



Characterization of reservoir sands using 3D seismic attributes in the coastal swamp area of Niger Delta Basin

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Abstract

Hydrocarbon accumulation and production within the Niger Delta Basin are controlled by varieties of geologic features guided by the depositional environment and tectonic history across the basin. In this study, multiple seismic attribute transforms were applied to three-dimensional (3D) seismic data obtained from “Reigh” Field, Onshore Niger Delta to delineate and characterize geologic features capable of harboring hydrocarbon and identifying hydrocarbon productivity areas within the field. Two (2) sand units were delineated from borehole log data and their corresponding horizons were mapped on seismic data, using appropriate check-shot data of the boreholes. Petrophysical summary of the sand units revealed that the area is characterized by high sand/shale ratio, effective porosity ranged from 16 to 36% and hydrocarbon saturation between 72 and 92%. By extracting attribute maps of coherence, instantaneous frequency, instantaneous amplitude and RMS amplitude, characterization of the sand units in terms of reservoir geomorphological features, facies distribution and hydrocarbon potential was achieved. Seismic attribute results revealed (1) characteristic patterns of varying frequency and amplitude areas, (2) major control of hydrocarbon accumulation being structural, in terms of fault, (3) prospective stratigraphic pinch-out, lenticular thick hydrocarbon sand, mounded sand deposit and barrier bar deposit. Seismic Attributes analysis together with seismic structural interpretation revealed prospective structurally high zones with high sand percentage, moderate thickness and high porosity anomaly at the center of the field. The integration of different seismic attribute transforms and results from the study has improved our understanding of mapped sand units and enhanced the delineation of drillable locations which are not recognized on conventional seismic interpretations.

Keywords Characterization · Reservoir sands · Seismic interpretation · Seismic attributes · Stratigraphic feature · Niger delta basin

Introduction

Reservoir characterization is a model that describes and evaluates reservoir, and its subsurface features, based on its ability to store and produce hydrocarbon. The description and evaluation of these subsurface features, in terms of structure, stratigraphy and reservoir properties, from conventional interpretation of seismic data is always challenging because the complexity of the subsurface to seismic wave propagation (Chopra and Marfurt 2005; Nasser 2020). An idea to fully identify and evaluate these features on seismic data is by emphasizing on the individual component of the

seismic wave in terms of the arrival time, frequency, amplitude, and attenuation through seismic attribute analysis. Sub-surface quantitative interpretations require seismic attributes to supplement conventional seismic reflection amplitudes (Rinks and Jauffred 1991; Lefeuvre and Wrolstad 1995).

Reservoir properties such as the geometry, sand thickness, sand/shale ratio, porosity, permeability, and water saturation define the accumulation and production of hydrocarbon in a field. Seismic attributes describe these reservoir properties by giving derivatives of quantities extracted from the seismic data (Chen and Sidney 1997) to relate the seismic wave's event directly or indirectly to geology. As such, seismic attributes analyze subsurface heterogeneity by describing its geomorphology (Chen et al. 2020; Fengming et al. 2018; Karbalaali et al. 2018; Schneider et al. 2016), facies changes (Bueno et al. 2014; Chinwuko et al. 2015; Wang et al. 2017) and physical properties (Dupucy et al. 2016; Ogiesoba et al.

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2019; Nawaz et al. 2020) in terms of quality, quantity, and area extent. Seismic attributes analysis has been efficient, over the years, for geomorphology analysis (Bailey et al. 2016; Karbalaali et al. 2018) qualitative and quantitative interpretation (Torrado et al. 2014; Ngoc et al. 2014; Bhat-tacharya and Verma 2020; Malik et al. 2020) of hydrocarbon fields. The application and efficiency of seismic attributes for stratigraphic features characterization is emphasized by the works of Chopra and Marfurt (2005, 2008), Cuesta et al. (2009), Vohs et al. (2015), Roden et al. (2016), Zhao et al. (2016), Jie et al. (2017), Othman et al. (2018), Xing et al. (2019), Adekunle et al. (2020) among others.

The Agbada Formation of the Niger Delta Basin has been the largest producer of oil and gas in Nigeria. The control of the accumulation and production of this hydrocarbon are numerous and include variety of geologic features depending on the depositional history and tectonic activities across the basin. “Reigh” field is a field located within the transition zone of Niger Delta basin. The field, according to Numair et al. (2017), is one of the environments that hold vast hydrocarbon resources due to the heterogeneity and different generic hierarchy of the stratigraphic architecture. The location of the field within the shallow marine environment poses the possibility of presence of subtle stratigraphic and combination plays. In this research, seismic attributes analysis was applied to delineate geologic features capable of harboring hydrocarbon within the field. The basic idea was to use multiple seismic attributes sensitive in evaluating the geomorphology, facies distribution patterns, and high hydrocarbon productivity areas within the field. From the analysis, suitable locations for exploitation activities were identified based on their reservoir properties.

Location and geology of the study area

The field under consideration is an onshore oil field in the Niger Delta Basin, located in the south-western part of Nigeria. The major rock types of the Quaternary are sandstone, pebbles, and shale (Fig. 1) and it is within the abandoned beach ridges, which is in the Coastal Swamp area of Niger Delta Basin. The structure present in the field is composed of growth faults and large collapsed crest rollover anticline trending East–West.

Niger Delta Basin is in the continental margin of the Gulf of Guinea in equatorial West Africa, occupying an approximated area of 300,000 km² (Kulke 1995). As described by Petroconsultants (1996), the onshore part of the Niger Delta Province is delineated by the geology of southern Nigeria and southwestern Cameroon. The offshore boundary of the province is within the Cameroon volcanic line to the east and the eastern boundary of the Dahomey basin to the west (Tuttle et al. 1999). The deeper Niger Delta is defined by

the outcrops of the Cretaceous. In the Eocene, a switch in coastline occurred (Reijers et al. 1997), thereby changing the course of sediment deposition, resulting in long shore drift causing delta progradation from wave dominated sedimentation. Also, starting from the Eocene, growth fault bounded depobelts were created as the delta progrades. These depobelts have been subdivided into five by (Reijers 2011) as the Northern Delta depobelt, Greater Ughelli depobelt, Central Swamp depobelt, Coastal Swamp depobelt and offshore depobelt. The stacked succession of regressive sediments deposition from Eocene to Present resulted into the formation of threefold diachronous siliciclastic lithostratigraphic units (Reijers 2011; Doust and Omatsola 1990; Short and Stable, 1967). Starting from the deepest, these formations include the basin’s source rock, which is of marine shale Akata Formation. Overlain by Akata formation is the Agbada Formation with a characteristic intercalation of shale and sand. Finally, overlaying the Agbada Formation is the Benin Formation (alluvial and upper coastal plain sands). The sands within the Agbada Formation have been the target for hydrocarbon reservoirs in the Niger Delta Basin.

Materials and method

3-D post-stacked seismic data comprising of 320 Inlines and 380 crosslines with 25 m line spacing was used as input data. Two (2) reservoir sands (sand A and sand B), with thickness between 85 and 200 ft, were defined from borehole log. The petrophysical parameters of the delineated sands were calculated using empirical petrophysical parameters, that is, volume of shale (V_{Shi}), effective porosity (ϕ_e) and water saturation (S_w) were determined using Steiber (1984), Dresser Atlas (1979) and Poupon and Leveaux (1971) equations, respectively. Well log to seismic tie was done to tie as accurate as possible the information of well logs to the seismic section using check-shot data of the boreholes. Horizon tracking was carried out by identifying equivalent horizons of the delineated reservoir sands and mapping the horizons on 3-D seismic sections of the field. Horizon mapping of the sand bodies across the field was followed through by creating horizon maps of the delineated sand bodies. Seismic attributes generation and analysis (Dewett et al. 2021) was gone on the 3D seismic data of the field. Three key steps were involved for the seismic attribute analysis, (1) defining the geomorphology of the sand units using geometrical attributes (Taner et al. 1994; Zhai and Pigott 2020), which are seismic time related; (2) analyzing seismic facies distribution and reservoir properties using physical attributes (Taner et al. 1994; Qi et al. 2020), that are frequency related; and (3) evaluating the hydrocarbon potential of the sand units, using physical attributes that are amplitude related.

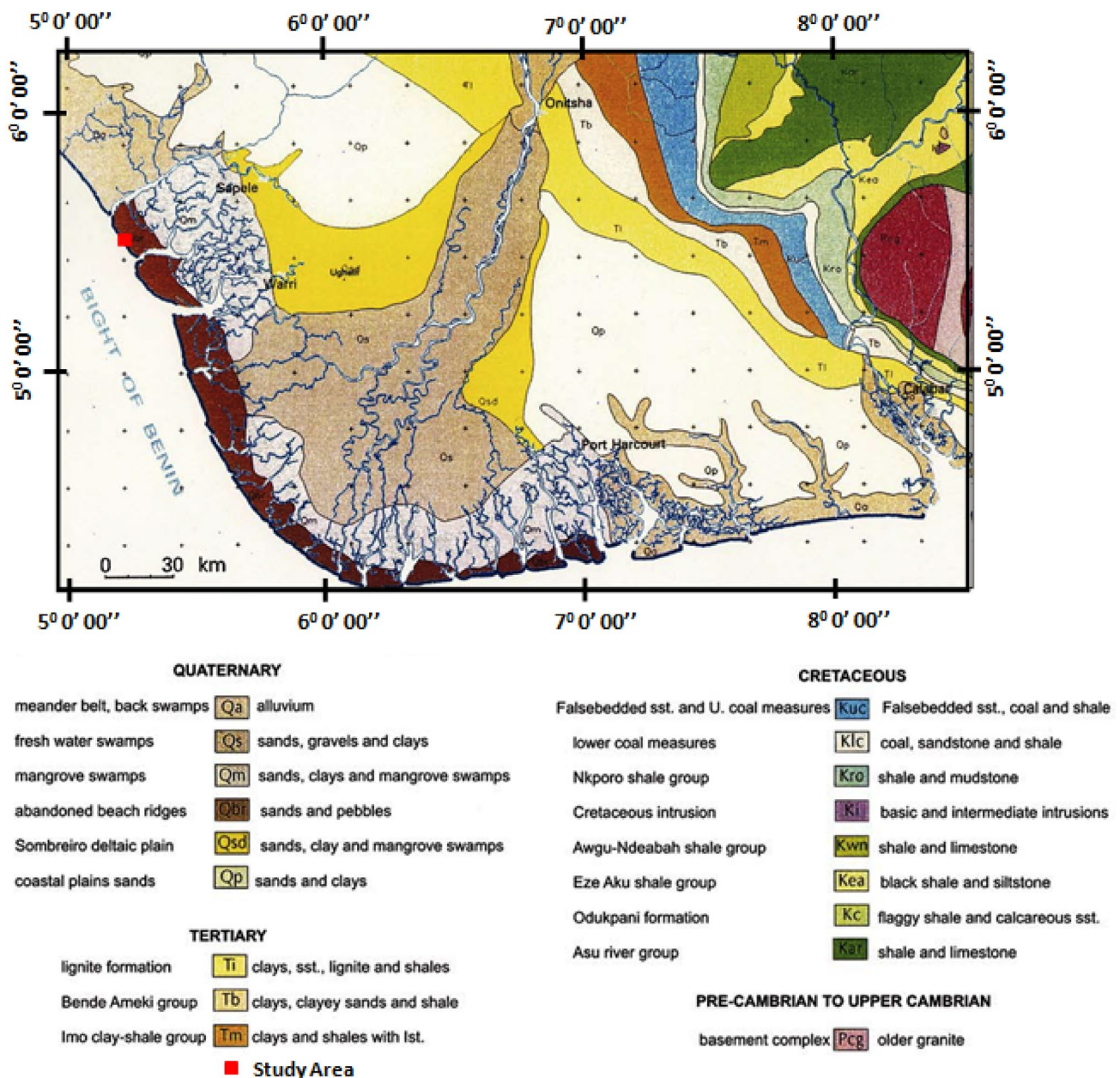


Fig. 1 Geological map of Niger Delta and surroundings showing the Study Area (After Reijers 2011)

These generated seismic attributes were used to produce time attribute maps, frequency maps and amplitude maps to assist in the structural, stratigraphic and fluid properties interpretation of the delineated sand bodies respectively. Seismic structural interpretation was carried out to identify and ascertain the conformity of the interpreted geologic features with structure. In doing this, depth structure maps of the delineated sand bodies were produced by using the time-depth relationship of the boreholes' check-shot data. The results were then compared to optimize the results of the interpreted reservoir properties.

Results and discussion

Petrophysical summary

Table 1 gives the computed petrophysical parameters of the studied sands. From Table 1, it was deduced that the sands' Volume of shale (V_{sh}) accounts for up to 25% in some areas within the field. Effective porosity of the sand units is ranged from 16 to 35%. This effective porosity range is considered sufficient to influence reservoir

Table 1 Computed petrophysical parameters of the studied sands

Well		TVD (ft)	Gross Res (ft)	V_{sh} (%)	ϕ_e (%)	S_h (%)	Fluid
004	Sand B	5155	58	11	23	–	Wet
	Sand A	5536	117	16	22	88	Oil
005	Sand B	5289	78	12	26	–	Wet
	Sand A	5780	151	15	16	–	Wet
006	Sand B	5331	83	10	–	–	Wet
	Sand A	5815	156	12	–	–	Wet
008	Sand B	5115	70	10	29	–	Wet
	Sand A	5575	130	16	32	90	Oil
011	Sand B	5242	68	14	23	–	Wet
	Sand A	5672	163	16	23	72	Oil
019	Sand B	5280	60	23	23	–	Wet
	Sand A	5710	120	16	28	82	Oil
021	Sand B	5225	58	13	28	–	Wet
	Sand A	5690	102	25	27	–	Wet
029	Sand B	5175	60	10	27	–	Wet
	Sand A	5575	115	12	35	90	Oil
032	Sand B	5329	81	9	29	–	Wet
	Sand A	5821	166	13	27	–	Wet
036	Sand B	5310	86	8	29	–	Wet
	Sand A	5825	151	14	26	–	Wet
038	Sand B	5211	79	14	28	78	Oil
	Sand A	5745	175	11	29	75	Oil
046	Sand B	5438	50	9	27	80	Oil
	Sand A	5950	130	17	36	81	Oil
056	Sand B	5330	90	12	28	–	Wet
	Sand A	5800	147	15	28	–	Wet

TVD=Total Vertical Depth, V_{sh} =Volume of Shale, ϕ_e =Effective Porosity, S_h =Hydrocarbon Saturation, – = No pay sand

hydrocarbon productivity according to Bullet and Konen (1970) classification. The sands have moderate to low water saturation value resulting to maximum hydrocarbon saturation value between 72 and 90%.

Seismic attributes analysis

Figure 2 a and b shows the display of geomorphology of sands A and B respectively using coherence attribute. Geomorphological features identification is an important element in seismic interpretation (Karbalaali et al. 2018). This is because these features control hydrocarbon accumulation in a reservoir by serving as hydrocarbon traps and/or seals. Seismic data coherence property is great in highlighting these features and most widely used (Feng et al. 2018). Coherence attribute is a geometrical 'time-related' attribute, measuring trace-by-trace seismic amplitudes similarities by computing a localized, normalized cross-correlation of adjacent traces, hence identifying geomorphological features. The narrow bands of low coherence values on the map (Fig. 2 a and b) are created by seismically resolved features

such as fault and fractures that disrupt the lateral continuity of the reflection event. High coherence value indicates high similarities around geologic features of the same physical properties. Interpretation on Fig. 2 shows intense faulting. It was observed that most of the faults strike NW–SE direction.

Extracted instantaneous frequency maps of the sand units (Fig. 3a and b) give facies distribution in terms of overall sand thickness and sand percentage. Instantaneous frequency is generally used for facies distribution as regards lithology and sand percentage (Ogiesoba et al. 2018), as well as abnormal attenuation and thin beds (Liyuan et al. 2019). This was possible because instantaneous frequency represents the average frequency of the amplitude spectrum of seismic wavelet. An increase in density of a medium due to the presence of shale in a reservoir increases its instantaneous frequency hence analyzing shale/sand distribution. Likewise, at higher frequencies, there is always an increase in the vertical resolution and as such, highlighting thin reservoir layers. Thickness decreases with increase in instantaneous frequency (Ogiesoba et al. 2018). Observations on Fig. 3a shows that the center of the field was mapped by lower

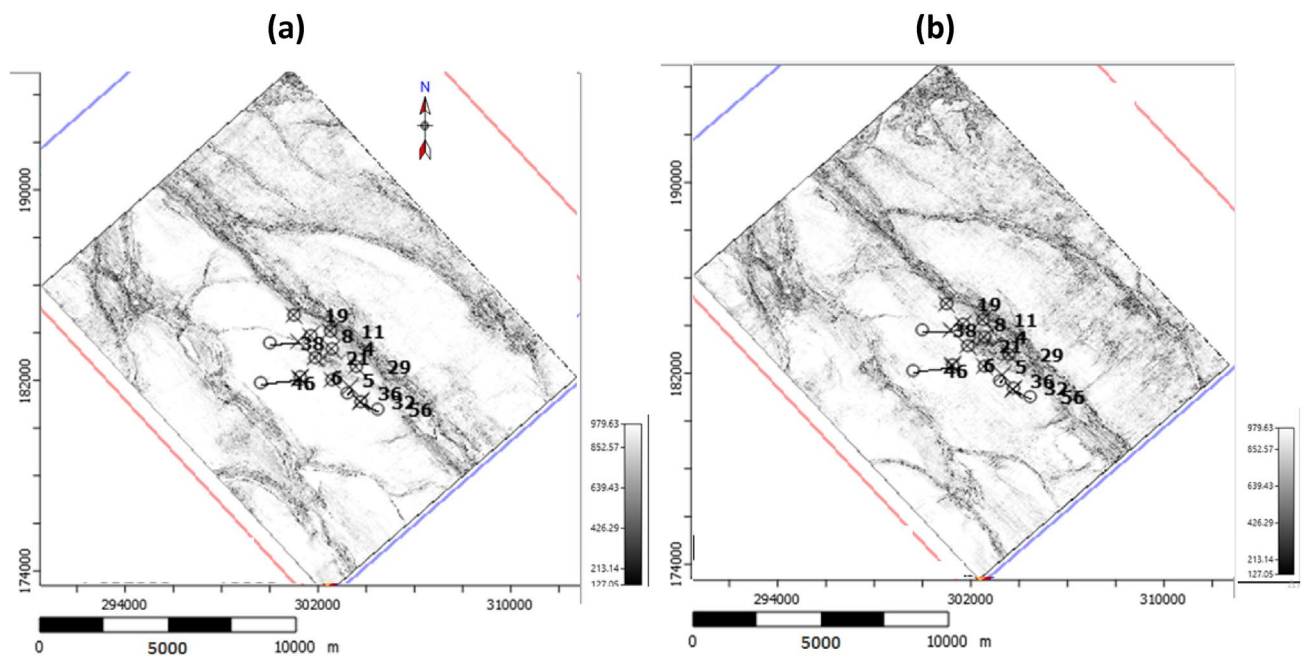


Fig. 2 Coherence Seismic Attributes showing the structural complexity the Study Area: **a** Sand A; **b** Sand B. Seismically resolved faults delineated by low coherence values

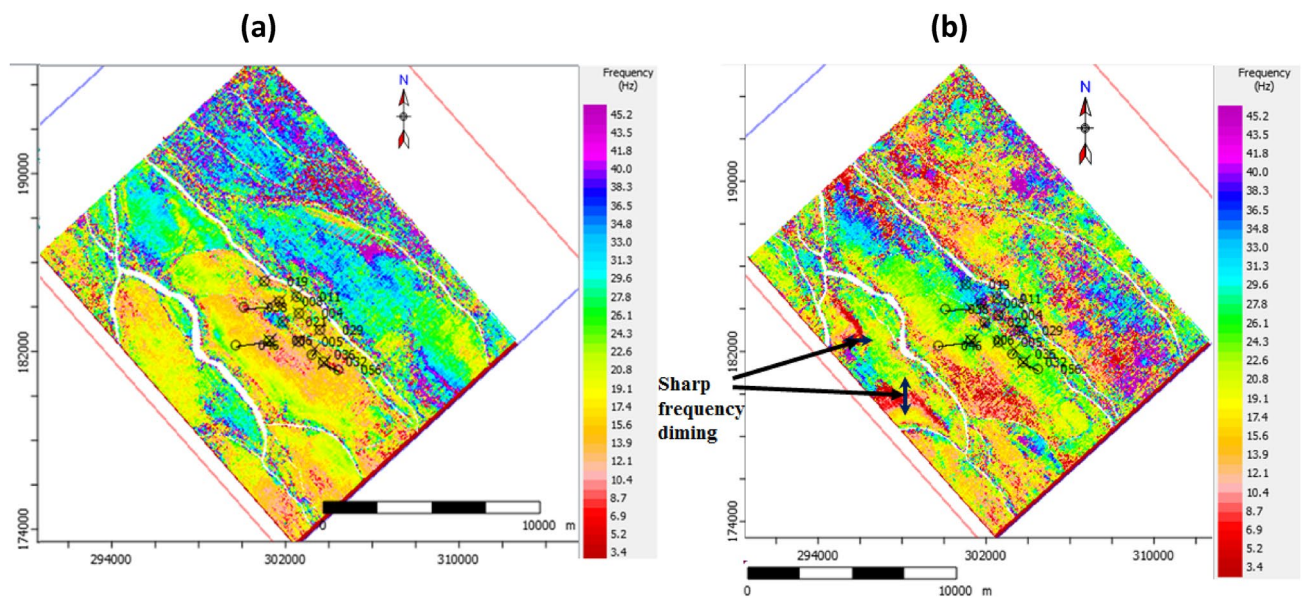


Fig. 3 Instantaneous Frequency Attribute showing the facies change on: **a** Sand A, Southwestern part consists of sands with less volume of shale and less sand thickness. **b** Sand B, sharp frequency dimming

indicating abrupt change in sand percentage and thickness observe in the southwestern part

frequency range 8 to 16 Hz, indicating that this part comprises of substantially thick facies compared to its surroundings. It was also observed that the thickness at the center of the field is controlled by the eastern bounding growth fault. It was observed on Fig. 3a that the southwestern part consists of sands with less volume of shale, and thickness of the

reservoir sand increases towards the southwestern part with decrease instantaneous frequency. On Fig. 3b, gradual frequency dimming was observed in the eastern bounding fault at the center of the field. This was interpreted as decrease in the amount of shale in the sand body with decrease frequency and it was confirmed by the Vsh interpretation of

the penetrated sand bodies (Table 1). Also, facies distribution in the area (Fig. 3b), revealed irregular thickness of the reservoir down to the southern part. A significant feature was observed at the southwestern part of Fig. 3b from the sharp frequency dimming, indicating sudden change in facies in terms of thickness and sand percentage. This sharp frequency dimming is an indication of stratigraphic play around the area. The characteristic frequency dimming at this part of the field distinctively analyzes the thickness and the amount of shale in the stratigraphic body.

Figure 4 gives the hydrocarbon potentials of the delineated geologic features using Instantaneous frequency attribute. This was done by analyzing the amplitude changes and relating them to possible change in subsurface porosity within the sand units. Instantaneous frequency attribute measures reflectivity of seismic events, as such, high porosity is inferred at high reflectivity (also referred to as bright spots). Figure 4a reveals two main characteristic display of high and low amplitude areas, indicating high and low porosity respectively. Along the western part of the major fault at the center of the field (Fig. 4a), bright amplitude anomalies (P1) were observed. The bright amplitude anomalies are reflection surface resulting from matrix fluid contact on the surface of the sand unit. All the wells penetrated through this reservoir at this point (P1) have high porosity averaged 28% and moderate water saturation averaged 19% (Table 1). Two other high reflectivity anomalies (P2 and P3) were identified on Fig. 4a, which could serve as hydrocarbon prospects for

hydrocarbon exploitation. Figure 4b highlights two prospect zones (P4 and P5) with high instantaneous amplitude. The prospect zone P5 on Fig. 4b coincides with the previously identified stratigraphic feature on Fig. 3b. This confirms the possibility of prospect P5 (Fig. 4b) for hydrocarbon exploitation, if structurally conformable. Prospect P6 is an amplitude anomaly identified within the structural high part of Fig. 4b.

Figure 5 is the Root Mean Square (RMS) amplitude attribute maps of the sand unit to confirm the high amplitude anomaly identified on Fig. 4. RMS attribute are extracted from a user-defined time window generally on a picked time horizon. It measures the acoustic intensity of a seismic wave. In a less dense medium, the intensity is expected to be high compared to a dense medium. Since the amplitude of the wave determines its intensity, this attribute was used to compliment the instantaneous amplitude attributes as high RMS attribute indicates spatial correlation to porosity. High magnitude reflection strength observed as prospects P1, P2, P3, P4, P5 and P6 in Fig. 4 corresponds to bright amplitude response observed on Fig. 5. Since both figures measures the seismic reflectivity of the subsurface, the higher the amplitude, the higher the porosity and the better the hydrocarbon productivity of the reservoir unit.

From the stratigraphic geometry of the hydrocarbon prospect (Fig. 5), the depositional process/stratigraphic deposits were identified on the basis of reflection termination and lateral changes in seismic reflection amplitudes. The preserved facies along and across the field in the northern and

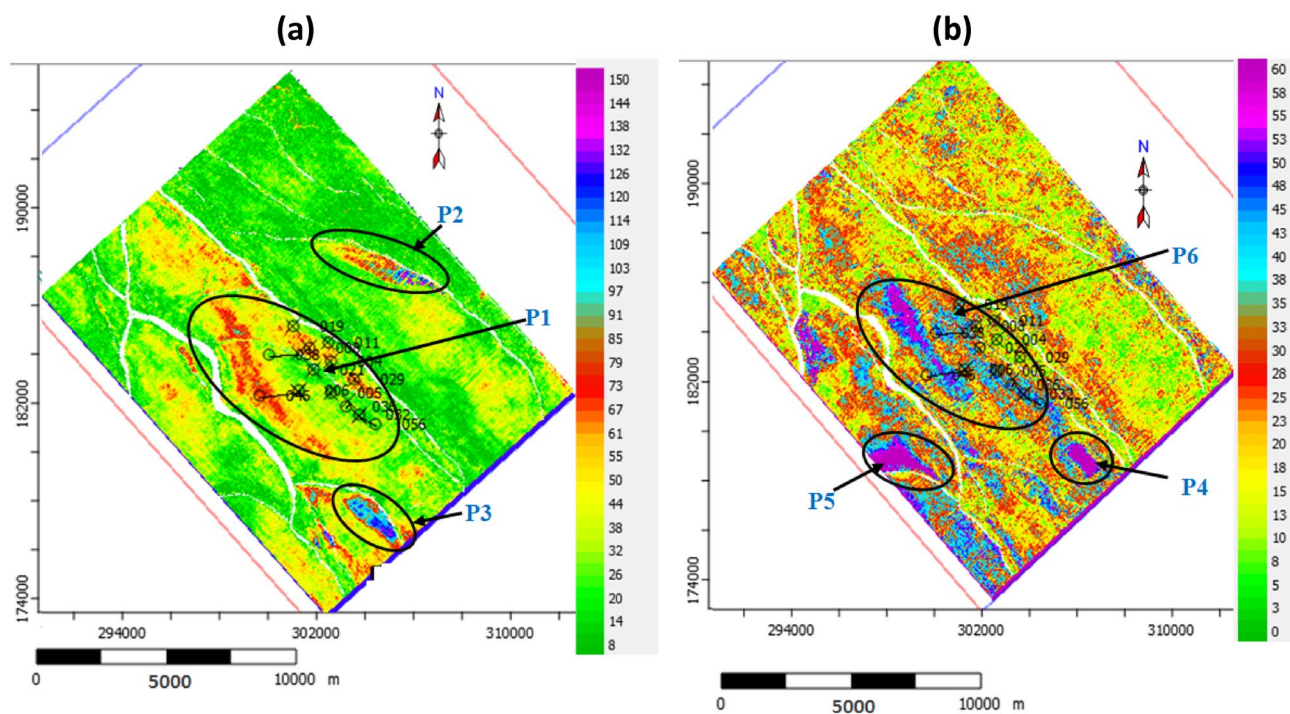


Fig. 4 Hydrocarbon Potential Analysis using Instantaneous Amplitude for porosity mapping **a** Sand A; **b** Sand B

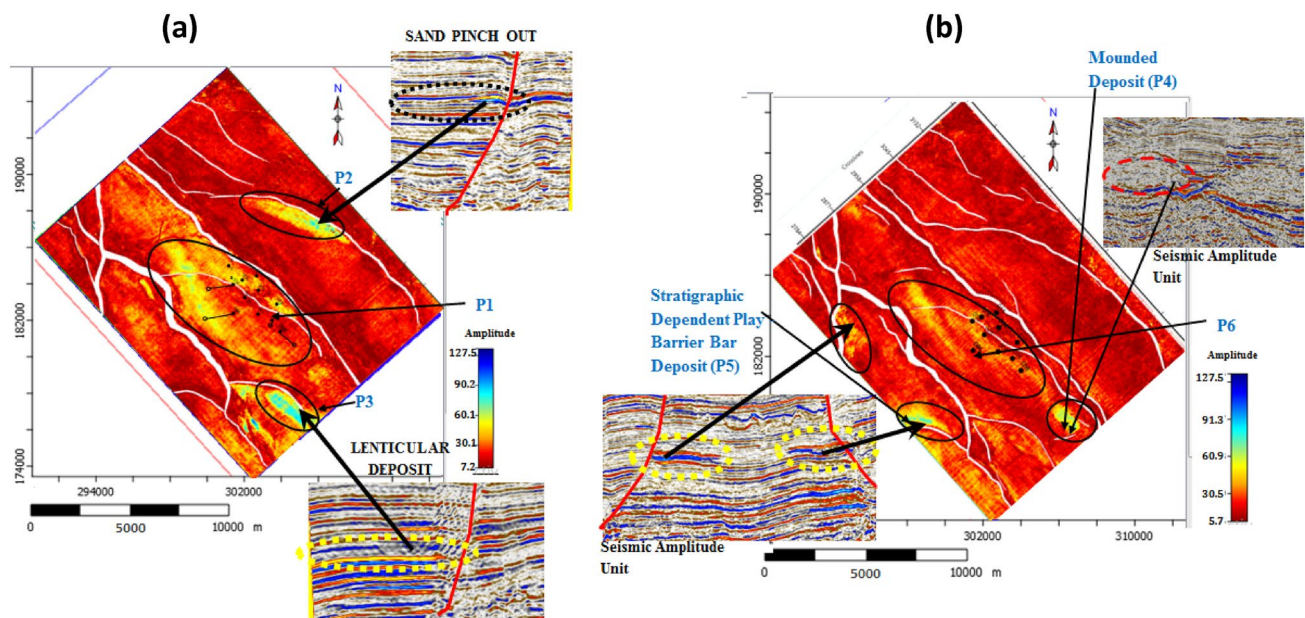


Fig. 5 Hydrocarbon Potential Analysis using RMS Amplitude for porosity mapping, with their corresponding description on seismic amplitude unit of **a** Sand A; **b** Sand B

northeastern part is mainly aggradational (building-up) while that in the southwestern and southern parts are progradational (building-forward). On the basis of the observation on the seismic reflection amplitudes of Fig. 5, P2 is a seaward pinch-out terminating against one of the major faults of the study area at the western part of Fig. 5a. This pinchout (Fig. 5a) represent SW thinning segment of a confined sand deposit within the field. Hydrocarbon prospect, P3, is lenticular in nature. The hydrocarbon prospects have high reflectivity indicating high porosity as interpreted on both the amplitude attributes (Fig. 4a and Fig. 5a). The combined interpretation of the attribute maps and seismic amplitude units (Figs. 3b, 4b and 5b), assisted in interpreting hydrocarbon prospect P4 as a mounded sand deposit and hydrocarbon prospect P5 as a barrier bar, having good reservoir quality in terms of moderate thickness, high sand/shale ratio and high porosity.

Seismic structural interpretation

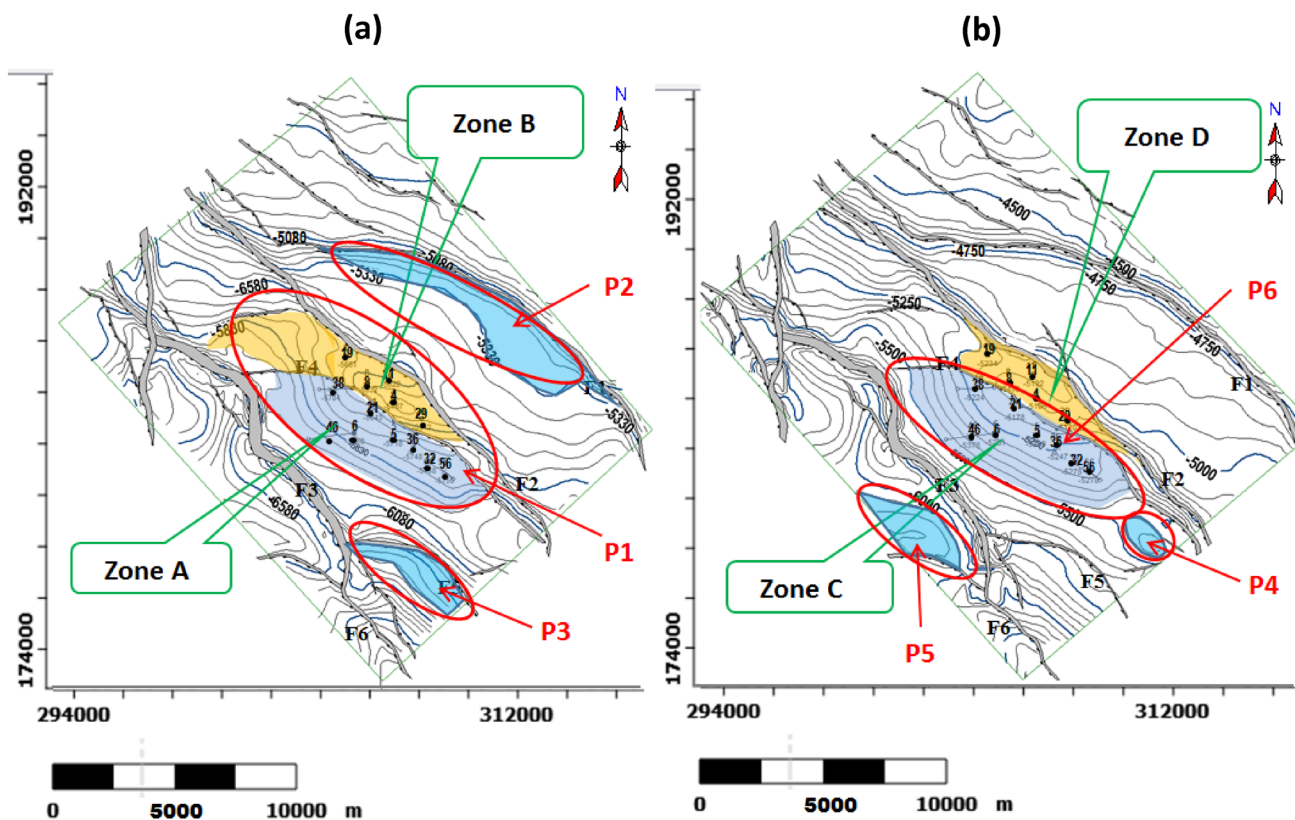
Figure 6 is the depth structural map of sand units used in evaluating the conformity of the delineated prospects with structure. The contour lines on Fig. 6a is between -5100 and -6600 ft, while that on Fig. 6b is between -4500 and -6000 ft. The geometry of the reflector indicates direction of sediment deposition being from the north-eastern part to the south-western part of the study area. Three major growth faults (F1, F2 and F3) trending approximately NW–SE were interpreted, while the other faults are synthetic and antithetic faults to the major growth faults. These growth faults strike

in approximately NW–SE direction and the faults are parallel to sub parallel to each other. The major faults and their corresponding synthetic faults dip towards the western part of the study area, therefore these faults are considered extensional.

Observations in the central part of the field of study (Fig. 6) show structural highs bounded to the north by one of the major faults which define the field of study. An intra-reservoir fault, which is synthetic in nature, was interpreted to divide the geologic structural high into two, forming three-way fault assisted (zone A) and two-way fault assisted (zone B) closures on Fig. 6a (prospect P1) and three-way fault assisted (zone C, prospect P6) and two-way fault assisted (zone D) closures on Fig. 6b. The structural high part on Fig. 6a and Fig. 6b are considered viable prospects P1 and P6 respectively as they are attributed with low shale volume and moderate sand thickness (Fig. 3), and high porosity anomaly (Fig. 4, and Fig. 5). Prospects P2 and P3 with high amplitudes are structurally conformable (Fig. 6a), which makes the prospects geological feasible amplitude anomalies. The two hydrocarbon prospects (P2 and P3) were interpreted as thick with P3 substantially thick and of great extent compared to P2 (Fig. 3a). Also, prospects P4 and P5 conform to structure (Fig. 6b) and indicate high porosity and possible presence of hydrocarbon.

Conclusion and recommendations

The research was carried out to delineate geologic features capable of harboring hydrocarbon within Reigh Field. Two (2) reservoir sands (sand A and sand B) were delineated



Contour Interval = 50 feet

- LEGEND**
- Fault
 - Well Location
 - Contour Value
 - Well Number

Fig. 6 Depth Structure map showing the positions of the hydrocarbon prospects on a Sand A, b Sand B

from the study area. Petrophysical summary of the boreholes in the field revealed that the delineated sands have gross reservoir thickness between 50 and 175 ft, moderate to low sand/shale ratio ranged 8 to 25%, effective porosity ranged from 16 to 36% and hydrocarbon saturation between 72 and 92%. The integration of coherence, instantaneous amplitude, instantaneous frequency, and RMS amplitude attributes of the delineated sands has led to the characterization of the field for the possibility of stratigraphic plays. Geomorphology interpretation of the reservoir sand units revealed major control of hydrocarbon accumulation of the study area being structural, in terms of fault and its associated rollover anticline, stratigraphy has a minor contribution. Simultaneous mapping of various seismic attributes

has helped in highlighting subtle stratigraphic and structural features such as faults, pinch-out, mounded deposit and barrier bar. Seismic attributes analysis has also demonstrated that this technique can be used effectively to understand the sand thicknesses and lateral facies distribution in the area.

Six hydrocarbon prospects, which are: stratigraphic pinch-out terminating against a major fault (hydrocarbon prospect P2); lenticular thick hydrocarbon sand (hydrocarbon prospect P3); mounded sand deposit (hydrocarbon prospect P4); barrier bar deposit (hydrocarbon prospect P5); and prospective structurally high zones (prospects P1 and P6) were delineated for possible hydrocarbon exploitation in “Reigh” Field. The reservoir properties of these delineated hydrocarbon prospects were compared with the reservoir

properties interpreted from the existing wells, using seismic attribute signatures, and adjudges appropriate for hydrocarbon exploitation. The interpretation and assessment of the field revealed that the most exploitable hydrocarbon prospect area is in the southwestern part based on the efficient reservoir qualities in terms of low shale/sand ratio, good sand thickness, high porosity, and efficient hydrocarbon saturation, as interpreted from seismic attributes transforms of the field. However, further work is recommended to be concentrated on the identified exploitable part of the field with the intention to upgrade the area into drillable prospect by estimating its reserve. Therefore, to effectively evaluate the prospects, geostatistics is required to predict reservoirs properties from areas with well control to the prospect areas.

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Data availability Available upon request.

Declarations

Conflict of interest On behalf of all the co-authors, the corresponding author states that there is no conflict of interest.

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