RESERVOIR CHARACTERIZATION AND DEPOSITIONAL ENVIRONMENTS OF DEEPWATER SEDIMENTS IN THE LOWER CRETACEOUS SUCCESSION, OFFSHORE ROVUMA BASIN, MOZAMBIQUE

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Abstract

The Passive Margin in the Offshore Rovuma basin, northern Mozambique is the Study area location. 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, Key et al., (2008). This Research Project was designed to investigate an area around the Cachalote-1 well location in two major topics as follows: (1) Reservoir Characterization and (2) Depositional Environments to outline Depositional Processes and types of Reservoir shapes, geometries and poroperm prediction based on the Caracol Gas Sandstone Reservoir, Albian, Lower Cretaceous. Furthermore, to analyze the implications of the depositional environment settings and the model that can identify the key concerns and challenges for Petroleum exploration and exploitation in the Lower Cretaceous Succession. Therefore, to achieve the Aims and Objectives regarding to the (1) Reservoir Characterization and (2) Depositional Environments the following Dataset, Methodology and Techniques were used: [i] Well Data Analysis by (1) Biostratigraphic Data Analysis, (2) Thin-Section Ditch and (3) Well Log Analysis. In addition, the [ii] SEGY 3D PSTM Seismic Facies Analysis by (1) Subsurface Depth Horizon Slices mapping, (2) Isopach TWT Maps generation, (3) Root Mean Square-RMS, (4) Spectral Decomposition-SD and (5) Envelope attributes Maps Analysis and also integrated Reservoir imaging using the [iii] Advanced Seismic Facies Analysis by (1) Geobody Analysis. As a result, the Mud Forams interpretation suggested most likely an Upper Bathyal Depositional Environment. The Seismic Facies Analysis by using the Root Mean Square-RMS as follows: +20ms in the Sand Unit III, +15ms, in the Sand Unit II and +10ms, in the Sand Unit I, Spectral Decomposition at 23.2Hz in the Sand Units III, II and I attributes Maps assisted by Electrofacies and Electrosequence Analysis agreed that, Caracol Gas Sandstone facies had been deposited in open Deepwater Environment as Channel-Leveed System in which their Sand facies had been transported from the Shallow restricted marine by turbidity currents and turbidity submarine channels similar to those investigated by Walker, (1992). The Envelope attribute Maps by Root Mean Square at +20ms, +15ms and +10ms enhanced clearly the DHI's in the Sand Unit III, Intra III, Units II and I. The Middle Fans/lobate geometries is the key Characteristics of Sandstone Reservoir Units III, II and I interlayered by thick submarine Clay/Shale Successions in the area of investigation. The Reservoir Quality by Poroperm analysis revealed Porosities of ~10-36%, Permeability (K) ~10-110mD. However, Thin-Section Ditch Analysis revealed immature Sands as being, poor-well sorting, fine-grained, angular-sub-angular roundness, Quartz, K-feldspar, Plagioclase, Amphibole Clasts, matrix completely supported by Clay and highly Calcite cemented Sands. The irregular distribution of spatial Sand facies associations and their high ratio of disconnectivities revealed by Geobody Analysis indicate as the key challenges for Petroleum exploration and exploitation of Sandstone Reservoirs, Lower Cretaceous Succession.

Keywords: Upper Bathyal; Immature Sands; Mid Fans Turbidites; Disconnected Lobes.

1. Introduction

The Mozambique basins have become an important area for Petroleum exploration. Both Onshore and Offshore as follows:(1)Mozambique and (2) Rovuma basins are attracting International Oil Companies (IOC's) to hunt new Oil and Gas fields. In Mozambique, hydrocarbons have been discovered in the Onshore, Mozambique basin with significant GIIP such as (1) Dry, (2) Condensate Natural Gas. These Resources are under production and most likely OIIP mainly (1) the Light Oil and (2) Associated Natural Gas, in the southern part of the country. Recently there, has been reported by the National Petroleum Institute-INP huge discoveries of more than 180Tcfs of Dry Natural Gas in the northern part, Offshore Rovuma basin which those discoveries have increased the interest for Petroleum exploration and exploitation in the country.

1.1. Geological Settings

The Study area is located at southern part of Rovuma basin, Offshore Mozambique. The Rovuma basin has been reported as a Passive Margin System lying at the southern end of the extensive East African Rift comprising the coastal plains of Somalia, Kenya, Tanzania and Mozambique. The depositional Settings of Rovuma basin has been reported as follows: (1) syn-rift Triassic-Jurassic (200-145Ma) and (2) post-rift Cretaceous-Neogene (145-2.6Ma). Sedimentary deposits including the Sand and Clays/Shale facies of the Rovuma Delta complex and Pemba Formation which the Caracol Gas Sandstone Reservoirs belong to the multiple Tectonic episodes where both syn and post deposition took place. The Ibo High Structure growth orientated to NNW-SSE and the bathymetrical feature, the Davie Ridge are the Ancient deepest Geological Structures Framework ECL, (2000), Key et al., (2008) (Fig. 1.), Offshore Rovuma basin, Mozambique.

1.2. The Key Problem in the Study Area

Two Drilling Projects in the Study area have been reported technical discoveries from two Wildcats (Exploration) Wells as follows: (1) Cachalote-1&1A and (2) Búzio-1. These Wells were drilled into Deepwater Sediments and for that reason in those Successions are expected high risk and uncertainties for Petroleum Resources exploration from the Lower Cretaceous Sandstone Reservoirs.

Previous Studies carried out by an IOC E&P Oil & Gas Company were documented in the Final Well Report (FWR) and recently, the academic Thesis and Researches for instance, Chibielo A., (2016), Chiulele S., (2016) and Matlava E., (2016), they have only reported and concluded with limited information about the Depositional Environments, spatial distribution of Reservoir shapes and geometries and challenges and implications for Petroleum exploration. In these Studies they have focused on the Cachalote-1, Haliote-1&2, Caracol and Percebes Gas Sandstones Reservoirs within the Upper Jurassic to Paleocene Successions. Thus, the shortage of detailed information of Reservoir shapes, geometries and their spatial distribution continues being the key challenges for the exploration Geoscientists studying the Deepwater Sediments in the Offshore Rovuma basin. As can be expected, to come up with ideas regarding to the above concerns it requires High Resolution Study. Therefore, this Research was designed so that it can continue investigating the area looking for alternatives solutions.

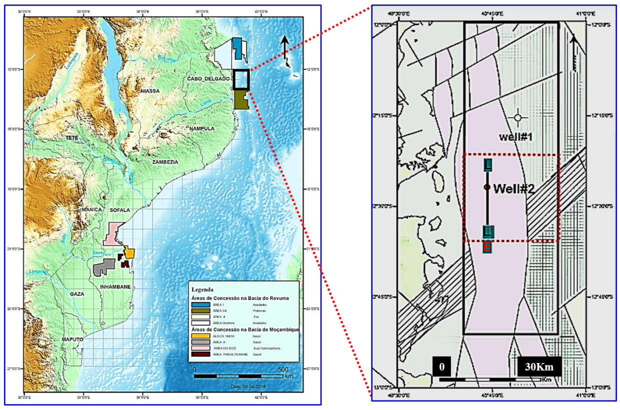

Figure 1. Location Map of the Study area. The L-L' is a cross-section line showing the structural and seismic sequence within the study interval (Albian Lower Cretaceous) (Fig. 5). Well#1 (Buzio-1) and well#2 (Cachalote-1&1A), in the Albian, Lower Cretaceous.

2. Aims and Objectives, Methodology, Dataset and Techniques

To achieve the aims and objectives regarding to the Reservoir characterization and depositional environment the following Methodology was used: [i] Well Data Analysis by (1) Biostratigraphic Data Analysis, (2) Thin-Section Ditch and (3) Well Log Analysis. In addition, the [ii] SEGY 3D PSTM Seismic Facies Analysis by (1) Subsurface Depth Horizon Slices mapping, (2) Isopach TWT Maps generation, (3) Root Mean Square-RMS, (4) Spectral Decomposition-SD and (5) Envelope attributes Maps Analysis and also integrated Reservoir imaging using the [iii] Advanced Seismic Facies Analysis by (1) Geobody Analysis. The Study focuses on the:

2.1. Aims

For understanding the:

- Major Depositional Environments;

- Depositional Processes and Products;
- Reservoir Sand source and origin;
- Reservoir spatial distribution and key controlling factors.

2.2. Objectives For predicting the:

For predicting the:

- Potential Reservoir quality;
- Reservoir shape, Geometry and connectivitiy;
- Implications for Petroleum exploration and exploitation.

For reconstructing the:

- Gross Depositional Environments (EODs Models);
- Reservoir Sand facies (Facies Model).

3. Results Description And Interpretation

3.1. Biostratigraphic Results Description

To determine Depositional Environments in this Study, the Biostratigraphic Data Analysis and Thin-Section Ditch facies, such as the presence of shell fragments and glauconite provided evidence about the sand facies depositional processes and Depositional Environments. To which the Sand facies may have been transported from the Shallow marine to the open Deepwater environments have been combined with the mud forams evidence revealing the presence of benthic foraminiferal assemblages characterized by species of Epistomina and Gavelinella, with common Quinqueloculina antiqua and Lenticulina spp. and tubular agglutinants indicating the Glomospira charoides with persistent Marssonella spp. This information was used to interpret the depositional settings of the Caracol Gas Sandstone Reservoir as most likely being the upper bathyal environment into Mud Rich System in the Lower Cretaceous Succession.

3.2. Well Log Analysis

3.2.1. Electrosequence Analysis

To describe the sedimentological Successions in the Reservoir, the Electrosequence Analysis was carried out as a technique. Gamma Ray-GR changes analyzed assisted by Caliper Logs Analysis, Thin-Section Ditch description from the Side Wall Core-SWC rotary. The analysis revealed four main shapes (1) Bell and (2) Cylinder Unit III and Intra Unit III, (3) Funnel Unit II and (1) Bell Unit I and (4) Serrated into Clay/Shale Successions. There were also observed three Trends (1) Fining up-retrogradational and (2) Block-aggradational Unit III, (3) Coarsening up-progradational Unit II and Fining up-retrogradational Unit I and Block-aggradational in the Clay/Shale successions.As a result, the Caracol Gas Sandstone Reservoirs are characterized by four Stratigraphic Units (Figs. 2A-B), the Reservoir Sand Units III, intra Unit III, Reservoir Sand Unit II and Unit I interlayered by Clay/Shale Successions. The Abrupt breaks enhanced by Caliper log were interpreted as erosional channel base and the Tight Spots as due to Clay/Shale swelling. The observed Cavings as due to "bad hole" perhaps in the loose Sands sections. The Electrofacies Analysis combined with the Facies Analysis (Figs. 2A-B) in the successions confirm the interpretation of sedimentation in Deepwater environments.

- **Electrosequence Analysis**
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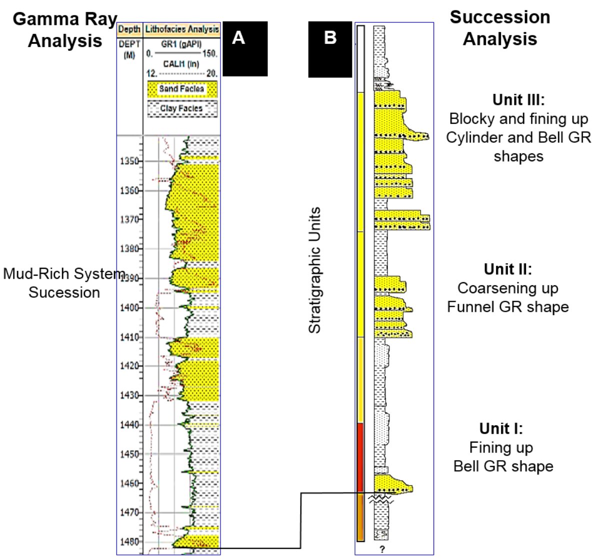

Fig. 2A is the Caracol Gas Sandstone Reservoirs Succession evaluated using the Gamma Ray and Caliper Logs. Fig. 2B is an interpretative Stratigraphic Column of lithofacies associations. The Reservoir Sand Units III, II and I were interpreted as middle Fans. Those classical Turbidites facies consist in depositional Fans/lobes forming the stacked complexes of Channel-Leveed Systems into upper bathyal environment within the Lower Cretaceous Succession.

3.2.2. Bulk Density (RHOB) and Neutron Pulse Hydrogen Index (NPHI) Cross-Plots Analysis

The crossplots the Bulk Density (RHOB) and NPHI logs. This approach revealed a most likely discrimination between the Sand and Clay/ Shale Lithofacies. The Sand facies are identified by a Gamma Ray cut-off of less or equal to 55-API. The Clay facies are outlined as Gamma Ray (GR) values above 55-API. In addition, it was useful to analyze the matrix Bulk Density and cement trend into Caracol Gas Sandstone Reservoir Units III, II and I.

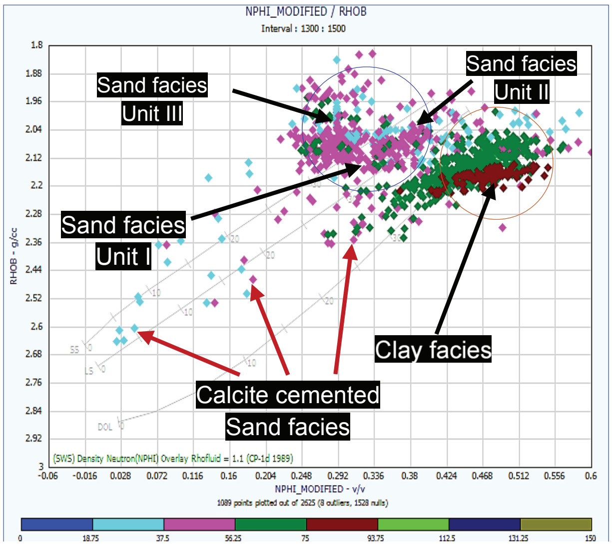

Figure 3. Shows the RHOB-NPHI crossplot (IP. 43.) and two Sand facies were discriminated as calcite cemented Sands with the LS-DOL trend at least 05-30% into matrix Bulk Density. These facies show as high RHOB and non-Calcite cemented Sands with low RHOB, in the [1300 md-1500md] Succession.

3.2.3. Poroperm prediction

The absolute permeabilities in K-mil Darcy [K-mD.] prediction was calculated based on porosities from the Log [NPHI] values taken at Side Wall Cored depths of 1357.90md, 1394.50md, 1485.50md and within these depths for high resolution analysis. The Wyllie & Rose, (1950) Equation II was applied. As a result, the absolute permeabilities calculated by these analysis for the Caracol Gas Sandstone revealed high values. These values were therefore, rejected in this Study. Hence, to solve this inconsistence of Wyllie & Rose, (1950) Equation II which they ignored the Formation factor F, an Equation I was developed considering the Formation factor F. As a result, the absolute permeabilities revealed more accurate as shown in (Table.1.) and they were plotted in (Fig. 4) so that it can summarize them.

Log [NPHI] Analysis		Parameters			Permeability Analysis	
Cored & non-Cored Depth-SWC	Porosity (Fraction)	a	m	Swi	K (mD.)	Interpretation
		0.62	**2.0**	**0.20**		
1357.90md	**0.33**				**15**	**Acceptable**
No SWC	0.31				11	Acceptable
No SWC	0.33				15	Acceptable
1394.50md	**0.41**				**51**	**Acceptable**
No SWC	0.32				13	Acceptable
No SWC	0.42				59	Acceptable
1485.90md	**0.44**				77	**Acceptable**

Table.1. Log [NPHI] porosity and calculated absolute permeability in mil Darcy (mD.) values. Code: KmD =< 10 fair; KmD >= 10 High (good) Reservoirs.

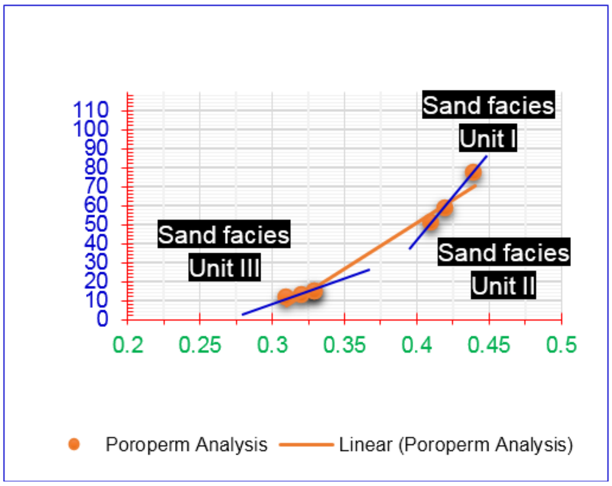

Figure. 4. Shows a plotted (M.S. Excel) between Log [NPHI] porosity and the calculated Permeability (mD.). The results enhance as being good Reservoir with three trends of Poroperm (Blue and Orange lines) and were interpreted as due to permeability barriers.). Thus, poroperm classification into Caracol Gas Sandstone Reservoir continues being a challenge so, is strongly recommended further investigation using the Side Wall Core-SWC Analysis.

$$KmD = \left[\frac{100\, x \phi t^2 x\,(1-Swi)}{Swi}\right]^2 x \left[\frac{(Swi\; x\; \phi t)^m}{a}\right] + C. \quad \text{Equation I.}$$

4. Seismic Facies Results Description and Interpretation

4.1. Synthetic seismogram and Reservoir Units III, II and I

To begin with the correlation and definition of the Reservoir Tops Units III, II and

I was completed so that they can be up-scaled to the Seismic Facies. The Synthetic Seismogram in the Caracol Gas Sandstone Reservoir was generated by using Bulk Density (RHOB), Sonic (DT) and Gamma Ray (GR) as Reference logs and Ricker wavelet at 25Hz as shown in (Fig. 5). This method showed a Synthetic Seismogram with a correlative Coefficient-R equal to 0.873 and it was described as a reasonable correlative Coefficient-R between the Well Data and the Seismic Facies from the SEGY 3D Pre-Stack Time Migration-PSTM Data. Therefore, the Seismic Data can be related to the Reservoir Sand Units III, II and I in the Lower Cretaceous.

- Synthetic Seismogram Analysis and Caracol Reservoir Units III, II and I

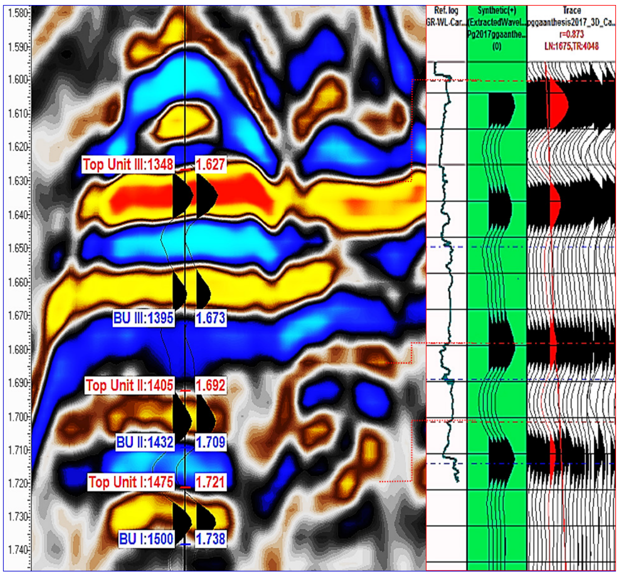

Figure. 5. Shows the Synthetic Seismogram generated using the (TSK. 8.8) with defined the Top Units III, II and I in the Caracol Gas Sandstone Reservoir. High amplitudes reflectors (Red-Yellow) enhance the Gas and Wet Sand facies. Low amplitudes reflectors (Brown-Blue) enhance Clay/Shale facies. The Synthetic Seismogram is correlative with the Sand and Clay/Shale facies in the Study interval [1330md-1500md] True Vertical Thickness-TVT.

4.2. Root Mean Square-RMS Attribute Maps for the Electrofacies [Logs] Units Correlation

The Caracol Gas Sandstone Reservoir in the interval of [1334md-1500md] TVT (IP.4.3) consists of three main Sand Units. Sand Unit III [1348md-1384md] and Intra Sand Unit III [1386md-1395md], Sand Unit II [1410md-1432md] and Sand Unit I [1475md-1485md]. In order to image the Sand facies distribution strata slices were generated from the main Seismic horizon slices. Ten strata slices in the Sand Unit III [1348md-1395md] were created by adding 0.5ms-5.0ms (TSK. 8.8). Four strata slices in the Sand Unit II [1410md-1432md] by adding 0.5ms-2.0ms (TSK. 8.8) and three strata slices in the Sand Unit I [1475md-1485md] by adding 0.5ms-1.5ms (TSK. 8.8) based on their Top Sand Units (Fig. 5).

The Sand facies spatial distribution decrease from the Top of Sand Unit III [1348md-1384md] to Sand Unit I [1475md-1485md] as can be seen in the (Figs. 6A-B, 7A-B and 8A-B). This decreasing of Sand facies was interpreted as due to the Sand source and sedimentation variation in different Sand layers in these Units. The results of Root Mean Square-RMS attribute Maps of Sand Unit III [1348md-1395md], Sand Unit II [1410md-1432md] and Sand Unit I [1475md-1485md] were presented as an integrated Studies of Electrofacies Analysis (Figs. 6A, 7A and 8A) described by Well Log Analysis using the Gamma Ray-GR, Deep Resistivity-RD, combined Bulk Density-RHOB and Neutron Porosity-NPHI, Thin-Section Ditch description (from Side W. Core) and Seismic Facies Analysis by Root Mean Square-RMS attribute Maps (Figs. 6B, 7B and 8B).

- **Sand Unit III [1348md-1395md]**

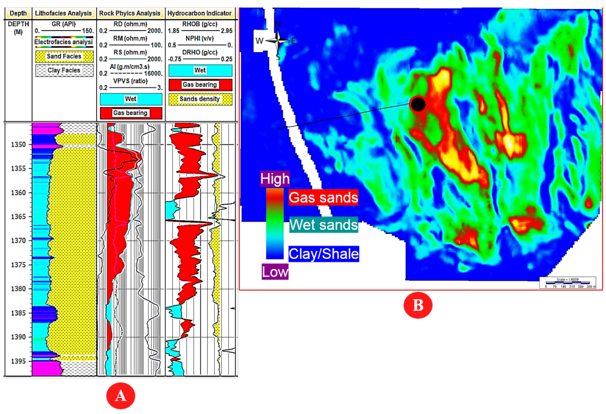

Fig. 6A. Shows the Caracol Gas Sandstone Reservoir Unit III [1348md-1395md]-TVT. The Reservoir thickness was based on the Electrofacies Analysis and stratigraphic rich Sand/Clay ratios by Well Log Analysis (IP. 4.3). GR shape descriptions is cylindrical motif shape enhancing an even block sharped top and base-aggradational succession. The Deep Resistivity-RD shape was described as effect of Gas saturation. Fig. 6B. Shows the Caracol Gas Sandstone Root Mean Square-RMS attribute Map at 20ms (TSK. 8.8.). It shows Sand Fan/lobate shapes distribution and affected by normal reactived fault most likely within the Paleocene-Albian and dips to the western side.

- **Sand Unit II [1410md-1432md]**

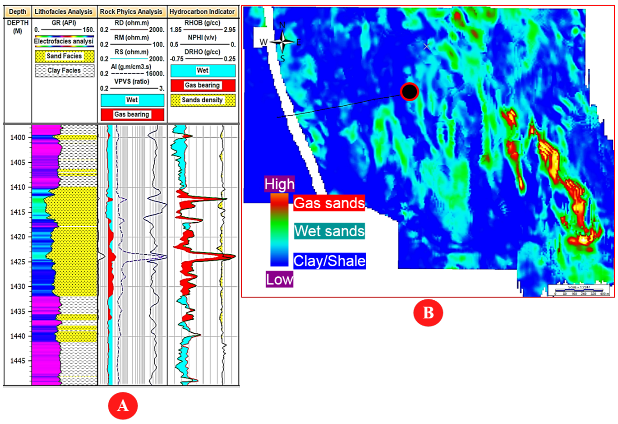

Fig. 7A. Shows the Caracol Gas Sandstone Reservoir Unit III [1410md-1432md]-TVT. The Reservoir thickness was based on the Electrofacies Analysis and stratigraphic rich Sand/Clay ratios by Well Log Analysis (IP. 4.3). GR shape descriptions is funnel motif shape enhancing a coarsening up-progradational succession. The Deep Resistivity-RD shape was described as effect of Gas saturation. Fig. 7B. Shows the Caracol Gas Sandstone Root Mean Square-RMS attribute Map at 15ms (TSK. 8.8.). It shows Sand Fan/lobate shapes distribution and affected by normal reactived fault most likely within the Paleocene-Albian and dips to the western side.

- **Sand Unit I [1475md-1485md]**

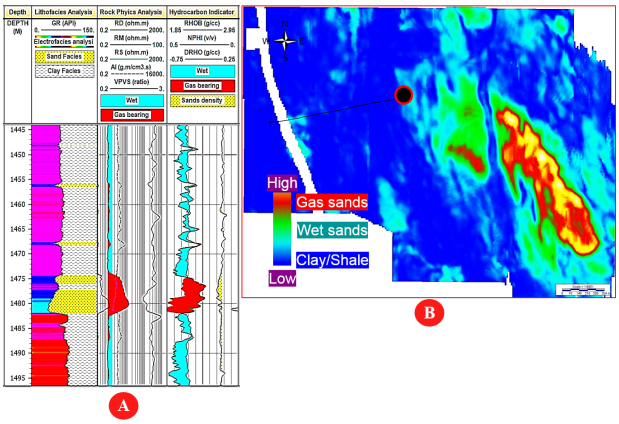

Fig. 8A. Shows the Caracol Gas Sandstone Reservoir Unit III [1475md-1485md]-TVT. The Reservoir thickness was based on the Electrofacies Analysis and stratigraphic rich Sand/Clay ratios by Well Log Analysis (IP. 4.3). GR shape descriptions is bell motif shape enhancing a fining up-retrogradational succession. The Deep Resistivity-RD shape was described as effect of Gas saturation. Fig. 8B. Shows the Caracol Gas Sandstone Root Mean Square-RMS attribute Map at 10ms (TSK 8.8.). It shows Sand Fan/lobate shapes distribution and affected by normal reactived fault most likely within the Paleocene-Albian and dips to the western side.

4.3. Spectral Decomposition-SD Attribute Maps and DHI's Analysis

The Spectral Decomposition-SD and 3D volume attribute was primarily used to evaluate the Caracol Gas Sandstone layer thickness to determine and identify the Stratigraphic Units variations and to predict possible Direct Hydrocarbon Indicators-DHI's. Therefore, the Spectral Decomposition-SD by Envelope at 23.2Hz Frequency Volume were applied. As a result, it revealed thick Sand Units to western and thinning to the eastern sides of Caracol Gas Sandstone Reservoir Units III, Intra Unit III, II and I (Figs. 9, 10 and 11) in the Lower Cretaceous Succession.The Direct Hydrocarbon Indicators-DHI's Analysis were enhanced by Bright Spots the High amplitudes (Red) and therefore were then interpreted as due to Gas Sand facies. The Dim spots-Moderated amplitudes (Yellow) are correlative with the

(Blue) were associated to Clay/Shale facies as follows: in (Figs. 9, 10 and 11.).The Spectral Decomposition-SD attribute Maps at 23.2Hz also revealed the most likely thickness of the Sandstone Reservoir Units III, Intra Unit III, Units II and I (Figs. 9, 10 and 11.).

- **Sand Unit III [1348md-1395md]**

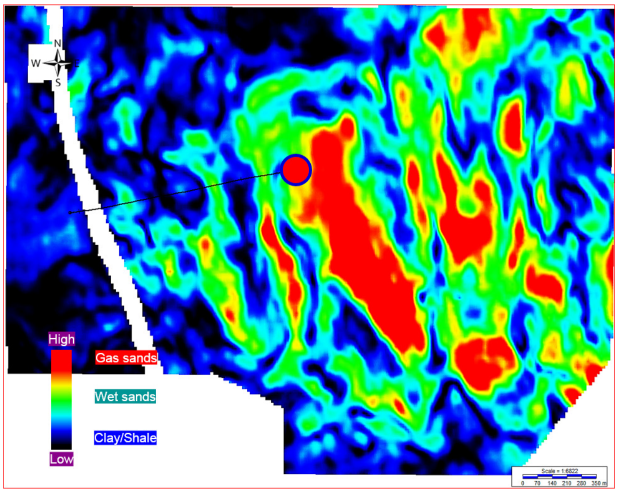

Fig. 9. Shows the Spectral Decomposition-SD, Envelope sub-band by octaves at 23.2Hz (Frequency domain) (TSK. 8.8) Map of Top Caracol Sandstones Reservoir, Unit II [1348md-1395md] in True Vertical Thickness-TVT (IP. 4.3) (Fig. 6A) measured from Well logs Analysis at Cachalote-1 well location (Red Circle). High amplitude locations indicate Gas Sand facies and low amplitude enhances Clay facies. The DHI's Analysis shows Bright spots which the High amplitudes (Red) are enhancing the Gas Sand facies and was reported discovery according to well information. The Dim spot, the Moderated amplitudes (Yellow) were interpreted as wet Sands and Low amplitudes values (Blue) highlight Clay facies. This Reservoir Unit II, is thickening to the south-eastern side while thinning to the north-western side from the well location.

- **Sand Unit II [1410md-1432md]**

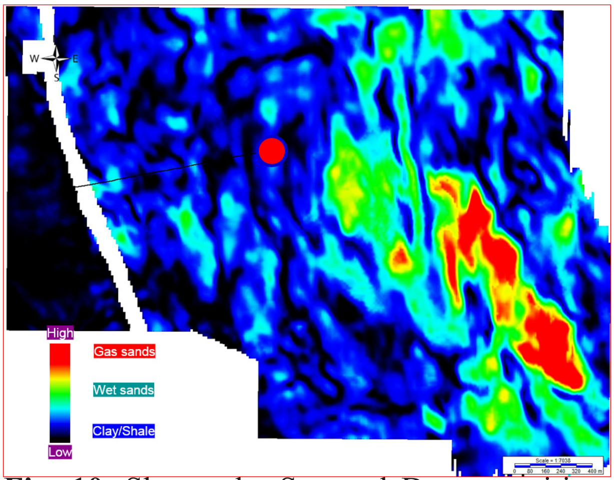

Fig. 10. Shows the Spectral Decomposition-SD, Envelope sub-band by octaves at 23.2Hz (Frequency domain) (TSK. 8.8) map of Top Caracol Sandstones Reservoir Unit II [1410md-1432md] in True Vertical Thickness-TVT (IP. 4.3) (Fig. 7A) measured from Well logs Analysis at Cachalote-1 well location (Red Circle). High amplitude locations indicate Gas Sand facies and low amplitude enhances Clay facies. The DHI's Analysis shows Bright spots which the High amplitudes (Red) are enhancing the Gas Sand facies and was not reported discovery according to well information. The Dim spot, the Moderated amplitudes (Yellow) were interpreted as wet Sands and Low amplitudes values (Blue) highlight Clay facies. This Reservoir Unit II, is thickening to the south-eastern side while thinning to the north-western side from the well location.

- **Sand Unit I [1475md-1485md]**

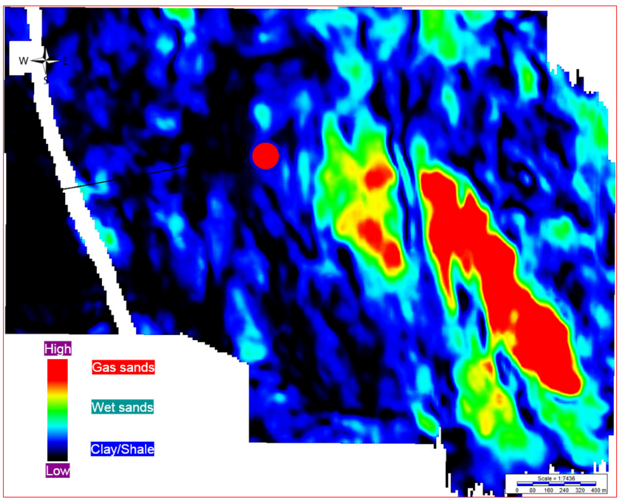

Fig. 11. Shows the Spectral Decomposition-SD, Envelope sub-band by octaves at 23.2Hz (Frequency domain) (TSK. 8.8) map of Top Caracol Sandstones Reservoir, Unit I [1475md-1485md] in True Vertical Thickness-TVT (IP. 4.3) (Fig. 8A) measured from Well logs Analysis at Cachalote-1 well location (Red Circle). High amplitude locations indicate Gas Sand facies and low amplitude enhances Clay facies. The DHI's Analysis shows Bright spots which the High amplitudes (Red) are enhancing the Gas Sand facies and was reported discovery according to well information. The Dim spot, the Moderated amplitudes (Yellow) were interpreted as wet Sands and Low amplitudes values (Blue) highlight Clay facies. This Reservoir Unit II, is thickening to the south-eastern side while thinning to the north-western side from the well location.

6. Seismic of Ancient Sand Facies Origin, Submarine Modern Fan Models, Reservoir Geometries and Connectivities Description and Interpretation

6.1. Ancient Sand Facies Origin and Splays Description and Interpretation

Based on the integrated Analysis of foraminiferal Data, Thin-Section Ditch description, Seismic Facies interpretation (Figs. 6B, 7B and 8B) and Electrosequence Analysis (Figs. 2A-B) the results clarified and agreed that, the Ancient Sand facies source have been from Shallow marine sediments which had been transported away and deposited as Turbidites facies as those studied by Mutti and Ricci Lucchi, (1972). They have been deposited into upper bathyal environment as Upper Series as those described by after Droz and Bellaiche, (1985) (Figs. 12A-B) by turbidity currents and turbidity submarine channel forming stacked complexes of Channel-Levee Systems (Figs. 12A-B), in like manner to those investigated by Walker, (1992).

6.2. Submarine Modern Fan Models, Reservoir Geometries and Connectivities Description and Interpretation

Further attempt at imaging the Caracol Gas Sandstone Reservoir on Seismic Facies by using the Geobody Analysis in (Petrel 2014) software. The attribute of these Geoblobs enhanced Fan shape and lobate geometries of the Caracol Gas Sandstone Reservoir Units III, II, and I (Figs. 13A-B). In addition, the Geoblobs Analysis revealed ratios of disconnectivities of lobate Sand separated and interlayered by Clay/Shale facies such as Low disconnectivities into Reservoir Unit III, High into Reservoir Units II and Moderate into Reservoir Units I. The Sand interlayered by Clay/Shale facies in this manner have been reported as the key characteristic of classical Turbidites deposited by the turbidity currents acting in the immature passive margin which spread sediments away depending on the Tectonic Settings and Depositional Environments similar to those investigated by Walker, (1992).

Based on the Geobody and Geoblobs results the Submarine Modern Fan Models, Reservoir geometries and connectivities in the Offshore Rovuma Basin most likely have similar characteristics to those studied by Walker, (1992) , nevertheless, those from the Rovuma basin have revealed high ratio of disconnectivities Fan/Lobe Turbidites Sandstone Reservoirs as obviously were observed using the Root Mean Square-RMS attribute Maps in (Figs. 6B, 7B and 8B) and finally highlighted by Geobody Analysis through the Geoblobs attributes (Figs. 13A-B).

Therefore, these disconnectivities might be due to the geomorphology and topography of the Upper Bathyal Depositional Environments that may have affected the Sand facies spatial distribution as seen through the Electrofacies Analysis (Figs. 6A, 7A and 8A) combined with the Root Mean Square attribute Maps in (Figs. 6B, 7B and 8B). Integrated Analysis of the Root Mean Square-RMS attribute Maps (Figs. 6B, 7B and 9B) and Spectral Decomposition-SD attributes Map (Figs. 9-11) with the Electrofacies Analysis (GR shapes) (Figs. 6A, 7A and 8A), Electrosequence Analysis (Figs. 2A-B.) and Geobody by Geoblobs Analysis (Figs. 13A-B), enhanced the imaging of the environments of Lobe complexes.

- **Modern Fan Models Reconstruction in the Lower Cretaceous Succession**

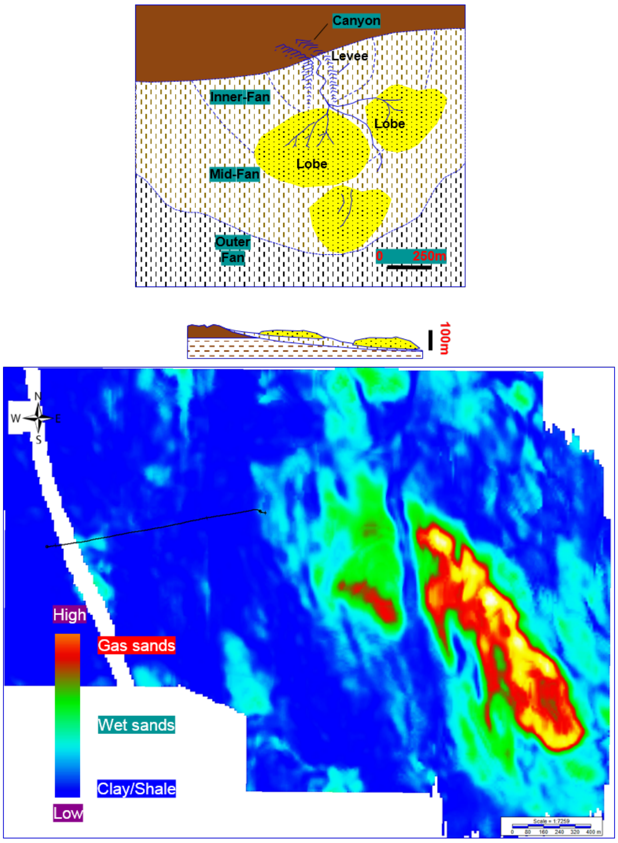

Fig. 12A. Shows the ancient Model of submarine inner-middle Fan modified from after Normark (1978). The Fig. 12B. is the Root Mean Square-RMS Map run at 10ms into (TSK. 8.8) and enhances unconfined sourced Splays and the Gas Sand prone by High amplitudes [Yellow-Red]. This RMS attribute Map enabled a complex of lobate Sand shape and is comfortable with the Electrofacies Analysis which revealed Fan shape and lobate geometry (Fig. 12B).

- **Reservoir Units III, II and I, Geometry and Connectivity Analysis and the Modern Fan Models**

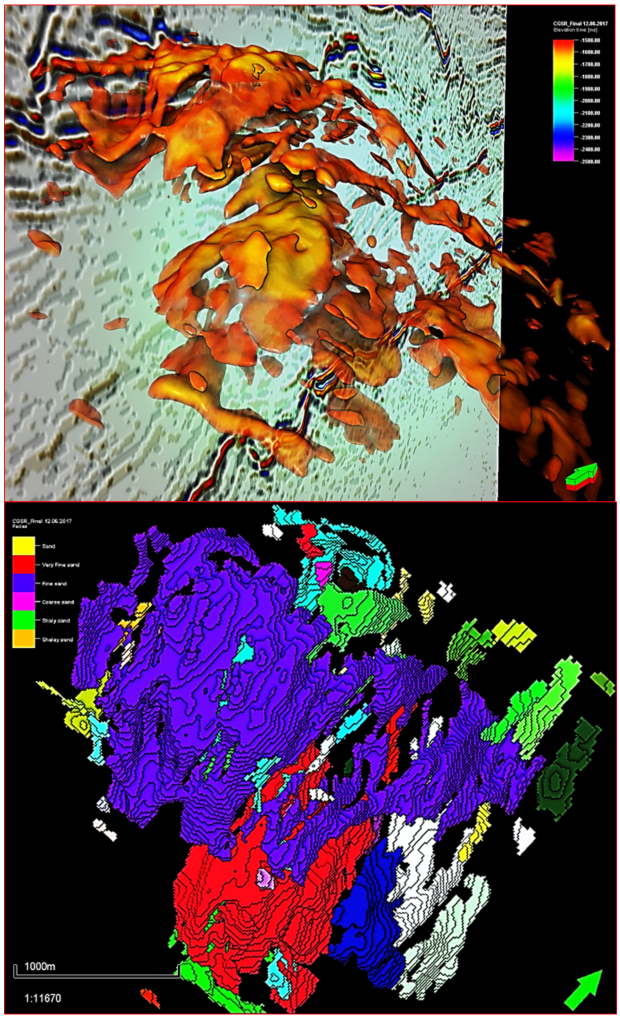

Fig. 13A. Shows 3D the amplitude extracted using the opacity at 21.2% (Petrel 2014) and related to Reservoir Units III, II and I. The horizontal scale is the same to (Fig. 6B) and V.E is 3x in Two Travel Time-TWT of a 3D PSTM-SEGY Data. The Fig. 13B. Shows the 2D Geoblobs generated applying the amplitude extracted (Fig. 13A) enhancing the Reservoir Unit III, II and I [1348md-1495md], [1410md-1432md] and [1475md-1485md] spatial geometries distribution and lateral extension and Connectivities. Each colored Geoblobs (Fig. 13B) is related to a single stacked Lobes as described in the Channel-Levee System likely to those investigated by Walker, (1992) revealed high ratio of disconnectivities in their geometries of Fan/lobate Turbidites Sand disconnectivities.

7. Discussion

7.1. Implications of Depositional Environment Settings, Depositional Processes and Their Depositional Facies Associations for the Hydrocarbons Exploration

7.1.1. Depositional Environment Settings and Model Analysis

Tectonically Mozambican coastal margin has experienced varies episodes of rifting and drifting which those events have formed the present day Rovuma basin geomorphology and topography, Key et al., (2008). The dispersal of the Fan/lobate Turbidites and spatial Sand facies distribution analyzed are believed to be deposited in response of post-rift Cretaceous-Neogene (145-2.6Ma) events including the Sand facies of the Rovuma Delta complex acting in the immature passive margin based on Walker, (1992) classification. These types of Depositional Environments result in large Sand-rich Fans deposited into Mud-Rich System and are characterized by the lack of well-developed Lobes. The sheet Sands rather than Lobes are found in the Lower-Fan. The (Fig. 14A) illustrates an interpretative Depositional Model of the Study area and is equivalent to that investigated in Mississippi-Gulf of Mexico by Maill, (1984) reported by Walker, (1992).

7.1.2. Depositional Processes and Spatial Distribution of Sand Facies Associations

Integrated Biostratigraphic Data, Thin-Section Ditch interpretation, Electrosequence Analysis (Figs. 2A-B), Electrofacies Analysis (Figs. 6A, 7A and 8A) and Seismic Facies-RMS (Figs. 6B, 7B and 8B) provided indications of turbidity currents and submarine channel as being the major and key depositional processes. Thus, stacked depositional Sands Lobes and Turbidites Fans with high complexities of spatial distribution shapes and geometries as revealed in (Figs. 6B, 7B and 8B) and (Figs. 13A-B) are the main Sandstone Reservoirs. These Fan lobate Turbidites Sands occur as Channel-Leveed Systems as those investigated by Walker, (1992) and were deposited as Upper Series based on Droz and Bellaiche, (1985). The Reservoir Units III, Intra Unit III, Units II and I are interbedded by thick submarine Clay/Shale deposits (Figs. 13A-B) with irregular Reservoir spatial geometries distribution and a high ratio of disconnectivities in these Successions.

7.1.3. Ancient Submarine Fan Origin and Their Spatial Distribution and Implication for Modern Fan Reservoir Geometries and Connectivities

The Seismic Facies Analysis by Geobody method (Petrel 2014) enhanced useful evidence about Sand facies associations and geological records revealing the modern submarine Fans, geometries and connectivities. The Geoblobs provided images of a single Channel-Leveed System (Figs. 14A-B) with Flow Direction in the WWN-SSE (Fig. 15A). Therefore, no more than two Sand facies source might occur using the average dimensions of modern submarine middle Fans from the previous Studies based on Walker, (1992) classification. In comparison with previous Studies, the middle Fans of Caracol Gas Sandstone Reservoir are too small. Hence, in this Study it is strongly believed that the small size of Fans and depositional disconnected Lobes probably are owing to the Sand facies source, sedimentation rate, geomorphology and topography of upper bathyal environment not only due to the depositional processes which are turbidity currents and turbidity submarine channels.

7.1.4. Reservoir Quality Analysis

Thin-Section Ditch provided evidence of immature Sand facies, fine grained, angular-sub angular and high potential of calcite cement. The immaturity of Sand facies can be interpreted as due to the origin of Sand facies probably not being transported far away from the source. The Poroperm prediction for these Fan Sand lobate Turbidites is critical because, Porosity log [NPHI] shows high NPHI values and thus these values are in conflict with Thin-Section Ditch description which revealed immature Sand facies are not expected to have Porosity and Permeability up 30% and 250mD (Fig. 4). Therefore, Poroperm calculation using the available Side Wall Core-SWC rotary are strongly recommended for further evaluation.

7.1.5. Exploration Challenges and Potential Risk Analysis

The irregular Reservoir spatial Geometry distribution and their high ratio of disconnec tivities due to Clay/Shale interlayering (Figs. 13A-B) and Reservoir quality for example the complexities of poroperm values (Figs. 3 and 4) which were affected by immaturity of Sands facies. This evidence was revealed in the Caracol Gas Sandstone Unit III, Unit II (?) and Unit I consequently, they are the key challenges for the exploration and exploitation in the Lower Cretaceous Succession.

- **Depositional Environments Analysis and Modern Fan Models Reconstruction in the Lower Cretaceous Succession**

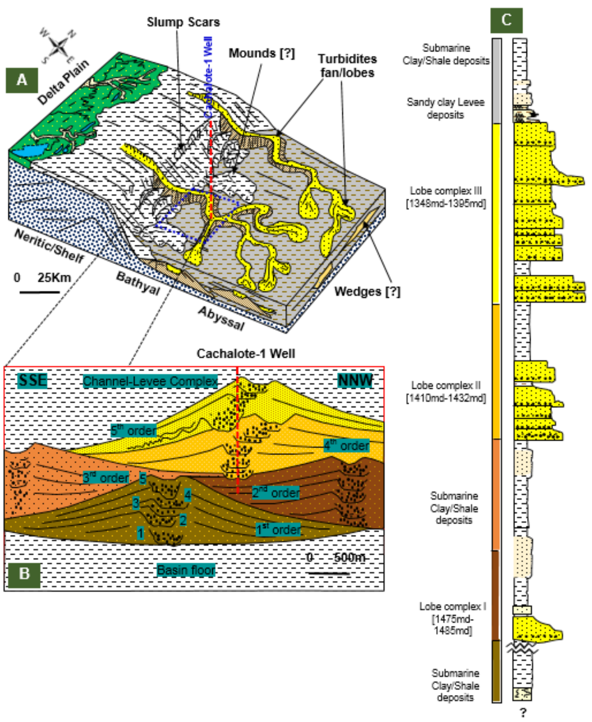

Fig. 14A. Shows an interpretative cartoon of depositional environments and the Study area (Blue doted rectangle ~ 7.0Km2) which is a Mud Rich System as reported in Mariani et al., (1984) and Key et al, (2008). Thus, integrated Analysis of biostratigraphic data such as mud forams, the Root Mean Square-RMS (Figs. 6B, 7B and 8B), combined with Spectral Decomposition-SD attributes Maps (Figs. 9-11) and Electrosequence analysis (Figs. 2A-B) indicate most likely the upper bathyal Turbidites deposits. These Fan/lobate Turbidites then had been deposited as Upper series of classical Turbidites. Hence, Reservoir Units III [1348md-1395md], II [1410md-1432md] and I [1475md-1485md] were interpreted most likely as middle-Fan Turbidites. The (Fig. 14B) indicates the profile enhancing stacked of Channel-Leveed Systems [e.g.: 1-5] in TWT vertical scale. This submarine Fan modified from Walker, (1992) of Channel-Leveed Systems are oriented to the WWS-SSE. The (Fig.14C) Indicates and interpretative stratigraphic column of the Reservoir Units III, II and I based on the Electrofacies Analysis (Figs. 2A-B) in the Lower Cretaceous Succession.

- **Reservoirs Units III, II and I Geobody Analysis and Lobes Elements Models**

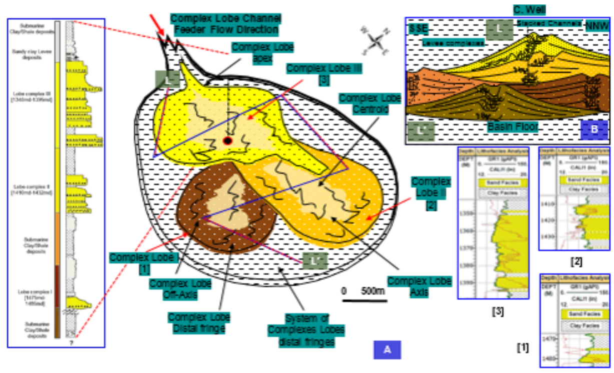

Fig. 15A. Shows an integrated Analysis interpreting the Geobody (Figs. 13A-B). The Geobody Analysis revealed stacked complexes of depositional Lobes in the Reservoir Units III, II and I with two trends and interbedded by Clay/Shale deposits. The complex Lobe I oriented to the NW-SE, complexes Lobes II and III shows low degree of shifting to the WWN-SSE. These shifting were interpreted as due to the effect of topography and geomorphology in the upper bathyal environment perhaps strongly controlled by submarine clay/shale deposits. The (Fig. 15B) is a vertical cross-section L-L' NNW-SSE of interpreted Fan/lobate geometries as an analogue of a Channel-Levee System based on Walker, (1992) scheme and for the horizontal scale can be used from the (Fig. 13B) and the vertical scale is in TWT as the same in (Fig. 5.) in the Lower Cretaceous Sucession.

8. Conclusions

The use of High Resolution of [i] Well Data by (1) Biostratigraphic Data Analysis, (2) Thin-Section Ditch, (3) Well Log Analysis. In addition, [ii] SEGY 3D PSTM Seismic Facies Analysis by (1) Root Mean Square-RMS, (2) Spectral Decomposition-SD and (3) Envelope attributes Maps Analysis. Finally, an integrated Reservoir imaging using [iii] Advanced Seismic Facies Analysis by (1) Geobody Analysis demonstrated to be useful Methodology for this Study and, therefore:

a) The Gross depositional Environment revealed by Mud Forams is specifically the Upper Bathyal and turbidity currents, turbidity submarine channels and middle Fan/lobate Sandstone Turbidites were reported as the Key most likely depositional processes and Products;

b) The Seismic Facies Analysis revealed Turbidites anciently deposited as Upper series in Channel-Leveed Systems. The Root Mean Square-RMS, Spectral Decomposition attributes Maps and Geobody Analysis enhanced Sand facies spatial distribution and thickness by imaging Fans/lobate shapes or geometries with high ratio of disconnectivities in the Units III, II and I;

c) The topography and geomorphology in the Upper Bathyal Environment are the Key highlighted factors under which controlled the spatial distribution, shapes and geometries of Sandstone Reservoirs and in those Unit III, Intra Unit III, Units II and I successions;

d) The Reservoir Quality (1) Poroperm properties, (2) Geometry and connectivity are critical and might be further investigated but some Fans/ lobate Turbidites may accumulate significant economic Hydrocarbons throughout the Lower Cretaceous Succession;

e) The (1) irregular spatial distribution and (2) complexities and high ratio of disconnectivities of Turbidites Lobes Sandstone Reservoirs which were promoted by topography and geomorphology in the Upper Bathyal Environment are the key elements identified as being the key concerns and challenges for Petroleum exploration and exploitation in the Study area.

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