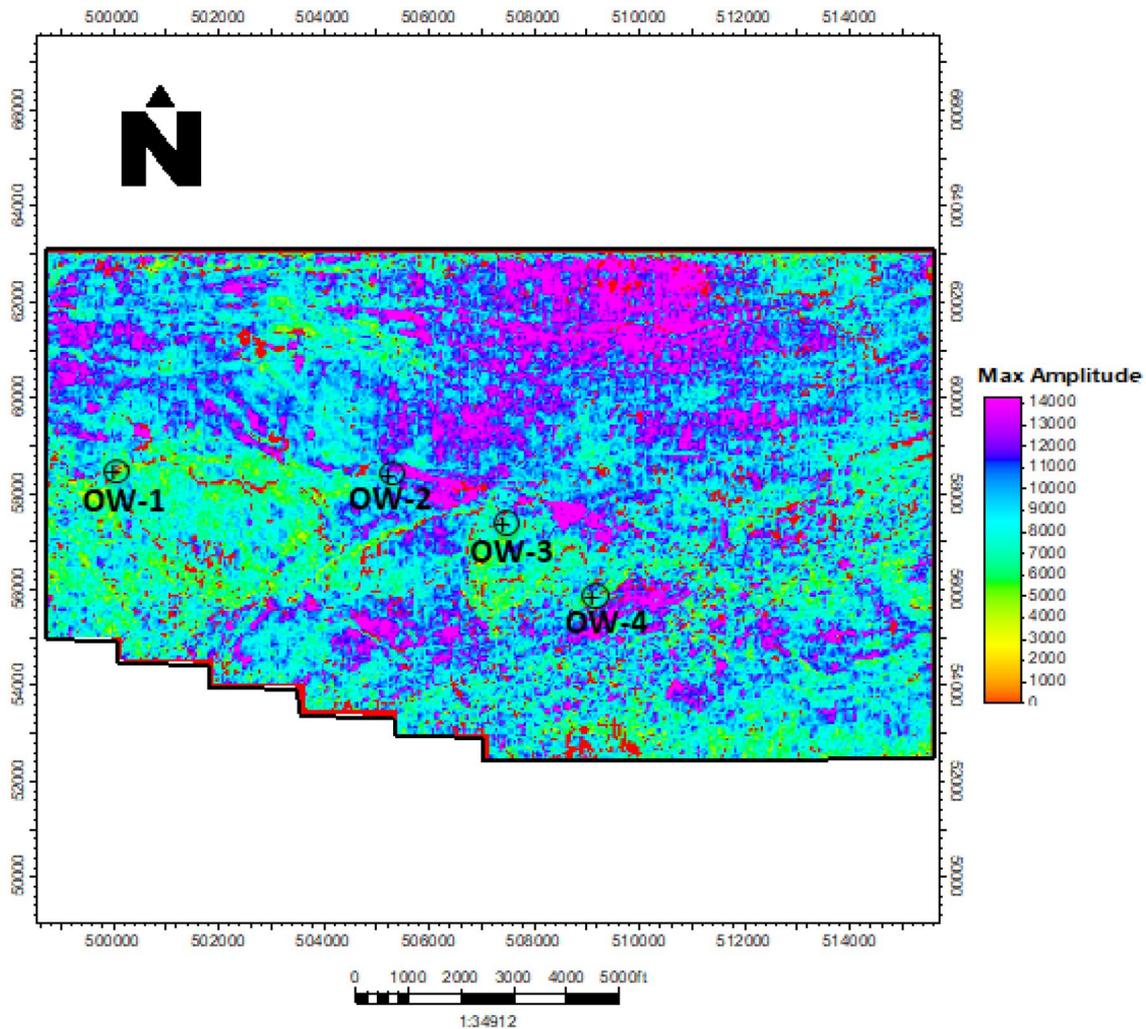


Fig. 11 Map of maximum amplitude attribute of horizon *T*

maps and it is more distinct at the northern part of the maps. It was observed that OW-2 lies directly on high amplitude. The behavioral pattern of amplitude distribution on maximum attribute conforms to the RMS map as distinct zones of anomalous amplitude in northern and central parts of the map were observed.

Figures 12 and 13 show the depth-structure maps superimposed on RMS attribute maps of the horizons. The bright spot (high amplitude) observed on the upthrown of one of the main structural building, major growth fault (F_1) and on the downthrown of the synthetic fault (F_9) supports the

outcome from the maps of depth overlaid on the map of amplitude. The closures observed on depth-structure maps conform to high amplitude.

Conclusion

The reservoir properties of the ‘Otan-Ile’ field in the transition zone, Niger Delta, have been characterized using 3D seismic and well log data. Two reservoir sand bodies were delineated crosswise the available wells. The estimated

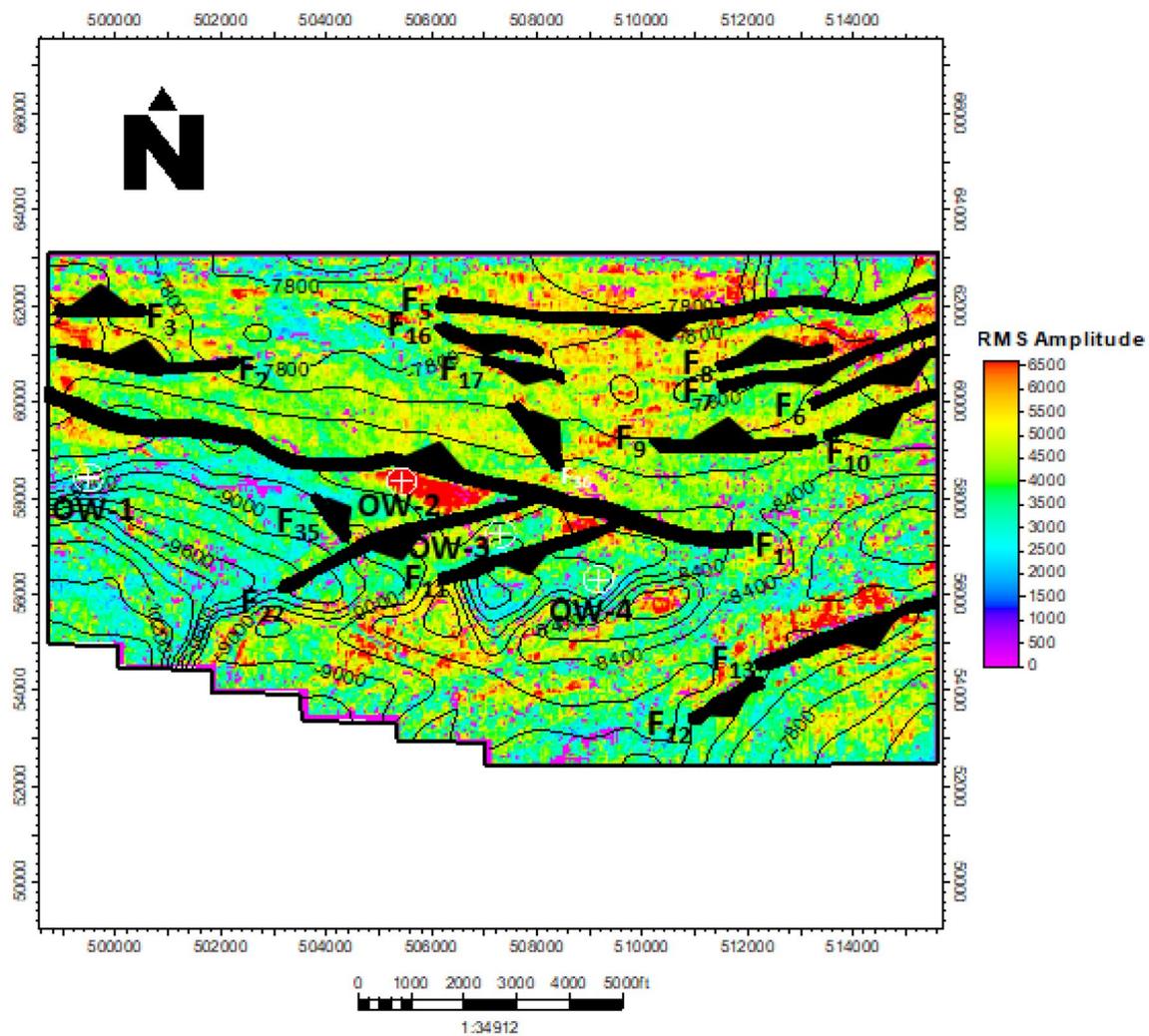


Fig. 12 Depth-structure map superimposed on RMS amplitude of horizon *T*

petrophysical properties show that the field is viable in terms of hydrocarbon production. The growth fault, F_1 nearly cut across the field and increases in throw with depth and could serve as trap for hydrocarbon in the field. The time and structural maps revealed the geometry of the subsurface and nature of hydrocarbon reservoir in the field, which are fault-assisted structural and anticlinal closures. The attribute maps generated conformed to the structural highs observed

on time and depth maps, which hereby validate the integrity of their interpretation. It has been shown from this study that the integration of 3D seismic and well log data can be used for hydrocarbon reservoir characterization and the information from this study would aid proper management of the reservoirs in the Otan-Ile field.

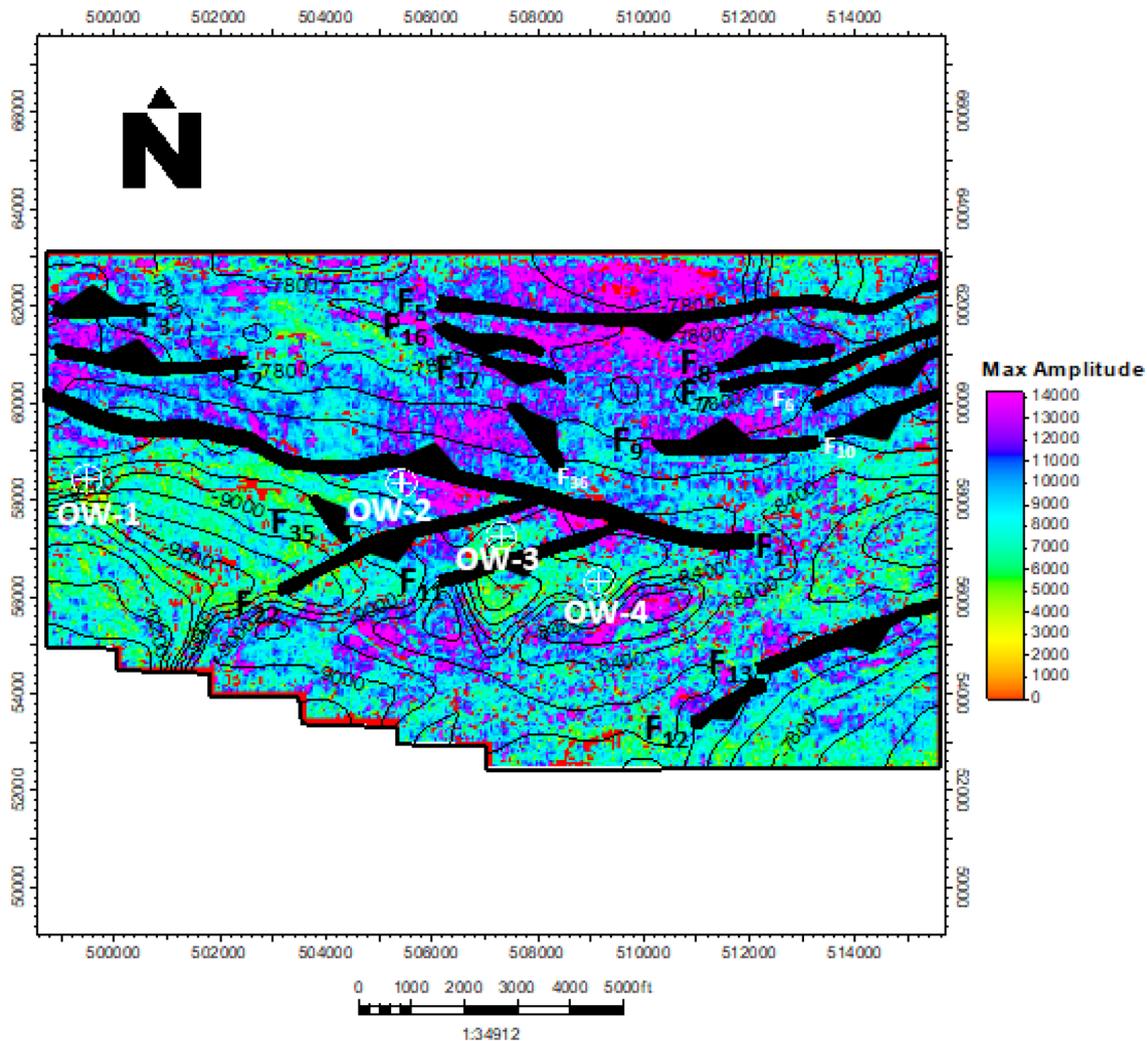


Fig. 13 Depth-structure map superimposed on maximum amplitude of horizon T

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Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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