AN INTEGRATED ANALYSIS OF WELL DATA & MULTI 3D SEISMIC ATTRIBUTES FOR RESERVOIR CHARACTERIZATION AND FORMATION EVALUATION A CASE STUDY OF DEEP JURASSIC-CRETACEOUS SANDSTONE RESERVOIRS, OFFSHORE ROVUMA BASIN, MOZAMBIQUE

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Abstract

The offshore Rovuma basin, northern Mozambique is the study area location. Actually it is a passive margin. The depositional settings of Rovuma basin consists of syn-rift Triassic-Jurassic (200-145Ma) and post-rift Cretaceous-Ne-ogene (145-2.6Ma) sedimentary deposits including the sand facies of the Rovuma Delta complex. Multiple tectonic episodes syn-post depositional took place and the Ibo High Structure growth orientated to (N-S) and the bathymetrical feature, the Davie Ridge are the ancient geological deepest structures (Key et al, 2008). This Research Project was designed for geochronostratigraphic identification of the poroperm lithofacies, characteristics and evaluate the potential controlling factors of distribution throughout the study area. The lower Cretaceous (Hauterian-Albian) holds poroperm (phi ~ 12-32%, K ~ 30-100mD) sandstones reservoirs which are characterized as well sorted, fine-grained sandstone, roundness: angular-sub-angular, clasts: quartz, k-feldspar, plagioclase, amphibole, completely apparent matrix density and transition cement type: limestone-dolomite whereas the upper Jurassic (Oxfordian-Tithonian) are tight sandstone reservoirs and hold the lowest poroperm properties with highest limestone apparent matrix density and cement type (compatible plots and projected throughout the well section evaluation, swc, petrographic and thin-section analysis). The 3D seismic multi attributes which are the spectral decomposition (SDE/SDT), relative acoustic impedance (RAI), trace envelope (TE), Root Mean Square (RMS), Semblance and Curvatures (-ve; +ve), RMS at windows of -+25ms to -+50ms and SDE 8-32Hz applied for the TS1 and Karoo horizons slices enhanced the geospatial lobate, isolated overbank, fans and sheets reservoirs shape/geometries distribution. The SDE at 32Hz brought up thinner fan sand facies shapes/geometries associated with small channels. Thus, the western to eastern meandering and straight single and multiple submarine channels control the geochronostratigraphic sand facies deposition and distribution into mud-sand rich to mud rich systems from the upper Jurassic to lower Cretaceous. The depositional environments (EODs) which tie with the sand facies distribution are the middle-outer Neritic (upper Jurassic) to upper bathyal (lower Cretaceous) whereas the reverse faults and three groups of normal faults: NW/SE, NNW/SSE and NNE/SSW associated with strong lateral lithofacies changes trap and compartmentalize the sandstone reservoirs in the study area.

Keywords: Rovuma basin, geochronostratigraphic distribution, lower Cretaceous, western and eastern, poroperm sand-stone reservoirs.

1. Introduction

The Mozambique basins have become an important attraction for hunt oil and natural gas fields. So far, Mozambique holds huge natural gas under production in southern part of the country. Recently have been reported discoveries of more than 200Tcf of dry natural gas found in the northern part of Mozambique basins (Rovuma basin) which has increased interests for the exploration projects.

1.1. Geological Settings

Actually it is a passive margin. The depositional settings of Rovuma basin consists of syn-rift Triassic-Jurassic (200-145Ma) and post-rift Cretaceous-Neogene (145-2.6Ma) sedimentary deposits including the sand facies of the Rovuma Delta complex. Multiple tectonic episodes syn-post depositional took place and the Ibo High Structure growth orientated to (N-S) and the bathymetrical feature, the Davie Ridge are the ancient geological deepeststructures (Key et al, 2008) (Figure1.).

The northern part of the basin includes

depositional complex of the Rovuma Delta (ECL, 2000).

1.2. Location of study area, constraints and aims

The study area is located at southern part of Rovuma basin, offshore Mozambique. Rovuma basin is a passive margin system and lies at the southern end of the extensive East African comprising the coastal plains of Somalia, Kenya, Tanzania and Mozambique.

The northern part of Mozambique, it covers an area of approximately 29,500 km2, of which 17,000 km2 is onshore and 12,500 km2 offshore (ECL, 2000).

Owing to the unsuccessful results from two wells: Cachalote 1&1A which the 1A is the deviated from the Cachalote 1 and Búzio 1 in the study area (Figure1) of the Rovuma basin northern part, brought into being evidence of constraints related to the reservoirs characteristics and lithofacies associated with unknown geochronostratigraphic distribution of the poroperm deepwater sandstone reservoirs and their controlling factors within the upper Jurassic to lower Cretaceous.

Hence, identification, evaluation, characterization of deep sandstone reservoirs, and assessment of potential factors under which are controlling the distribution poroperm lithofacies is the matter of aim designed for this Research Project. Therefore, to carry out this study, the following dataset were used: well information wireline logs (LAS and reports), petrographic (reports), SWC (photos and reports), geochemistry and biostratigraphic (LAS and reports) and 3D seismic PSTM.

1.3. Objectives for the upper Jurassic to lower Cretaceous study are to:

- Analyze the apparent matrix density, cement types and geochronostratigraphic distribution of the poroperm lithofacies;
- Evaluate the external shape/geometries types of the reservoirs and predict the potential pay zones;

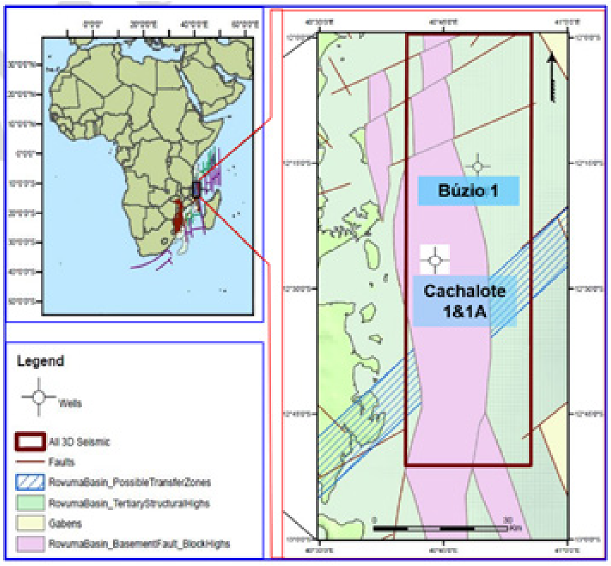


Figure 1. Location of Study area, offshore Rovuma basin, Mozambique. Cachalote 1&1A are the Research control data according to the available legacy 3D seismic and well data coverage.

- Examine the process(es) which is (are) controlling the geographical sandstone reservoirs distribution;
- Identify the geochronostratigraphic distribution of potential poroperm sandstone reservoirs.

2. METHODOLOGY

To fulfill the upper Jurassic to lower Cretaceous study so that achieve the aim and objectives designed for this research an integrated analysis of geology, petrophysics and geophysics results were the key. Geological well data analysis and formation evaluation was used as techniques for well logs analysis and petrographical re-evaluation using thin-section and side wall cores.

To enhance the sand facies geochronostratigraphic distribution throughout the study area, first were generated synthetic seismogram for the Cachalote 1 and 1A wells and tied to 3D seismic signatures and map subsurface horizons slices and analyze 3D seismic multi attributes so that enhance sand geographical distribution.

3. GEOLOGY AND PETROPHYSICS

3.1. Facies analysis

In order to enhance closely the sand facies changes geochronostratigraphycally in upper Jurassic to lower Cretaceous interval throughout Cachalote 1 and 1A wells and upscale them broadly to the study area based on the closest seismic characters.

Therefore, to achieve objectives the following wireline logs neutron porosity (NPHI), density (RHOB), acoustic impedance (AI), deep resistivity (RD), gamma ray (GR) were used using IP 4.3 software.

Facies analysis (Figure 2 and 3) were based on GR, RHOB and NPHI logs. The GR however shows highest values (0-250) API owing to the radioactive elements abundance throughout the study area (ECL, 2000) and hence the following cutoffs were defined: GR <= 100 API

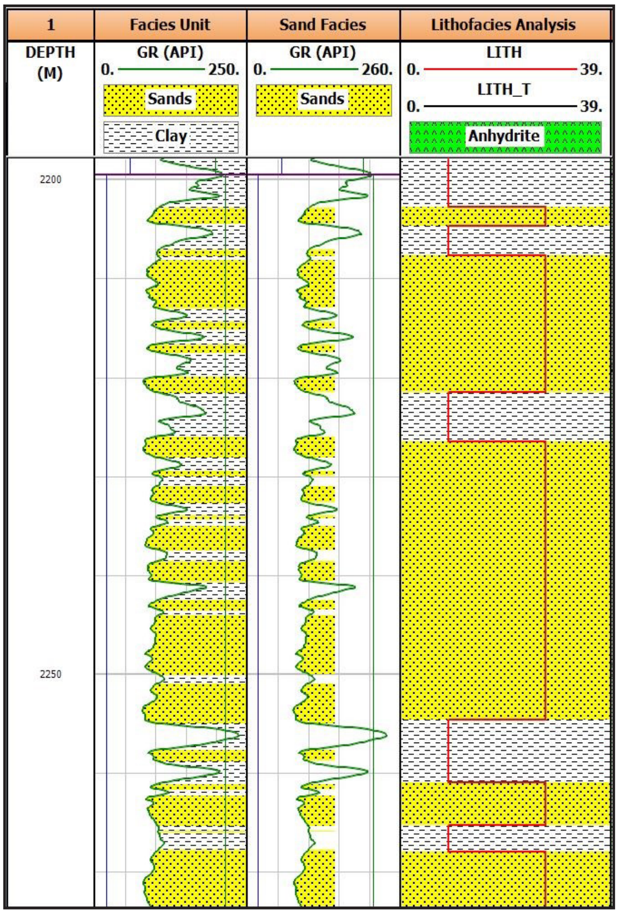


Figure 2. Cachalote 1. Lower Cretaceous sand facies occur as stacked within clay rich units. Cachalote 1A shows similar sand facies trend.

1 Geochonostratigraphic is a term used in this Research Project meaning the geographical (spatial) and chronostratigraphic (time scale) correlations and distribution of the lithofacies in the study area.

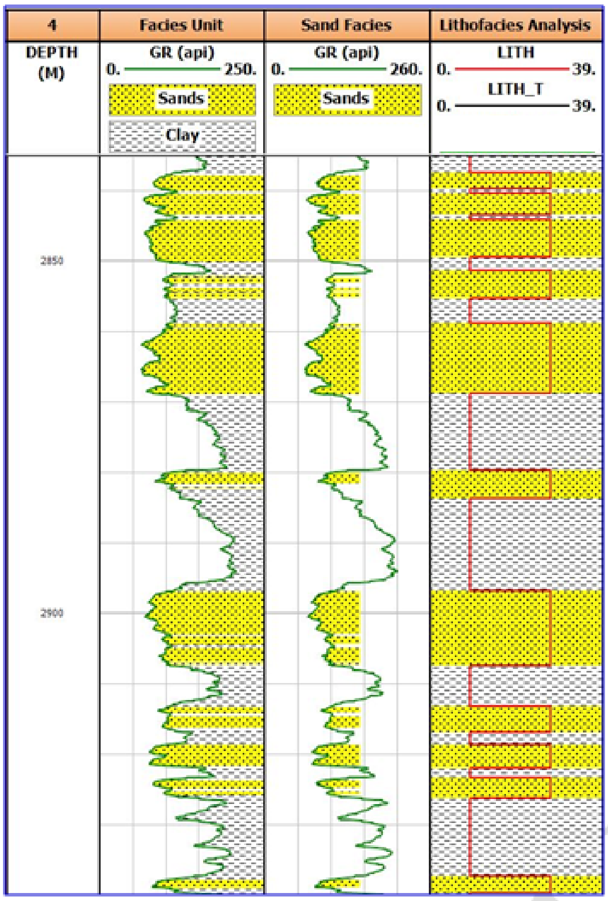


Figure 3. Cachalote 1A. Upper Jurassic sand facies occur as stacked within clay rich units. Cachalote 1A shows similar sand facies trend.

for sand facies and GR >= 100.1 API for clay facies, respectively.

Furthermore, using the GR patterns, SWC, petrographic and biostratigraphic re-analyzed data and reports show that, in the study interval is abundantly dominated by clay units and the sand facies occurrence outcome as single and stacked units (Figure 2 and 3).

3.2. Formation Evaluation

3.2.1. Thin-section analysis

The Cachalote 1 and 1A lithofacies are quite similar and the lower Cretaceous (earliest Hauterian-Albian) sandstones reservoirs are characterized as well sorted, fine-grained sandstone, roundness: angular-sub-angular, clasts: quartz, k-feldspar, plagioclase, amphibole, completely carbonate cemented (limestone-dolomite transition) whereas the upper Jurassic (Oxfordian-Tithonian) sandstone reservoirs consist of sand facies poorly sorted, fine-grained, matrix supported, roundness: angular to sub-angular, clasts: quartz, k-feldspar, plagioclase, mica, clay matrix, pyrite, carbonate cement) (Figure 4.1 and 4.2).

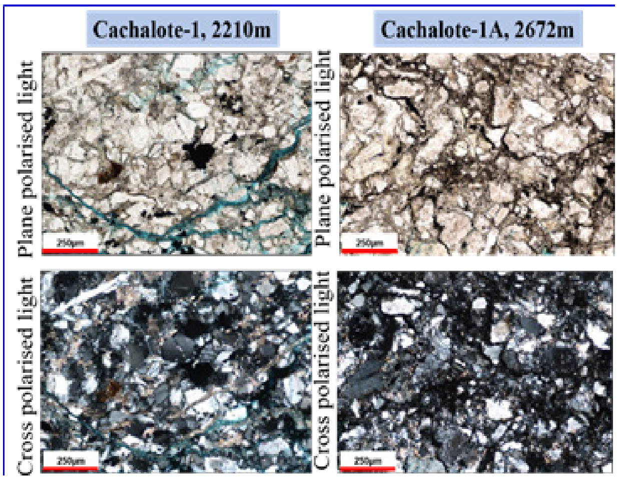
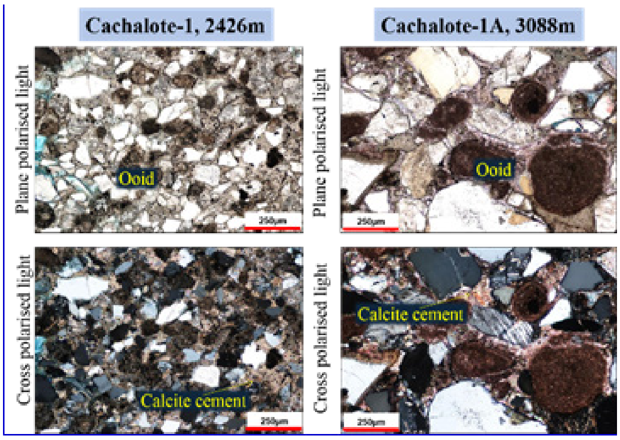


Figure4.1. Cachalote 1A, lower cretaceous.



3.2.2. Apparent matrix density and cement type distribution

Compatible crossplots: neutron porosity (NPHI) and density (RHOB) and additional plots using gamma ray (GR) and acoustic impedance (AI) were plotted so that evaluate the apparent matrix density, cement types and geochronostratigraphic distribution throughout upper Jurassic and lower Cretaceous within the Cachalote 1 and 1A.

As result, the lower Cretaceous (Aptian-Albian) shows that, had been affected by highest carbonate (limestone-transition to dolomite) fluid flow which have greatly changed the depositional matrix density and poroperm properties of the lithofacies (Figure 5.1and 5.2).

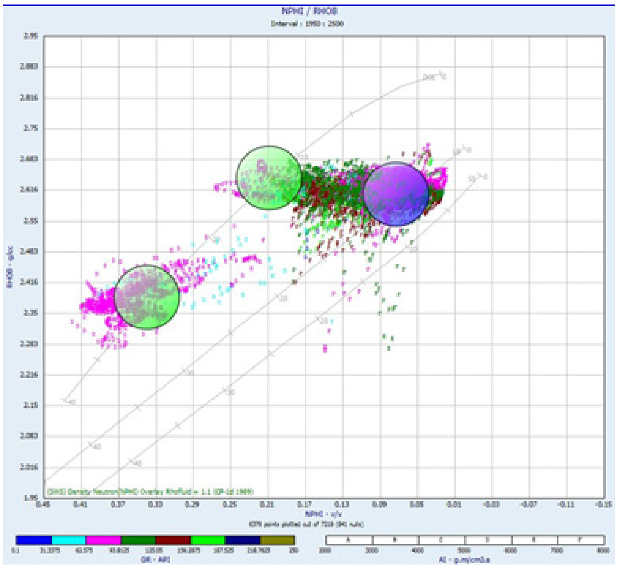


Figure 5.1. Cachalote 1&1A, compatible crossplots, apparent matrix density, cement type evaluation. The lower Cretaceous sand facies trends to dolomite whereas the upper Jurassic enhances limestone trend.

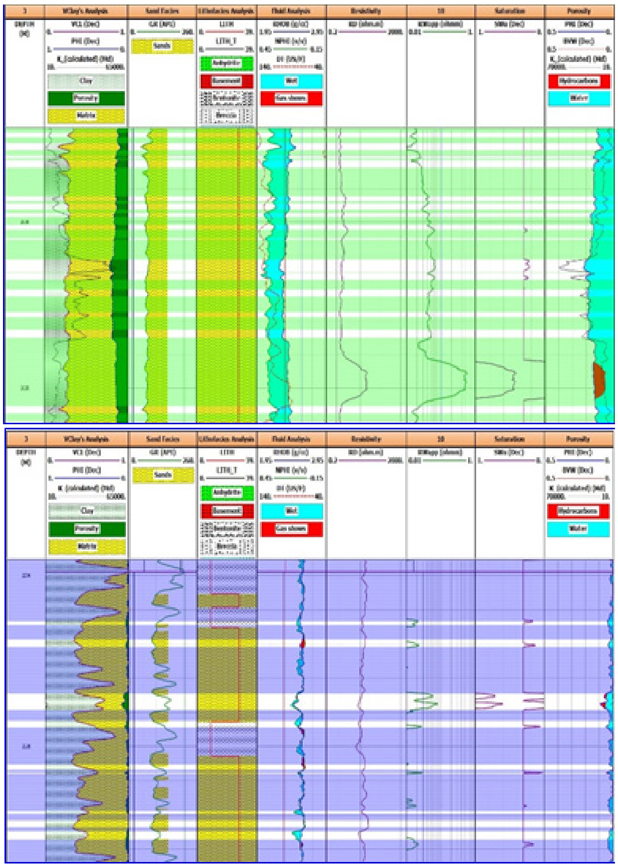


Figure 5.2. Cachalote 1&1A, apparent matrix density, cement type evaluation. Blue shadow represents lower Cretaceous and blue the upper Jurassic cement type's distribution based on the crossplots.

3.2.3. Poroperm evaluation

Total porosity and absolute permeabilities were calculated based on wireline logs so that evaluate the lithofacies response in upper Jurassic to lower Cretaceous.

3.2.3.1. Total porosity

$$\left[\frac{100x0^2x(1-Swi)}{Swi}\right]^2 \qquad (2)$$

3.2.2.2. Absolute Permeability

Cachalote 1 and 1A absolute permeabilities (K: mil Darcy) were calculated based on porosities logs values (PHIs) through the Wyllie & Rose II (Eq. 2) and confirmed with porosities values from side wall cores calculation. As result, the absolute permeabilities for the Cachalote 1&1A wells, both show the similar trends. The lower Cretaceous lithofacies show the highest absolute permeabilities values than the upper Jurassic lithofacies (Figure6.).

$$\left[\frac{100x0^2x(1-Swi)}{Swi}\right]^2 \qquad (2)$$

Where:
Swi is irreducible water;
Assumption for the sand facies:
$Swi = 0.2$

4. GEOPHYSICS

4.1. Synthetic seismogram generation

In order to evaluate sand facies response into seismic characters, was generated Cachalote 1 synthetic seismogram (A) by using density (RHOB), resistivity as sonic (DT), gamma ray (GR) logs and Ricker wavelet at 25Hz and extracted seismogram that gave an output of r = 0.725 to which is reasonable correlative to the seismic characters throughout the interval of interest (upper Jurassic to lower Cretaceous) and the results show the same trend for the Cachalote 1A the TD is 3191mD.

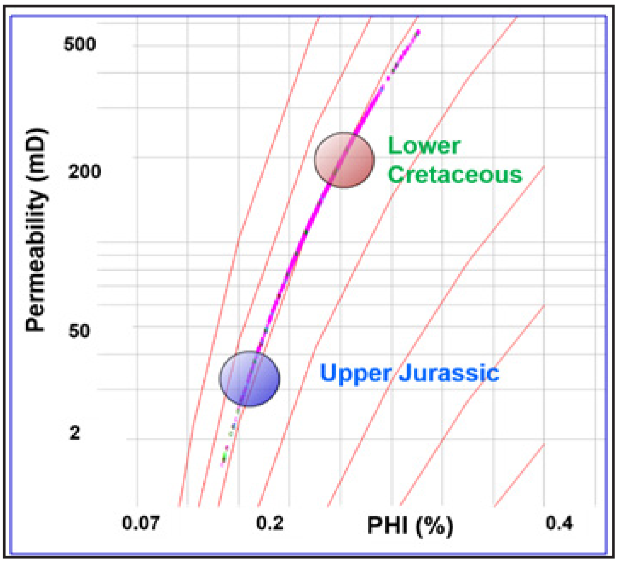


Figure 6. Cachalote 1&1A, poroperm evaluation. Lower Cretaceous shows relative good poroperm properties response than upper Jurassic.

4.2. Subsurface horizon slices mapping

The subsurface mapping was designed to enhance geochronostratigraphic sand facies distribution throughout the upper Jurassic to lower Cretaceous based on the Cachalote 1&1A electrofacies analysis results. Therefore, Top Sand 1 (TS1), Ibo High Structure (IHS) and Karoo horizons slices were mapped (Figure 8 and 9).

4.2.1. Subsurface mapping and 3D seismic multi attributes Analysis

Two (2) groups of 3D seismic multi attributes were generated: a) Geometric: Root Mean Square (RMS), Semblance, Curvatures (+ve; -ve); b) Instantaneous: Relative Acoustic Impedance (RAI), Spectral Decomposition (SDE/SDT), Trace. Emphasize that, the lithofacies in the study area were greatly affected by the carbonate cement (Figure41. 4.2) and the sand facies show relative high acoustic impedance (AI) (Figure 7).

In addition, owing to the frequency limitation in deep horizons slices (Karoo and its strata slices at +5ms; +8ms) was only analyzed the TS1 from the lower Cretaceous (Aptian).

4.2.1.1. Semblance and TE attributes for the geographic structural features distribution

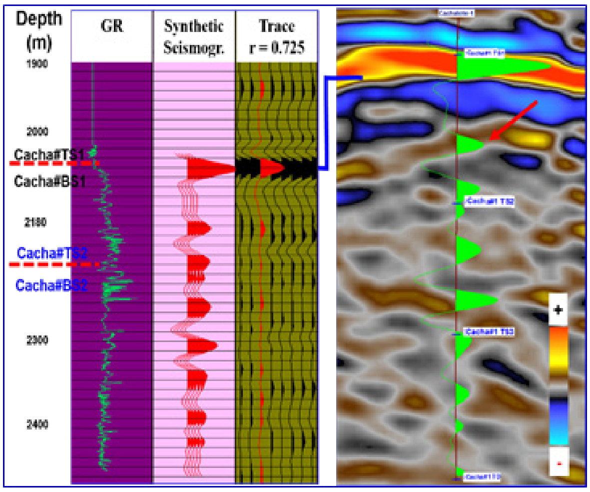


Figure 7. Cachalote 1, synthetic seismogram. Cachalote 1A show similar response which r = 0.795.

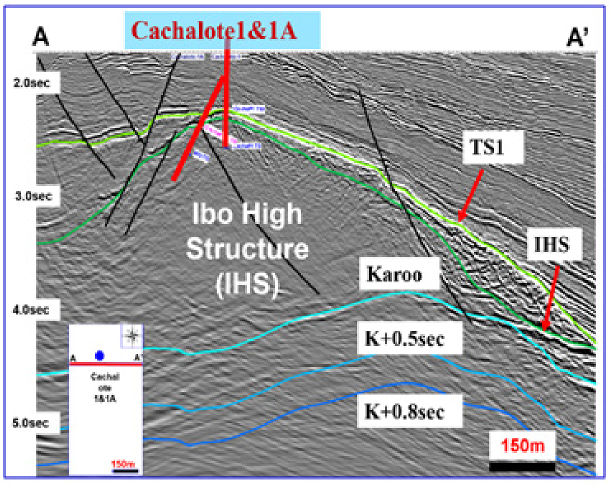


Figure 8. Cachalote 1&1A. TWT cross-section, shows the Top Sand 1 (TS1), Ibo High Structure (HIS) and Karoo horizons and Karoo +0.5sec; +0.8sec strata slices

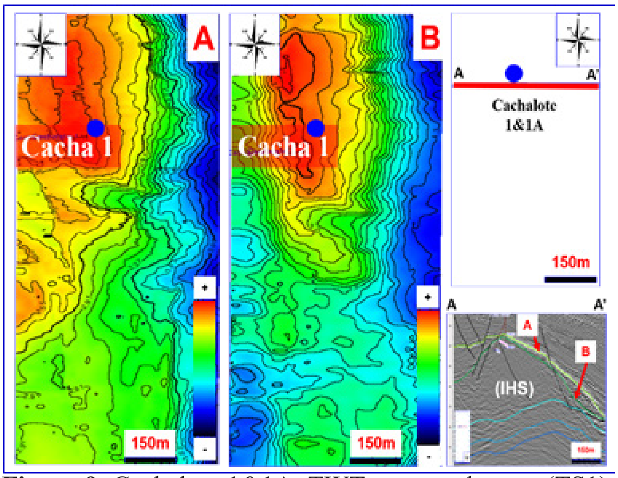


Figure 9. Cachalote 1&1A, TWT structural maps (TS1), Ibo High Structure horizons slices. The positive represents shallower and blue the deep section. Erosional clues are enhanced by contouring control.

4.2.1.1. Semblance and TE attributes for the geographic structural features distribution

To enhance the major structural features were generated two 3D seismic attributes volumes: Trace envelope (reflection strength) and Semblance or Incoherence. The lower Cretaceous, TS1 horizon slice was used as master because major faults cut through it in the study interval. As result, three groups of (thrust and normal) faults were discovered striking to the NW/SE; NNW/SSE and NNE/SSW along the Ibo High Structure boundaries dipping to the western part (Figure10). Those faults orientations impacted the sand facies distribution throughout study area.

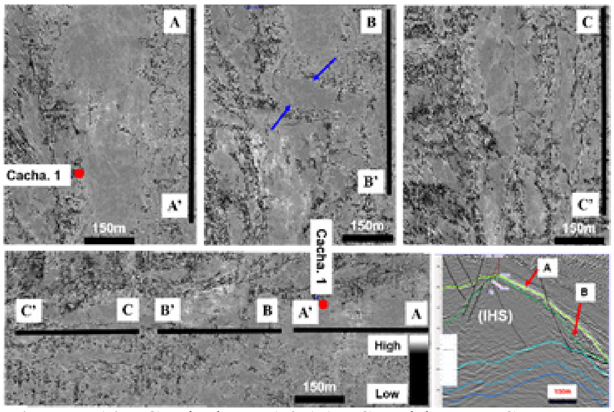


Figure 10. Cachalote 1&1A, Semblance. Structural features such normal faults: NW/SE; NNW/SSE and NNE/SSW and slump scar (blue arrows).

4.2.1.2. RMS and SDE attributes for the geographical sand facies distribution

Therefore, the Root Mean Square (RMS) window of -+25ms enhances thicker sand facies distribution and the Spectral Decomposition Envelope sub band (SDE) varying 8Hz, 16Hz, 24Hz and 32Hz (Naseer, 2011) for the variable sand facies tackiness (Figure 11.). Thus, to distinguish thinner geographic sand facies distribution throughout the area, the SDE at 16Hz was used and enhances thinner sand facies distribution trend W-E, NW-SE related to small channels (Figure 12.).

4.2.1.3. RAI and SDT attributes for the geographical sand facies thickness distribution and fluid prediction

The geographical sand facies distribution

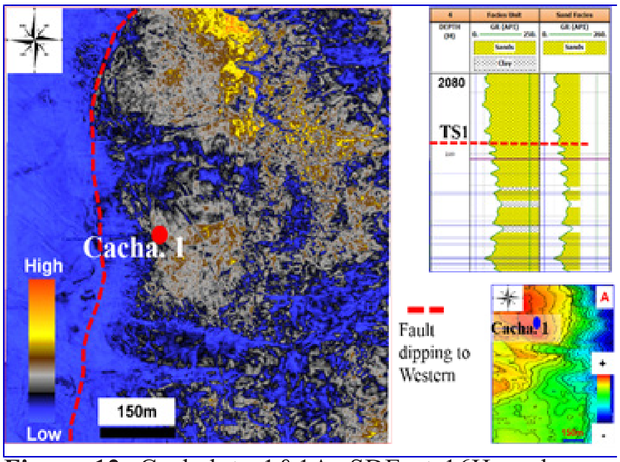


Figure 12. Cachalote 1&1A, SDE at 16Hz enhances channels features (black arrows) and slump scar (red arrows). Small channels trend W-E, NW-SE are potential source of the sand facies distribution.

in the study area are controlled by channels systems and faults spreading away. To evaluate the spreading thickness throughout the study interval, relative acoustic impedance (RAI) and spectral decomposition trace sub band (SDT) at 24Hz were used to attribute the TS1, TWT subsurface map.

The spectral decomposition trace sub band (SDT) at 24Hz (Figure12.) enhances reasonable sand facies thickness geographical distribution. High amplitude response are related to sand thickness and in the northern part is much enhanced than in the southern part (Figure 13).

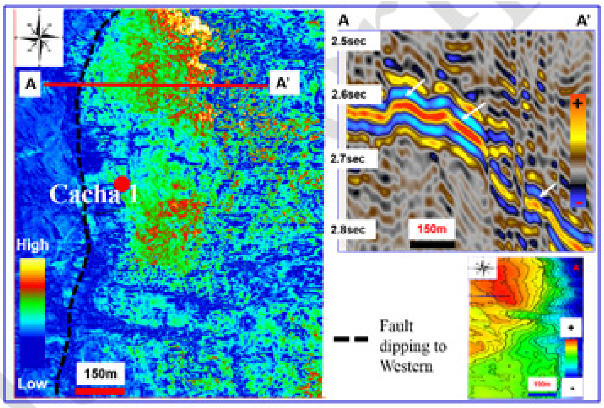


Figure 13. Cachalote 1&1A, SDT at 16Hz based on TS1 horizon slice. High amplitude enhances the sand thickness facies distribution.

5. RESULTS INTEGRATED ANALYSIS

A reasonable reservoir characterization and formation evaluation was carried out integrating the well data such as geological, petrophysical analysis and tied to 3D seismic features so that achieve an understandable results and accurate information related to the sand lithofacies geochronostratigraphic distribution, characteristics and their controlling factors throughout the study area.

Electrofacies analysis show that, the sand lithofacies occur as stacked in claystone units and laterally pinch-out in mud rich system within the upper Jurassic to lower Cretaceous.

5.1. Geochronostratigraphic sand facies correlation

The geochronostratigraphic correlation was reconstructed so that understand the geochronostratigraphic bodies of rocks, layered or unlayered that had been deposited during the upper Jurassic to lower Cretaceous in study area.

The result show that, within the upperJurassic to lower Cretaceous there is an unconformity splitting out the Cachalote 1 and Cachalote 1A lithofacies which the time gap assessed is from the upper Jurassic (Tithonian) to lower Cretaceous (Berriasian- Valanginian).

Those geochronostratigraphic bodies of rocks that were not encountered in Cachalote 1A but in Cachalote is suggested that, they may have been eroded away and deposited toward to the eastern basin (Figure 16.2). An erosional time gap was assessed and was suggested to have occurred during the lower Cretaceous and ended up at earliest Hauterian (Figure 13).

6. RESULTS DISCUSSION

The structural assessment within the upper Jurassic to lower Cretaceous revealed that, the study interval has in fact been experienced by multiple tectonic episodes as consequence, complexes structures had been generated such as the Ibo High Structure and various normal faults. Thus, the geochronostratigraphic reservoir facies distribution were strongly affected.

The Ibo High Structure (IHS) extending N-S, width tens kilometers to W-E played an important role for the facies pre-post-rift

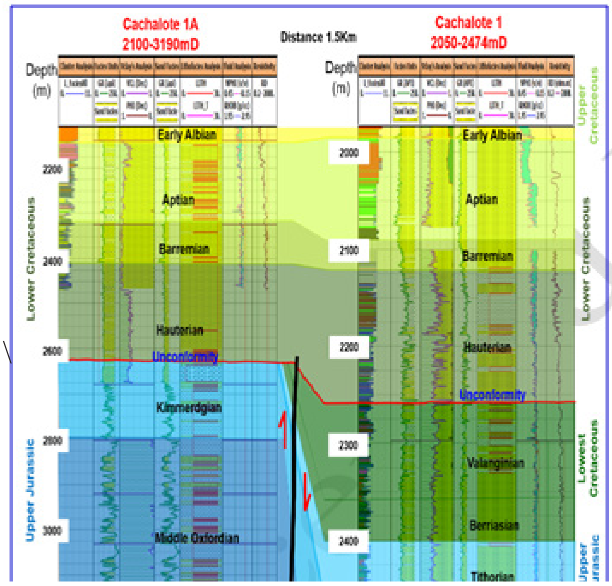


Figure 14. Cachalote 1&1A, chronostratigraphic correlation. Thrust fault and unconformity mark the major event within Cachalote 1&1A lithofacies.

depositional control. Most of channels systems however cut the (IHS) from the western to eastern and small channels at least WWS-EEN directions.

6.1. Geochronostratigraphic reservoirs quality and thickness distribution

Integrated analysis of geological, petrographical, geochemical data revealed that, the Cachalote 1 and 1A lithofacies are quite similar.

Thin-section analysis enhanced that, the lower Cretaceous (Hauterian-Albian) sandstones reservoirs are characterized as well sorting, fine-grained sandstone, roundness: angular-sub-angular, clasts: quartz, k-feldspar, plagioclase, amphibole, completely carbonate cemented (limestone-dolomite transition) whereas the upper Jurassic (Oxfordian-Tithonian) sandstone reservoirs consist of sand facies poorly sorted, fine-grained, matrix supported, roundness: angular to sub-angular, clasts: quartz, k-feldspar, plagioclase, mica, clay matrix, pyrite, carbonate cement).

As result, lower Cretaceous reservoirs are quite good than from the upper Jurassic which are high compacted and hold lower poroperm properties (tight sands).

6.2. Geochronostratigraphic reservoirs shapes/ geometries distribution

Electrofacies and 3D seismic attribute analysis enhanced that, subsequent submarine channels and cutoff resulted in isolation of fully developed overbank muds and originated sheets geometries deposited as stacked sands levees in western part whereas the eastern part slope single and multi-channels played an important role of fan deposition. Hence, the major geometries of sandstone reservoirs are greatly dependent of external shapes throughout the studied interval (upper Jurassic to lower Cretaceous).

The common sand lithofacies bodies distribution occur as stacked lobes, wedges, isolated fans and continues sheets/overbanked sands deposited as stacked levees with a high structural control such as normal faults. The (Figure 15), illustrate the geochronostratigraphic sand bodies distribution within the upper Jurassic to Lower Cretaceous.

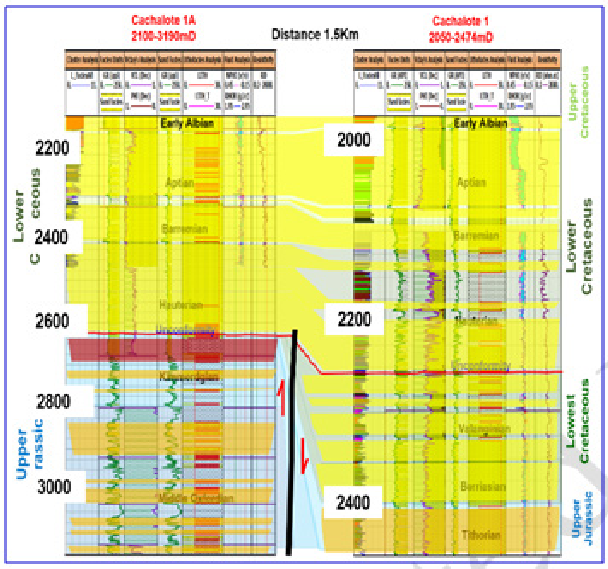


Figure 15. Cachalote 1&1A, chronostratigraphic geometries sand facies correlation. Red is the breccia and yellow-brown the upper Jurassic and yellow the lower Cretaceous sand facies correlations.

6.3. Geochronostratigraphic isochronal reservoirs maps and thickness distribution

Thrust faults and subsequent erosional event, caused the lateral continuity of sand facies. Hence, lithofacies which may had been eroded away shall be encountered within the deep eastern part in the study area as sigmoidal or mound deposits but their connectivity are quite critical and may greatly impact in reservoirs quality and thickness.

The isochronal reservoirs maps show the western part dominated by stacked channels and levees sand deposits whereas the eastern part, wedge/mounds deposits are enhanced (Figure16.1 and 16.2). Thus, the reservoirs

thickness are quite critical to be accurately assessed and evaluated in the study area

a) Isochronal western reservoir map, lower Cretaceous.

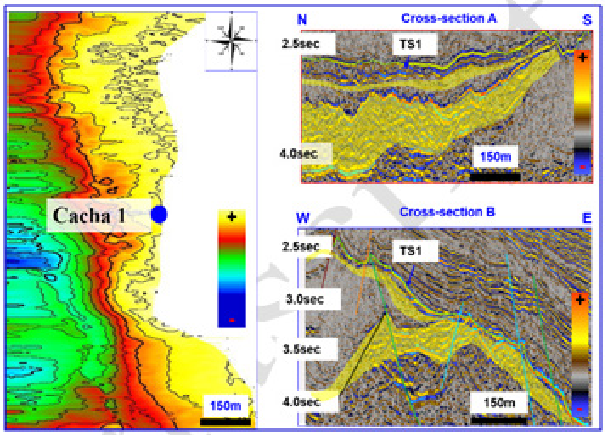


Figure 16.1. Cachalote 1&1A, Isochronal western lower Cretaceous reservoir maps, distribution.

b) Isochronal eastern reservoir map, lower Cretaceous.

In addition, Cachalote 1 & 1A show an approach of gross and net pays which may be an important clue to predict nearby sandstone reservoirs in the study area. The results shown in the (Table.1) were based on the Haliote 1&2 reservoirs from Cachalote 1A and Top Sand 1 (TS1) from Cachalote 1.

6.4. Paleodepositional environment modelling (PDEM)

Integrated analysis provided clues to reconstruct the paleodepositional environment. Geologic well data consisting of the side wall cores, wireline logs analysis, biostratigraphic-data, petrographic analysis combined with the horizons slices mapping and the 3D seismic multi attributes analysis were used so that reconstruct the depositional environment (Figure 17).

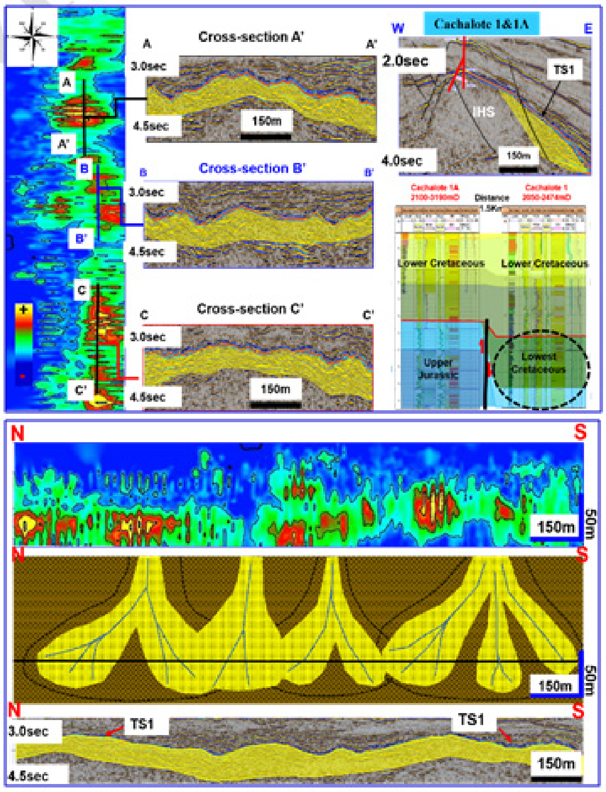


Figure 16.2. Cachalote 1&1A, Isochronal eastern and top view lower Cretaceous reservoir maps, distribution.

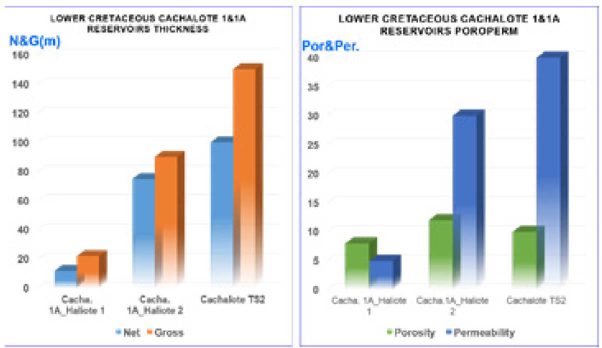


Table 1. Cachalote 1&1A lower Cretaceous reservoirs, net, gross and poroperm assessment.

6.5. Geochronostratigraphic sandstone reservoirs distribution

Based on the all integrated results and discussed here with the subsurface 3D seismic multi attributes maps analysis thereby allowed to reconstruct the geochronostratigraphic reservoirs distribution. Thus, the lower cretaceous holds good poroperm sandstone reservoirs (Figure 18).

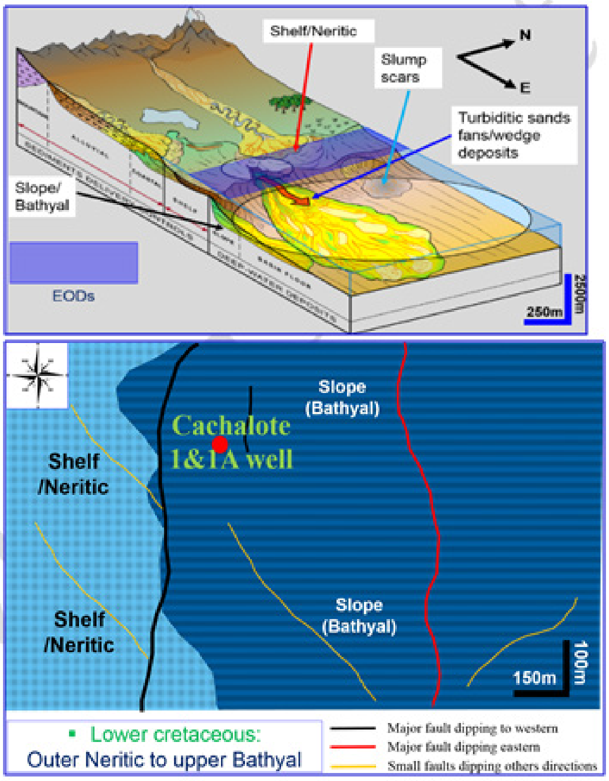


Figure 17. Cachalote 1&1A, 3D and top view of the depositional environments paleomodelling.

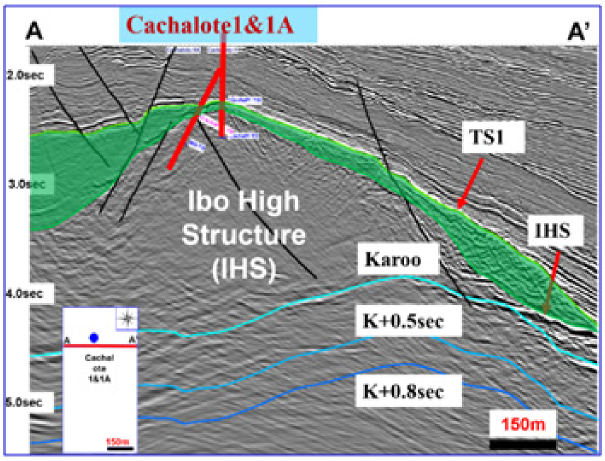


Figure 18. Cachalote 1&1A, cross-section, lower Cretaceous poroperm reservoirs distribution.

7. CONCLUSIONS

- Geochronostratigraphic apparent matrix density and cement types distribution: All lithofacies had been greatly affected by carbonate cement and the sand facies show strong amplitude response. Thus interpreters must aware when interpret reservoirs;
- Geochronostratigraphic sandstone reservoirs distribution factors: Turbiditic single and multi-channels sys tems with structural control (folded and faulted);
- Geochronostratigraphic poroperm sandstone reservoirs distribution:
  Western and eastern parts from the lower Cretaceous (Berriasian-Albian);
- Geochronostratigraphic geometries sandstone reservoirs distribution: Depositional lobes (mounds), isolated overbanks, continuous sheets; wedges and fans as stacked parasequences within claystone rich system.

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Finally, I would dedicate this Research Project to my memorial family: Amélia Mussa (mother); Charifa Magalhães and Sezária Domingos (sisters). Honorable dedication is given to Inês Fanuel Madime by her unconditional loving! Appreciable dedication is given to my younger brothers: Nordino and Estefânia Magalhães.

9. REFERENCES

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