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Implications of Sequence Stratigraphy for Hydrocarbon Prospectivity of the Late Miocene Shelf Edge Delta Play Onshore Niger Delta

Onyekachi Noble Ibezim [1*], Austin Nnaemeka Okoli[2] Derrick Oyinebielador Odondiri[3]Benedict Aduomahor[4]

[1] *Department of Earth and Atmospheric Science, University of Manchester, United Kingdom*
[2]*Department of Geology and Geophysics, Federal University of Technology Owerri,, Nigeria*
[3] *Department of Geology, Nigeria Maritime University, Okerenekoko, Delta, Nigeria*
[4]*Shell Center of Excellence in Geosciences and Petroleum Engineering, Benin, Nigeria*
[*]*Corresponding author: Onyekachi Noble Ibezim*

Abstract
The Niger delta has been through the first phase of exploration success with numerous discoveries made in shallower depths less than 12000ft. With a declining resource base from earlier discoveries, this study has shown that significant gas potential ~1TCF volume exists further down depositional dip confined in shelf edge deltaic systems. Such plays have been recorded in several passive margin basins to hold an enormous hydrocarbon resource base.
An integrated analysis from 565km^2 3D seismic data, log motifs, bio-stratigraphic and sedimentology information from selected 13 wells was used in developing a stratigraphic framework and to delineate depositional sequences for the Late Miocene Age deltaic system Onshore Coastal Swamp Depobelt Niger-Delta. Understanding the origin, position and depositional controls of sequences within shelf edge deltas are important in predicting the depositional limit of the play fairway and reducing risk to reservoir seal and source elements. These systems are exceptional exploration targets possessing various characteristics such as an expanded and over-pressured reservoir section enclaved in thick deep water shales. Controls on stacking patterns can be closely linked to interaction between relative sea-level and sediment supply. Understanding the scale of sequence hierarchy is crucial in predicting volume of sand that will be available in deep setting and in forecasting intra-reservoir connectivity
Two 3rd order depositional sequences approximately 0.9, and 1.1 M.Y. in duration bounded by type1 4th order sequence boundaries were delineated. The sequences were interpreted between two maximum flooding surfaces on the basis that they have been age dated from known biomarkers.
Sequence 1 corresponds to a relative still-stand having a sequence boundary (SB1) deposited during normal regression. The SB1 represents a surface filled with ~950ft amalgamated channel belt with its orientation mostly influenced by growth faults. Depositional controls can be related to frequent high order relative sea level changes. Facies within this sequence are mainly lower delta plain, abandoned channel fills and wave-tidally influenced prograding shallow marine sandstones.
Sequence 2 consist a lowstand wedge composed of a deltaic system that formed during falling relative sea level, at periods quite efficient in delivering huge sand budget from an up-dip could be tidally influenced distributary system flowing north-south. The sequence boundary was placed on a surface identified as an erosional base filled with amalgamated tidally reworked distributary channel and foreshore facies which also shows prints of stratigraphic termination at the top and base of the wedge. Five Major litho-facies which are the distributary and tidal channels, tidal mudflats and heteroliths and foreshore sands are inferred within this sequence.
Below this sequence boundary, seismic geometry shows shelf-margin clinoforms prograding into deep water. Interpretations suggest a shelf edge delta succession deposited at highstand sited inboard on the outer-shelf. This is evident from the wheelers model showing large volumes of sediments retained landward which tend to reduce into deep water areas.
Keywords: *Shelf edge deltas; Wheelers Model; depositional sequences; clinoforms; lowstand wedge; highstand*

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I. Introduction

There is growing need for newer discoveries as a result of a declining resource profile from most hydrocarbon fields within the Niger-Delta basin, as earlier discoveries within the basin where shallow and quite easier to explore. At deeper depth, challenging resolution of seismic data, lack of well penetration and with evidence of no DHI, it becomes necessary to predict and de-risk most element of the hydrocarbon fairway using accurate techniques that will certainly improve exploration thoughts within the basin and at prospect scale levels in a new hydrocarbon play. One important technique that has proved itself helpful involves making analysis from a sequence stratigraphic approach, by integrating information from seismic, biostratigraphy and well data in order to create time-stratigraphic framework to analyse depositional sequences, identify systems tracts, map and correlate sedimentary packages. Understanding the scale of sequence hierarchy is crucial in predicting sand distribution available in deep setting and in forecasting intra-reservoir connectivity. Such integration can reduce the scale disparity between seismic and well data. However any confident sequence and facies analysis relies heavily on the presence of facies indicator usually best observed from seismic configuration and termination patterns.

The study area lies in the middle part of the Coastal Swamp Depobelt of Niger-Delta Basin (Figure 1) and has produced huge hydrocarbon volumes since its first exploration well was spudded in 1958. This study was designed to create a high resolution sequence stratigraphic framework. The objective also stretches further to define and refine the hydrocarbon play and specific prospects as parts of efforts to support the ongoing HPHT exploration campaign within the delta. It was done to examine the joined effect of sediment supply and relative sea level on stacking patterns. Having a good idea of the controls on depositional sequences is crucial to understanding temporal and areal variations in depositional systems and distribution of sedimentary facies. These keys can help forecast the hydrocarbon potential of the recognized play mapped within the area of interest.

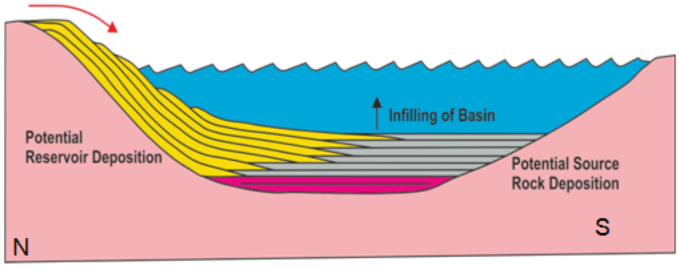
Shelf-edge delta plays have been discovered within the Niger-delta basin as of recent and only little information about such play type has been published in papers as compared to similar passive margin basin and world-class hydrocarbon province such as the Gulf of Mexico(Suter and Berryhill, 1985; Sydow and Roberts, 1994; Morton and Suter, 1996; Roberts et al., 2000). These play types are unique as they are vital to huge reserves holding enormous pay zones and can be conduit systems that deliver sediments into deep water environments. Correct identification of this delta type is important as they possess certain structural and stratigraphic fingerprinting character such as being linked closely with outer shelf growth faults, having significant section expansion with enlarged reservoir sections, fascinating facies change etc. Understanding the time of formation of this delta system whether during falling or rising relative sea level has gross implication in predicting available sand budget present in distal environments (Burgess and Steel; Patruno et al 2015;Steel et al 2000).

1.1. Geologic setting

Numerous papers over the last four decades have outlined the regional geologic setting of the Niger-Delta Basin (Webber and Dakoru, 1975; Lehner and De Ruiter, 1977; Evamy et al, 1978; Doust and Omatsola, 1980; Whiteman, 1982; Reijers, 1996; Turtle, 1999; Hooper et al 2002; Deptuck et al 2003; Steffens et al, 2003). Current sequence stratigraphic models for the basin (Ozumba, 1999; Olusola and Brian, 2007) have sub-divided sedimentary sections into depositional sequences, system tracts and their gross implications to prospectivity using integrated data sets. Recent work by (P Jermannaud et al, 2009, D. Rouby et al, 2011; V. Riboulot et al, 2012), were based on understanding the factors controlling geometry, architecture and migration of Pliocene-Pleistocene depositional sequences of shelf-margin deltas within the Eastern Niger-Delta using high resolution 2D seismic single-channel reflection seismic profiles. Their work showed how the combining effects of variation in sediment supply and eustasy driven by climatic changes controlled depositional sequence stacking and migration or retreat of delta beyond the shelf edge position.

Formation of the Niger-Delta basin can be related to the opening of the South-Atlantic before Cretaceous (Burke et al, 1972). So far the basin has been grossly impacted by gravity tectonics that has clearly modified and created the modern morphology of the delta today (Merki, 1972; Wu and Bally, 2000; Bilotti and Shaw, 2005).The delta has been through series of rapid progradation in a southward direction due to sea level fluctuations creating extensive deposition of reservoir and seal pairs. Total basin fill within the delta is about 11km and extends over an area of 75,000km^2(Short and Strauble, 1967). Models for basin fill for the delta can be compared closely to those of the Gulf of Mexico where loading and subsidence dominate within the basin.

Basin fill are all of Eocene-Recent age (



Cenozoic

- Eocene Akata and Miocene Agbada source rocks
- Miocene Agbada reservoirs
- Miocene shale seals

- 2styles of deformation
- Parallel normal fault & Down-Basin fault
- Down-Basin fault flattens at decollement surface
- Generating several depobelts
- 11km thick sediments

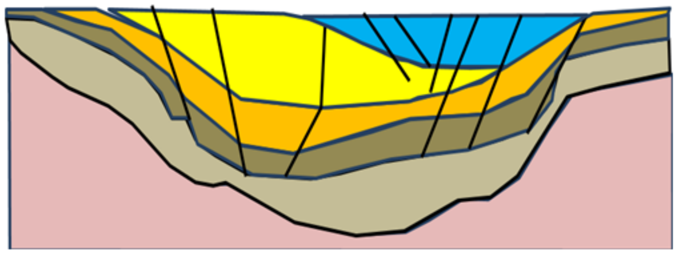


Figure 2) and are well known to be divided into three formations (Akata, Agbada and Benin).The basin was subdivided into five major depobelts (Figure 1)on the basis of structural-bounding faults that control deposition in the delta. These depobelts mark a break in regional dip in the delta and are bounded by growth faults landward and counter regional faults seaward (Doust and Omatsola, 1990). Parallel normal and down to basin growth faults are the major structural styles that dominate within the basin (Owoyemi and Willis, 2006), these faults generally show a curvilinear nature and are aligned concave to the south. Major faults show displacements over large areas, flatten unto a decollement surface at the top of under-compacted over-pressured shales sometimes referred to as shale ridges. These major faults cut into older faults that are characterized by branches commonly referred to as splays. Several structural and stratigraphic play configurations have been encountered in the basin but of renewed interest are shelf margin plays which are deep high pressure and temperature target.

1.2. Location, Dataset and Methodology

The study area lies in the Eastern part of the coastal swamp depobelt of the Niger-delta (Figure 1). The first exploration well within the study area was spudded in 1958

The dataset used for this study was an integrated data set consisting of seismic volume covering 5 hydrocarbon fields, a selected list of well log suites, information from biostratigraphy and sedimentology report were used in creating the depositional framework and correlating strata packages across the entire study area. In order to achieve a robust interpretation all datasets were tied together

About 575km^2 3D Post stack depth migrated seismic volume with a cross-line and inline sampling rate of 4s/25mhaving a vertical time limit to 6s was used. The quality of the seismic data was of good to fair resolution especially at shallower depths of up to 2.5s hence mapping was considered straight forward as visualization was easy. However interpretation became increasingly more difficult at deeper depth below 3.5s as several factors such as noise interference, fault shadow made mapping and interpretation difficult.

Biostratigraphy information was obtained from 3 wells within the study area for calibration. This information requires a high degree of reliability for it to be used in assigning the relative ages of depositional sequences using micro-faunal biomarkers of foraminifera/planktonic population and diversity. This helped in producing a rigid framework to examine the depositional systems through dating of the Maximum flooding surfaces so that cycles recognized together in relation to their position in respect to age can be compared to the global eustatic cycle.

About 13 Wells were used for this interpretation and were chosen on the basis of certain criteria such as depth of penetration, suite of log they possess etc. Interpretation from well logs and sedimentology reports were used in dividing sedimentary packages and identifying depositional facies. Changes in stacking patterns and character of specific log types such as neutron-density crossover and spontaneous potential logs were also used in placing correctly bounding surfaces maximum flooding surface were placed on the point of largest separation of the neutron- density logs. Facies identification and prediction involved an integrated approach using seismic, well and sidewall sample information. Analysis done on facies interpretation using seismic character was based on ability to make interpretation in terms of character, configuration and continuity (Van Wagoner et al 1988; Vail and Wornadt, 1991; Mitchum et al 1993; Posamentier and Allen, 1999) . Reflection discontinuities were used as criteria for marking sequence boundaries while amplitude character and down-lapping geometry was useful in placing maximum flooding surfaces. Responses from Neutron-density log separation combined with sidewall sample information provided for some wells were used in facies identification and interpretation. Specific log character and signature can be tied to certain depositional facies

External geometries of facies were also interpreted by recognizing patterns using seismic attributes that were extracted. This attributes were generated by mapping the top and base of reservoir tops at every 25m interval for a dense grid spacing and generating maximum amplitudes to look for subtle geologic features. Recognizing such pattern was quite difficult because there may be little or no amplitude contrast between a sedimentary fill in a shelf environment and its surrounding lithology. The attribute used was a spectral decomposition workflow produced by blending the original seismic volume and the semblance volume. Isochore or thickness maps trends between packages were also useful in making predictions of possible reservoir facies and predicting sediment source direction. Such maps are also useful in predicting depositional environment and sedimentation pattern.

Time stratigraphic charts or wheelers diagram were made both in 2D and 3D to provide hints about the temporal variations in the depositional system by predicting areas where sediment exist, where removed or were never deposited in the geologic time (Wheeler, 1959). The 2D model was hand drawn by representing the base and top of the strata on a cross-section and flattening the mapped events. A 3D time stratigraphic model was done using the thinning and layer-cake attribute to highlight areas with consistent seismic facies, to distinguish differing seismic characters and thickness of packages. Such stratigraphic analysis has been helpful in reducing risk to elements of the play fairway.

An exploration based risk assessment process was used in de-risking the prospects, the technique involved using a model risk (bottoms up) or data driven interpretation and observational risk (top down). Each play element was assessed and mapped on a risk matrix diagram. This risk matrix pattern can be useful in making informed decision of further analysis or data acquisition programme that should be carried out.

An assessment of the reserve base was done by mapping reservoir levels ascertaining areas with closure to prove the prolific nature of this shelf edge delta play. A three point estimate method was used in making the calculation by cross multiplying all low, mid and high of each parameter. This method is useful as it provides a nearly accurate estimate in the absence of a Monte-Carlo simulation program (REP software)

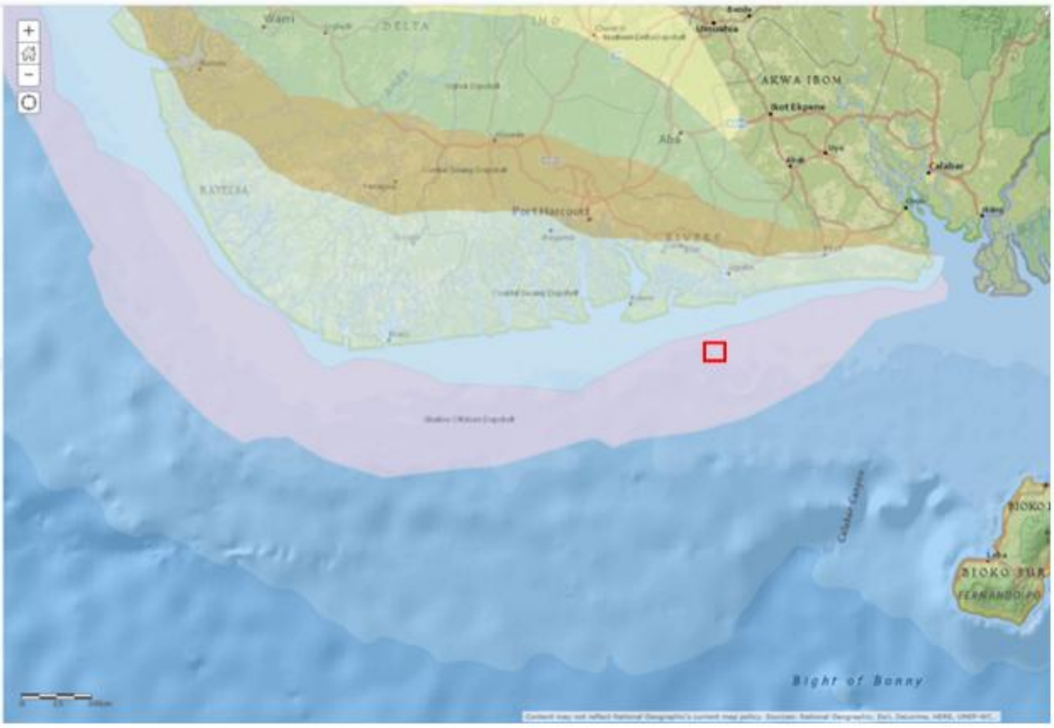


Figure 1: Map of Niger Delta basin showing the five different depobelts taken from my maps

Coastal Swamp   Shallow Offshore   Central Swamp   Ughelli

Northern Delta

High sediment influx into Niger delta

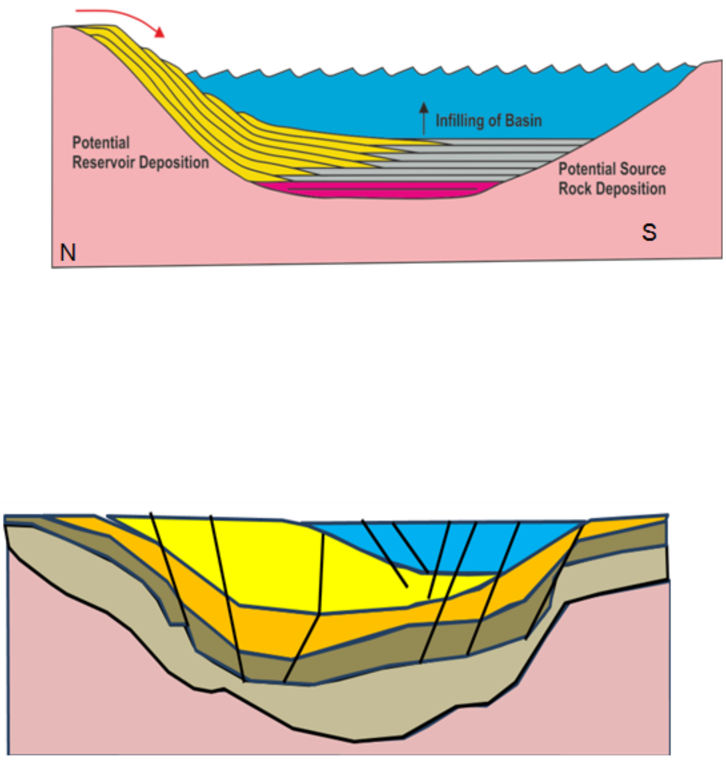


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Figure 2: Schematic diagram showing structural evolution of the Niger-Delta Basin (A) shows influx of sediments into delta depositing thick Eocene-recent sediments (B) shows the parallel normal and listric fault types peculiar in the delta

1.3. Structural Overview

Three main fault nuclei with well-defined fault boundaries and patterns were observed to be present within the study area as seen below on the semblance time slice map view at exactly 1800ms (Figure 3). These major fault nuclei control deposition and show a curvilinear trend which is concave to the south. These faults are related primarily to sedimentary loading showing displacements over large areas and tend to divide the area into several compartments. The middle fault seen below seems to be the major syn-depositional down to basin listric fault controlling accommodation on the shelf. This major fault systems act as major structural traps and flatten towards a detachments surface inferred to be a shale ridge .One characteristic of these major growth faults are the associated branching fault. These branching faults are splays and are older than the main growth faults. They were initially formed and were cut by the younger more active fault controlling deposition. Other parallel normal faults exist and are usually characteristically equally spaced.

There are equally spaced lines running from north – south and should not be mistaking for any geologic feature as they have been interpreted as acquisition imprints from the data.

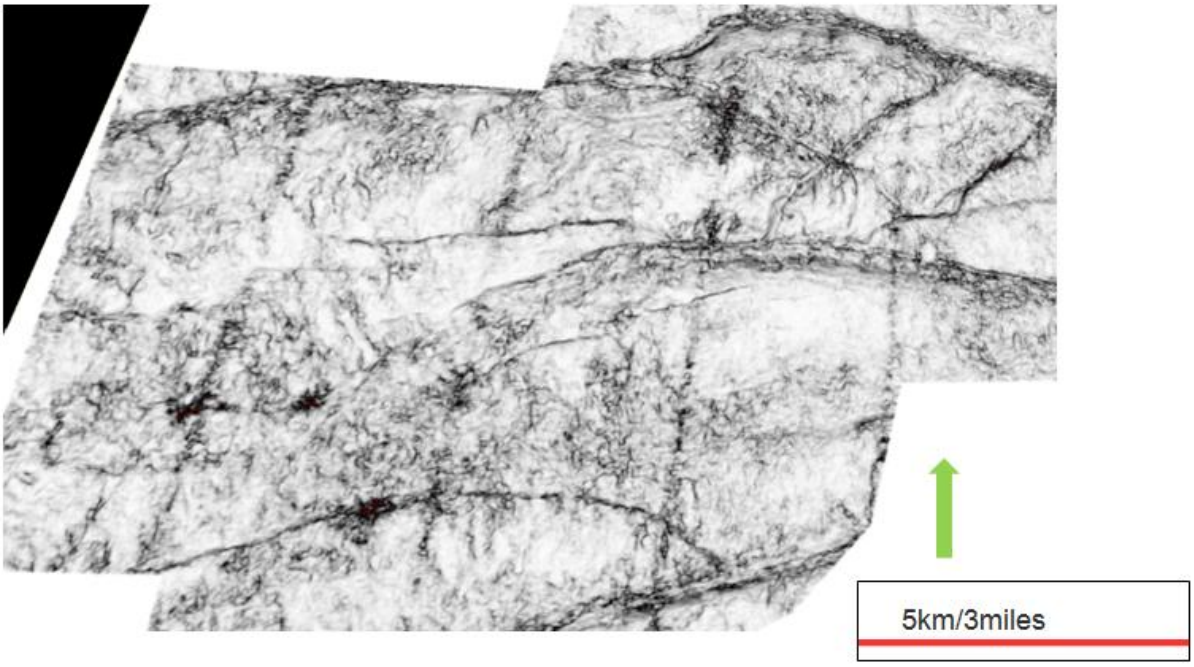


Figure 3: Semblance map view at 1800ms showing North-South orientation of major faults within the study area

1.4. Seismic –Well Integration

In order to bridge the gap between the well data and seismic data, a synthetic seismogram (Figure 4) was generated from the sonic and density logs from Chukku-01 well. Wavelets had to be extracted using the statistical method and a slight bulk shift of 20 milliseconds was used to enhance the degree of reliability of the synthetic generated. The generated synthetic seismogram was tied to the seismic data at a confidence level 0f 80%, below are the results of the generated well ties along with their stratigraphic markers. Soft loops marked the tops of the following stratigraphic markers, 1st Maximum flooding surface, 1stdepositional sequence boundary, 2nd Maximum flooding surface and UU 10000

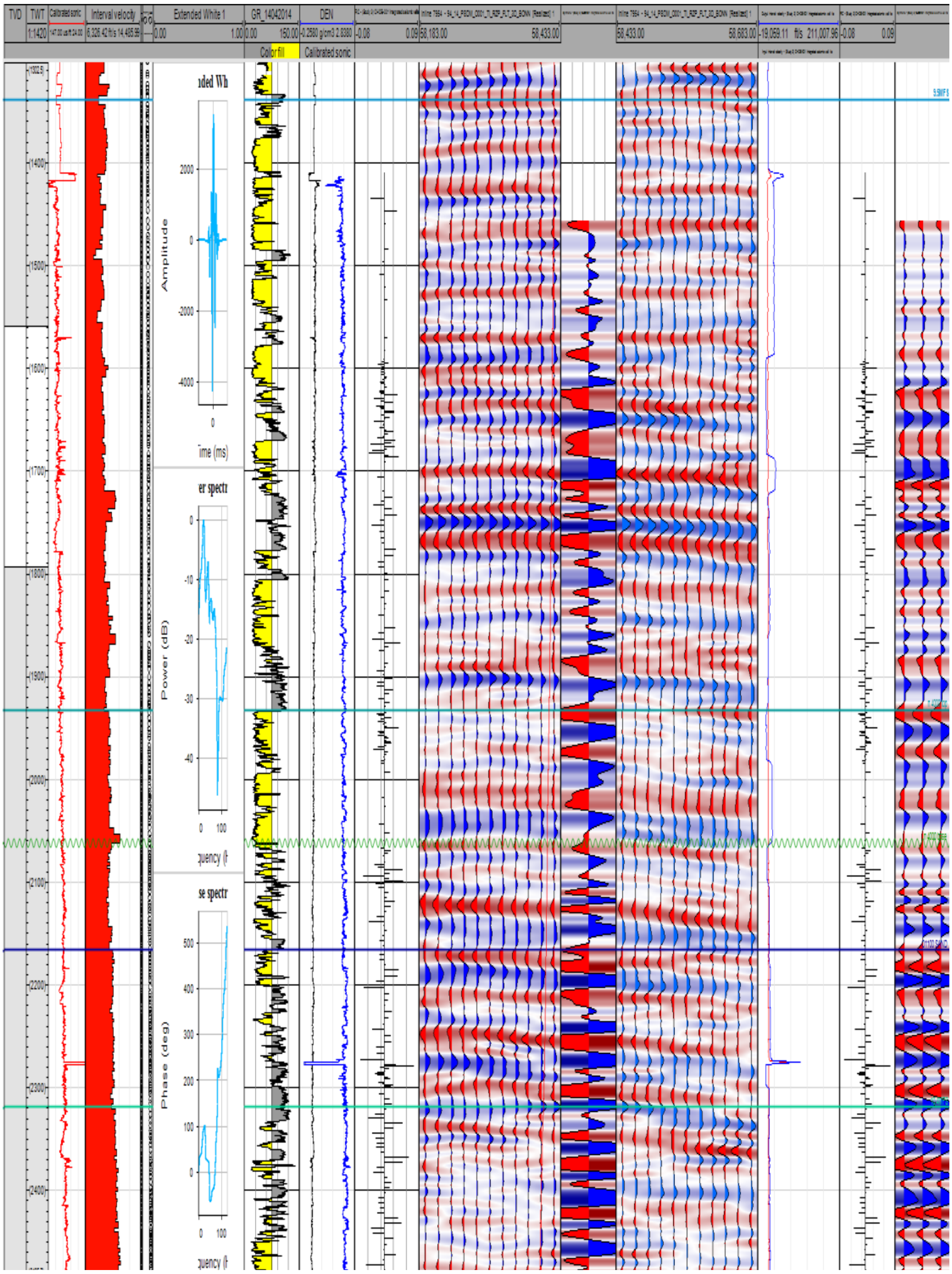


Figure 4: Well-Seismic tie using extracted wavelength from original seismic volume

II. High Resolution Description of Depositional Sequence 1

Depositional sequence 1 (figure 6) is defined by a Maximum flooding surface 1 (9.5) and a Maximum flooding surface 2 (10.4).This interval marks a period of 0.9myr placing it on a 3rd order sequence hierarchy which are useful exploration scale sequence. This interval is approximately 5000ft thick. Variations in thickness exist especially increasing towards major growth faults.

Maximum flooding surface 1 was placed as a timeline marking the base of the Benin Formation. Well information clearly shows that above this surface is an interval of approximately 5000ft of stacked units that are highly aggradational while seismic facies shows this unit to be highly chaotic typical of reflection patterns common in continental settings.

Maximum flooding surface 2 is represented by the Nonion- 4 Marker bug. On Chukku-1 and Borth-1 wells the Foraminifera and Planktonic abundance and diversity is high (**Error! Reference source not found.**)

and corresponds on logs to the same surface showing highest neutron-density log separation, the highest gamma ray, low sonic velocities in the more proximal parts indicative of possible coals associated with flooding events and the lowest resistivity value as compared to other candidate flooding surfaces. Seismic reflections show that this surface is easy to identify, characterized by high amplitude continuity within a fault block and downlap reflections at the top of the surface (**Error! Reference source not found.**). This downlap event gives some information of a condensed interval related to source deposition. On the major transgressive –regressive curve this surface is absent however one interpretation could be that the surface could have formed during the interaction between changes in base level and sedimentation rate.

A 3rdorder surface separating this interval into key depositional systems was delineated. This surface reflected a change in stacking style which could be a result of interaction between changes in base level fluctuations. It was marked the sequence boundary 1 and was identified using all data sets that pointed out the characteristics of such a surface. From well correlation this surface has a sharp base, filled with a typical amalgamated incised channel complex. This surface shows that the underlying coarsening upward packages clearly truncate against it. In some wells there were indications of very low minimum Foraminifera and Planktonic abundance and species diversity. The surface showed a trend of increasing flooding surface resistivity and a decreasing flooding surface neutron porosity. Above this surface to the maximum flooding surface 1 marks the Lowstand systems tract 1 (LST1), while below this surface to the Maximum flooding surface 2 marks the Highstand systems tract 1 (HST1) . This is a clear indication of a change in stacking pattern from a more progradational event below to a much more aggradational event above. This stratigraphic division represents 3rd order systems tract deposited within the shelf in marine water depths that range from inner neritic-middle neritic.

Generally the lowstand interval is characterized by parallel continuous high-low amplitude seismic facies however subtle loop scale highly resolvable seismic facies where observed at different scales on several line sections. The observed seismic facies can be divided into three.

1. Highly continuous transparent seismic facies with an erosive basal surface. This surface marks the 1st depositional sequence boundary was probably formed during normal regression at sea level still-stand when accommodation space was less than sediment supply. It is characterized by clear erosive cut closely associated with the fault systems (Figure 6), a curved geometry and good lateral extent (Figure 5) especially when viewed on a seismic section parallel to the depositional dip direction.
2. Loop scale, low angle oblique delta front seismic facies (Figure 7)

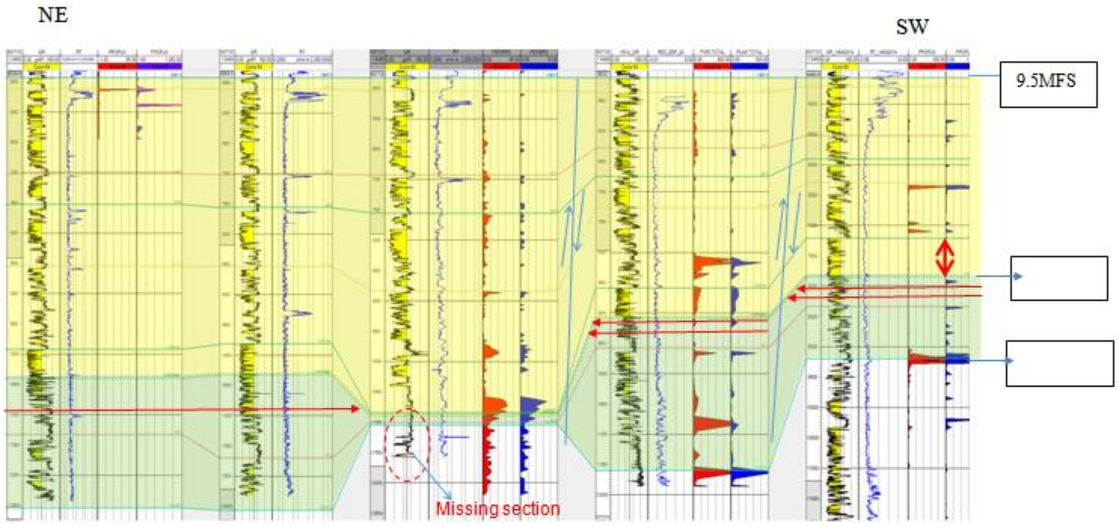


Figure 5: Dip line correlation showing the 1st depositional sequence and systems tract delineated within the interval

Lowstand systems tract 1

Highstand systems tract 1

Depositional sequence boundary 1(10.35SB)

Truncation

Parallel high and low amplitude continuous shelf seismic facies

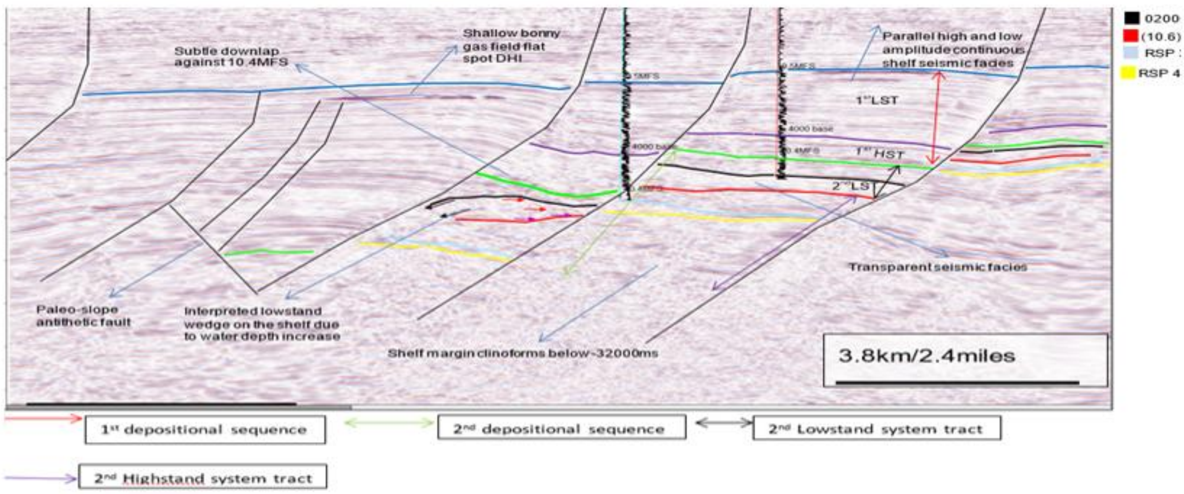


Figure 6: Seismic dip line 7950 section showing interpreted Listric faults, depositional sequences, and key stratigraphic surfaces

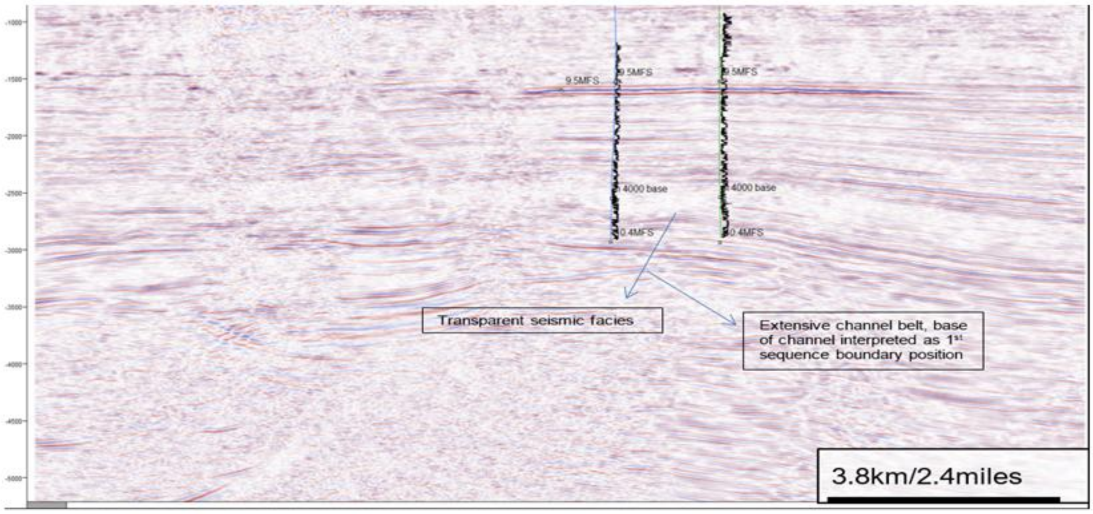


Figure 5: Seismic strike line section showing extensive nature of the amalgamated complex filling the 1st depositional sequence boundary surface

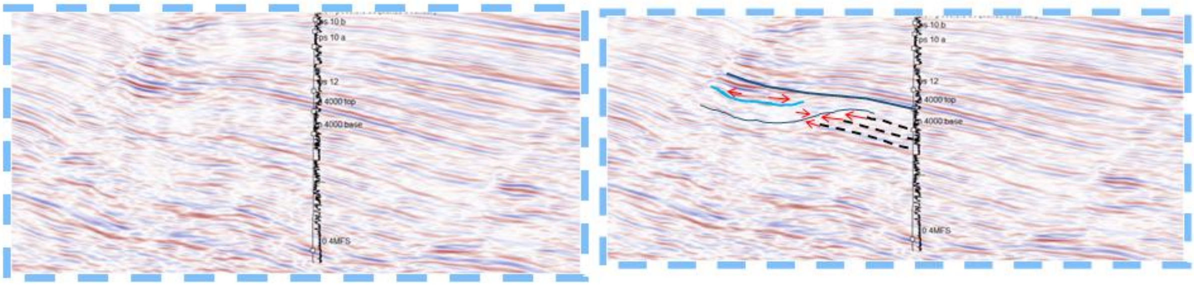


Figure 6: Seismic section of the Amalgamated channel fill of the 1stsequence boundary, observe clear truncation terminations behind channel: (A) uni-nterpreted line (B) interpreted li

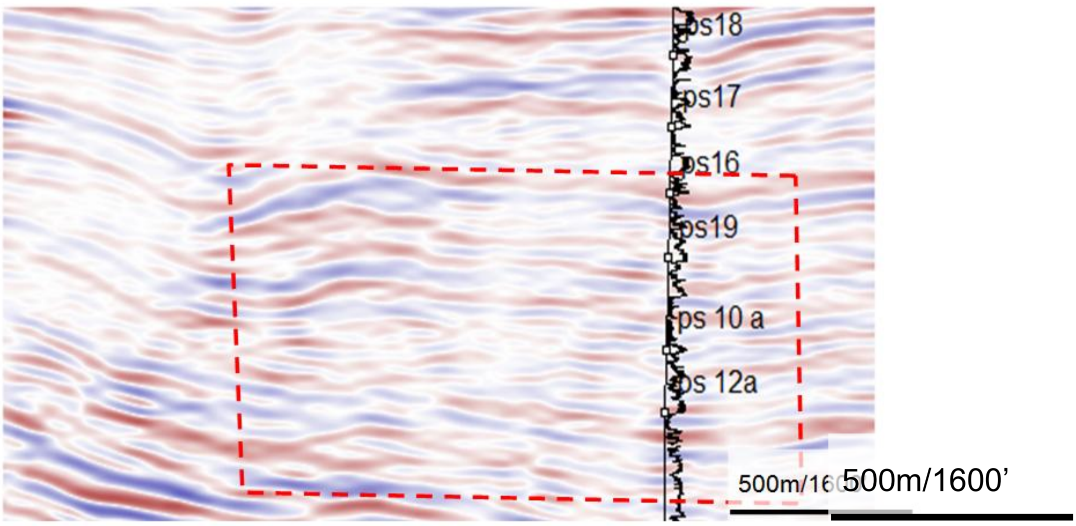


Figure 7: Screenshot seismic section showing loop scale delta front seismic facies observable at shallower intervals

a. ***Isochore Maps and Attribute Extraction*.**

Two isochore maps were generated between the lowstand systems tract 1 (LST1) and the highstand systems tract 1 (HST1). The objective behind this was not only to attain figure based information but also to see a visual perspective of thickness relationships to enlighten interpretation with regards to processes such as environment of deposition, growth, progradation energy regimes, sediment supply and direction of sediment sourcing. When integrated with seismic stratigraphy the thickness maps showed a change between depositional environment related to rise and fall of relative sea level.

i. Lowstand Systems Tract 1

The 3rd order lowstand systems tract is characterized by numerous high frequency order blocky-serrate, upward finning and coarsening sandstone units. It is widespread, usually at high angles and at times locally incises some of the underlying highstand systems tract. The interval shows a highly aggradational pattern at the base composed of amalgamated incised channel belt and a progradational-aggradational trend above this channel complex. There is a bifurcating thickness (Figure 8) trend to the SE suggesting a fluvial system that flowed from the NNW. There is an increased thickness associated with onlap and basal truncation towards the major depocenter, thus running the possibility of having one or more numerous feeder systems at the time of deposition.

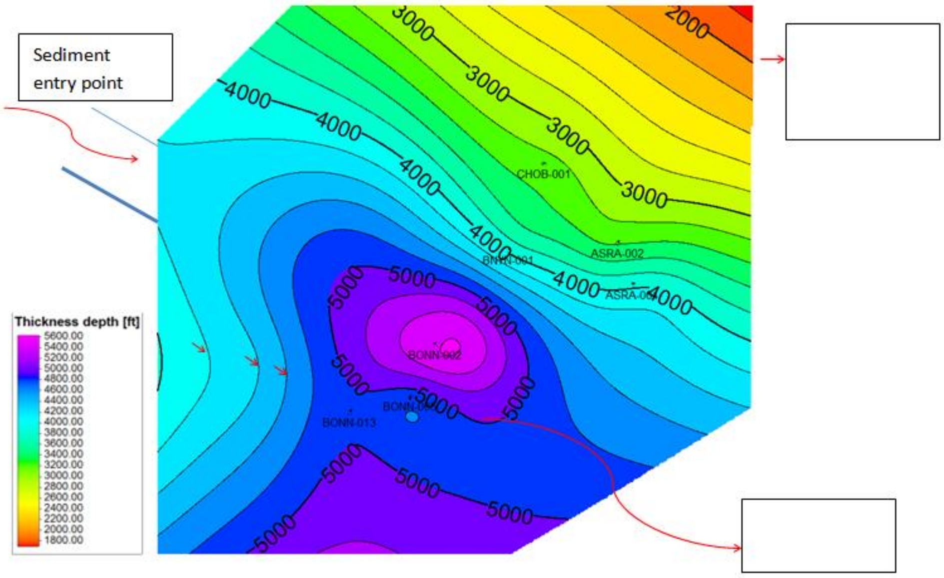


Figure 8: Isochore map generated for the 1st lowstand systems tract showing sediment source direction and possible depocenters

Attribute extraction (Figure 9) performed between the top and base of the N4000 (marking the position of the 1st depositional sequence boundary) reservoir shows geometry of a likely incised channel belt. There is no amplitude contrast from the extraction. This may be due to the fact that the fill of the feeder system is similar to those of the surrounding lithology. However the orientation of this channel belt tends to be affected by growth faulting mostly on the hanging wall of the fault. One interpretation shows that as this channel belt draws closer to the fault at a slightly increased angle to the strike of the fault, it may come up downstream of the fault mostly perpendicular to the strike of the fault. The tendency for frequent avulsion affecting this channel is less as this channel is a long lived feature believed to have been formed in the duration of 10,000-80,000 years. However above the top of the channel belt numerous short duration aggradation/progradation sequences exist and were probably caused by Milankovitch-type sea level variations. This feature strengthens interpretation on the depositional controls within the LST package to probably have been caused more by interplay between climate and eustatic driven variations.

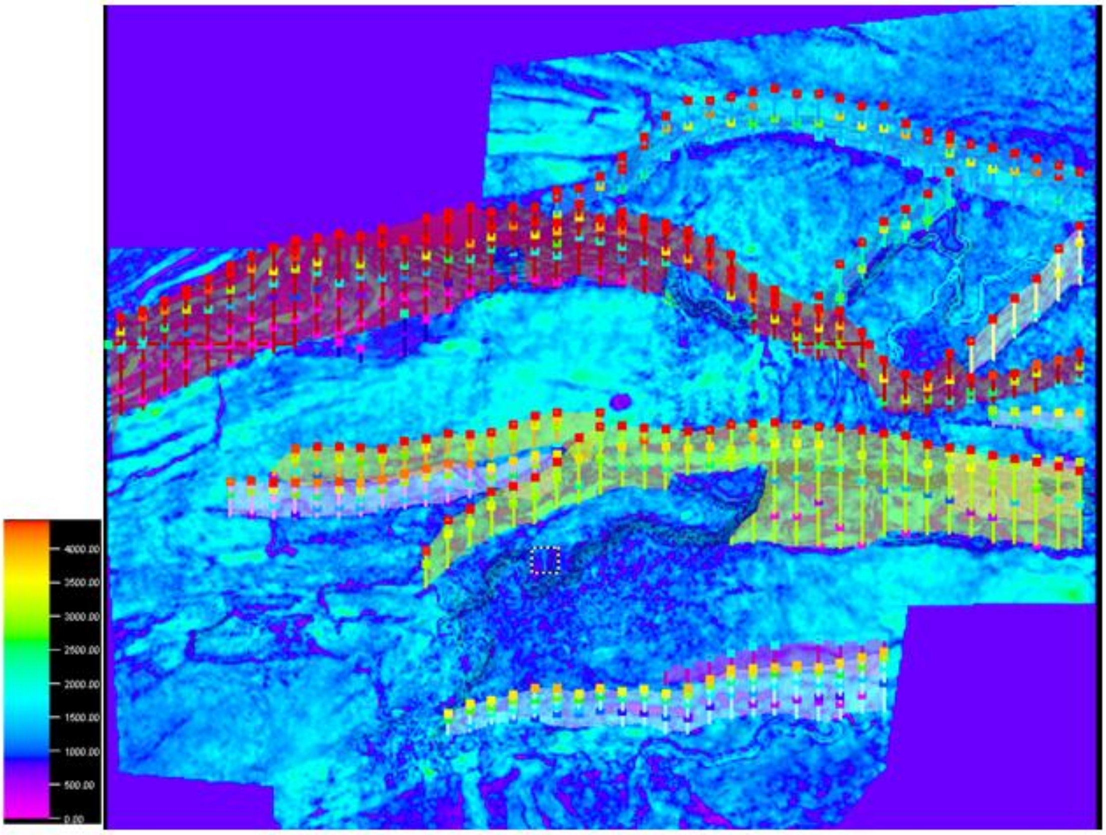


Figure 9: Amplitude extraction showing the Structural effect of the growth fault in controlling the orientation of the channel belt shown in especially on the hangingwall block.

ii. Facies Interpretation and Conceptual Model

Interpretations of facies were done based on selected suite of well logs (neutron-density, gamma, and resistivity) together with information from sidewall samples. This was useful in typing each identified facies to its depositional environment. Use of log shape only provides quantitative interpretation which sometimes may be misleading e.g. as shoreface sand may have both blocky and upward coarsening trend, however this bias can be overcome if trends are tied back to any other information. Five major litho-facies where identified, they include abandoned channels, channel heterolith, floodplain mudstones, shorefaces/delta front and offshore mudstones

Channel sands (figure 16) show blocky serrated trend having API values of 20-40 while Neutron density separation is in the range of +10 to -5.Analysis from ditch cuttings showed the sands are medium grained, loosely consolidated, contained carbonaceous matter and mica flakes. Typical occurrences of carbonaceous matter found in cores, outcrops and sidewall samples have been well recorded in published literature works (Hampson et al, 1997; Hampson and Flint, 1999; Olsen and Steel, 2000). One interpretation could be they were deposited as a result of decrease in current velocity allowing organic material to be deposited. They are found in depositional settings with slight fluvial influence such as the lower delta plain. This facies have been interpreted as abandoned channel facies.

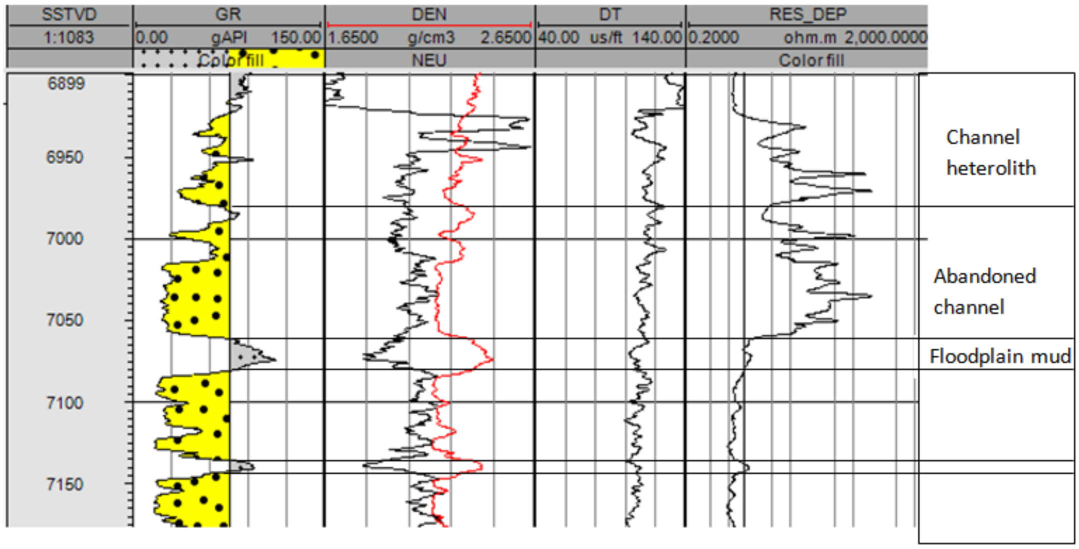


Figure 10: Well correlation panel showing interpreted depositional facies, interval mainly channels and heteroliths

Channel heteroliths (Figure 10) tend to have API values within 50-90 API with a neutron density separation in the range of -5 to +15. Shoreface/delta-front sands (Figure 11: Well correlation panel showing interpreted depositional facies, interval mainly shoreface and offshore mudstones) tend to show a gradational reduction in API value usually from 100-30 having neutron density separation in the range of -5 to +5. They also tend to have less mica flakes which could be a function of frequent removal from the effect of wave action and are usually well sorted. Offshore mudstones facies tend to differ from floodplain mudstones. The former tend to have a wider separation in neutron-density separation than the later.

The lowstand package is believed to have been deposited in the inner-middle shelf environment filled with abandoned channel facies and delta lobe switching composed of lower delta plain and shoreface sands.

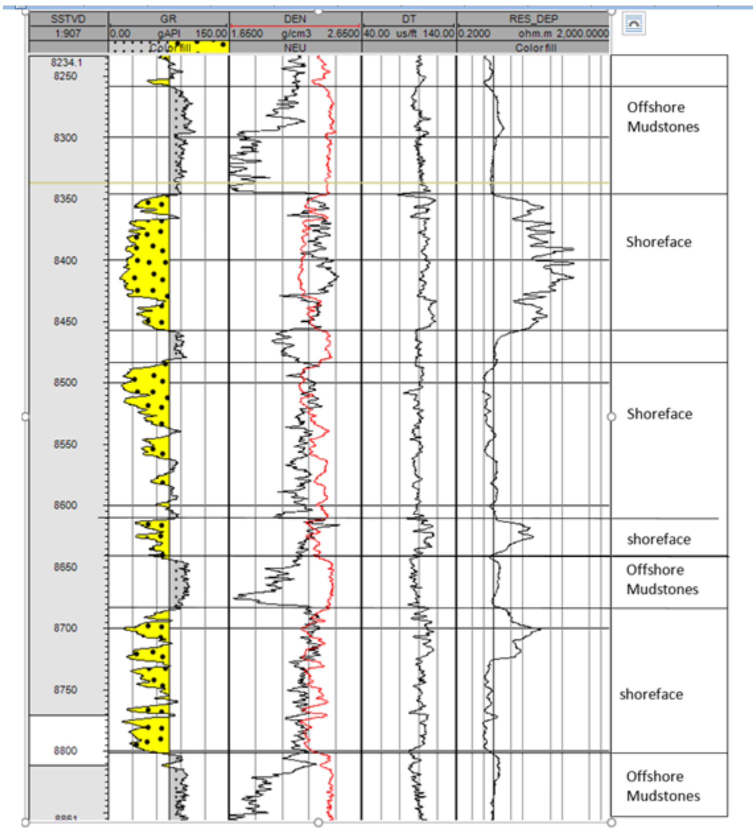


Figure 11: Well correlation panel showing interpreted depositional facies, interval mainly shoreface and offshore mudstones

A conceptual model (Figure 12) was done for the lowstand interval to provide a pictoral representation for the subsurface. It helps in reducing uncertainty in predicting spatial heterogenity within the field and provides prior knoledge for modelling the reservoirs. Model is consistent, matches all observed data as much available geological information has been put into it.

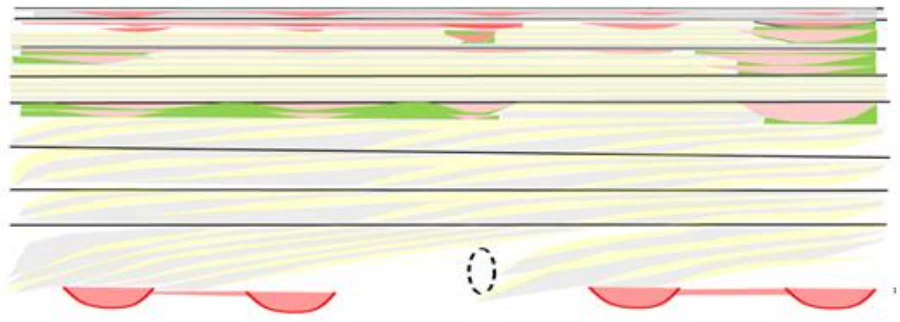


Figure 12: idealized conceptual model for the lowstand interval

b. The Highstand Systems Tract 1 (HST 1)

This interval beginning from the base of the sequence boundary 1 to the maximum flooding surface 2 was deposited within a duration 0.05kyr placing it in a 4th order sequence hierarchy. It is locally incised and usually at high angles to the overlying amalgamated channels. Reflection patterns for this interval shows prograding reflections and an actual downlap onto a condensed section that marks the surface of the maximum flooding surface 2.They show distinct progradational stacking pattern typical of deltas building out in an inner-middle shelf environment, generally recording a shallowing upward trend. Changes within the system such as lobe switching could be a primary factor influencing deposition. Isochore map (Figure 13) show geometry of one or more deltaic lobes that can be resolved in areas of well control. Thickness of sands within each individual parasequence is expected to decrease distally.

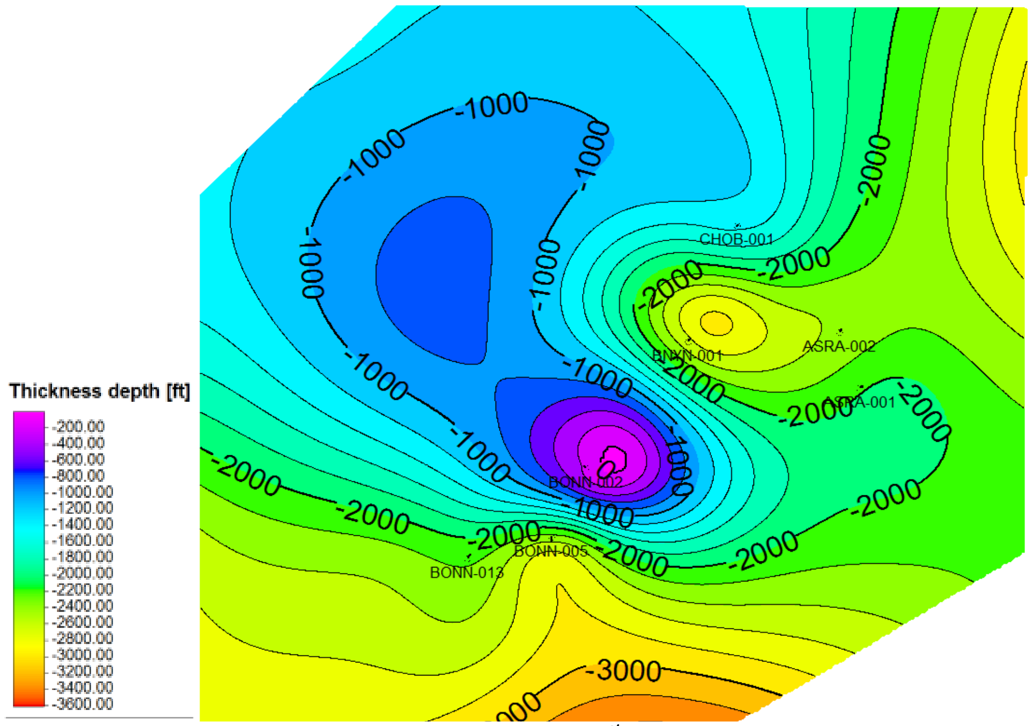


Figure 13: Isochore map generated for the 1st highstand systems tract

c. Implications for Prospectivity of the 1st Depositional Sequence

In terms of hydrocarbon prospectivity and reservoir development the amalgamated channel belt fill of the lowstand systems tract 1 will have excellent reservoir potential and may likely represent one flow unit as both vertical and horizontal permeability will be high and uniform. It can be very extensive mappable for more than 10km in a basin-ward direction. It has a high degree of connectivity and lateral extent as compared to the units above it characterized by very small channel systems which may be limited to less than 6km of lateral extent because of frequent avulsion rates. The tendency of this will be individual channel systems may likely not be connected and possibility of flow barriers may exist. Vertical and horizontal permeability may likely change or decrease as flow units are not connected. Porosity trends from few of the wells within this LST package run the possibility of a rich reservoir fairway. The lowstand systems tract has excellent reservoir quality and seal juxtapositions as hydrocarbons will be highly distributed. The highstand systems tract 1 (HST1) has some potential but net sandstone quality and vertical permeability will decrease in a downdip direction. Reservoir connectivity may likely be regarded to be moderate-fair as connectivity may be complex. Shales within the highstand interval are usually gas prone as each individual flooding surface will act as top seal. It should be noted that The LST 1 and HST 1 will form separate reservoir compartments.

III. High Resolution Description of Depositional Sequence 2

Depositional sequence 2 is defined by the maximum flooding surface 2 (10.4) and the yet to be identified maximum flooding surface 3 (11.5). This interval is further separated into key depositional systems by a 4th order depositional surface (sequence boundary 2). Identification of this surface from wells is quite easy and on seismic requires key interpretation skills. This boundary was placed on a surface that shows both an onlap at its top and a downlap termination. Oblique clinoforms found present in the more proximal position are associated with defining this sequence boundary. This sequence boundary was probably formed during interplay between changes in base level and rate of sediment budget at the shoreline. It could be as a result of interaction between a rising base level and a positive sedimentation rate leading to a wedge deposited above this surface at lowstand under normal regression. This wedge is situated on the outer shelf down to basin listric fault which could have created local subsidence and accommodation space. The interval discussed so far marks the lowstand systems tract 2. Two reservoir sections make up this interval, the RSP 1 and 2. So far only few wells have penetrated the RSP 1 and interval made up of tidally influenced amalgamated complex consisting of distributary channel system and foreshore deposits while the RSP 2 consists mainly of upper shoreface sands.

Below this sequence boundary 2 are shelf margin clinoform hundreds of metres in amplitude building out into a basin several hundreds of metres deep at a high rate probably at highstand conditions. Although loop scale clinoform that are indicative of the existence of a delta are absent probably due to data resolution. However stratigraphic models can only prove an initial deltaic phase with high sedimentation rate landward that actually reduces in the basinward direction. This interval has been interpreted to represent the highstand systems tract 2.

a. Lowstand Systems Tract 2

This interval contains the 02000 and 03000 reservoir prospects and begins from the maximum flooding surface 2 – the sequence boundary 2. It is roughly about 2500ft thick or more consisting of a tidally influenced amalgamated complex consisting of tidal channels, distributary channel and foreshore deposits. Regional strike correlation done in a west-east line of section (Figure 14) shows that this unit has great lateral extent for up to 30km. This observation constrains the prospect to still be within the inner-mid shelf depositional environments.

Core interpretations observed from a penetrated well Aso-2 (Figure 15) (22Km) away of same stratigraphic interval for the 02000 reservoir sands shows that this feature is tidally influenced consisting of very fine-medium grained planar – cross stratified sandstones and massive structureless beds. Sidewall sample analysis from Chukku 1 shows the presence of carbonaceous matter which supports the interpretation of a deltaic distributary system. Gamma ray curves are also blocky and display a decreasing-up pattern while neutron-density separation has similar character used in finger-printing channel sandstones. Four sub litho-facies were identified within this interval from core analysis, they include tidal channel, distributary channel, tidal mudflat and foreshore. Individual tidal and distributary channel sandstone body thickness is within 25-40 feet thick while tidal mudflats which make up shale inter-beds are very silty with thickness of 10-25ft. The 03000 reservoir sands are mainly shoreface parasequences. The presence of glauconite could suggest they were deposited at water depths greater than 30 m forming at sites of reduced sedimentation rates and could also be associated with an area possible close to a slight break in sedimentation leading to the formation of a sequence boundary

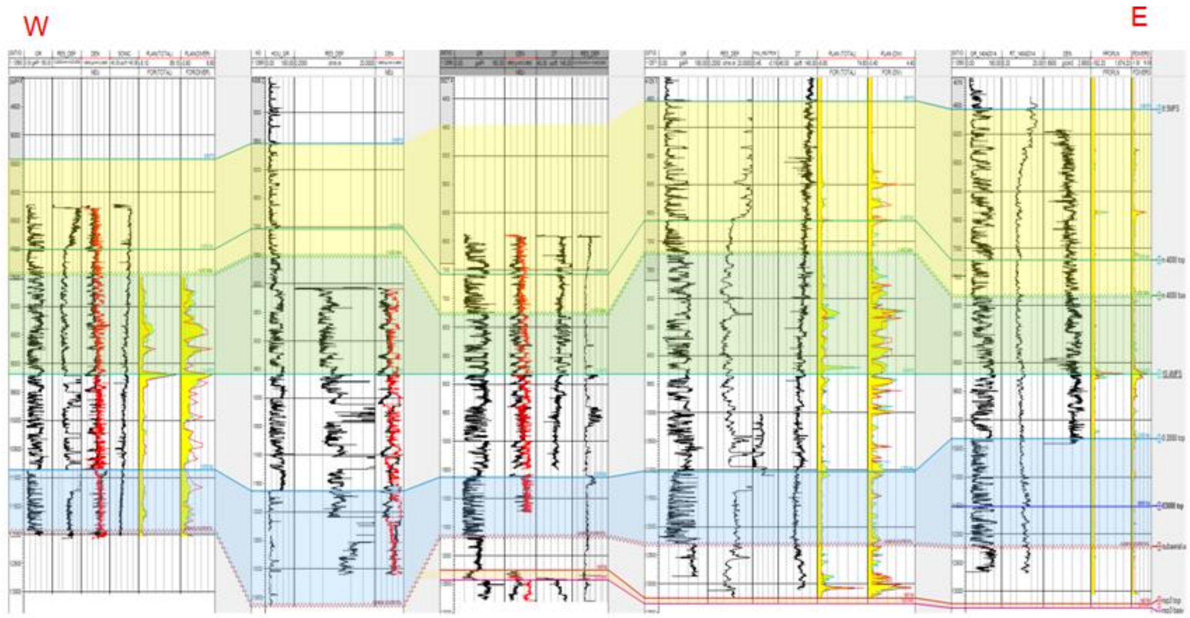


Figure 14: Regional strike Correlation showing the 1st and 2nd depositional sequence

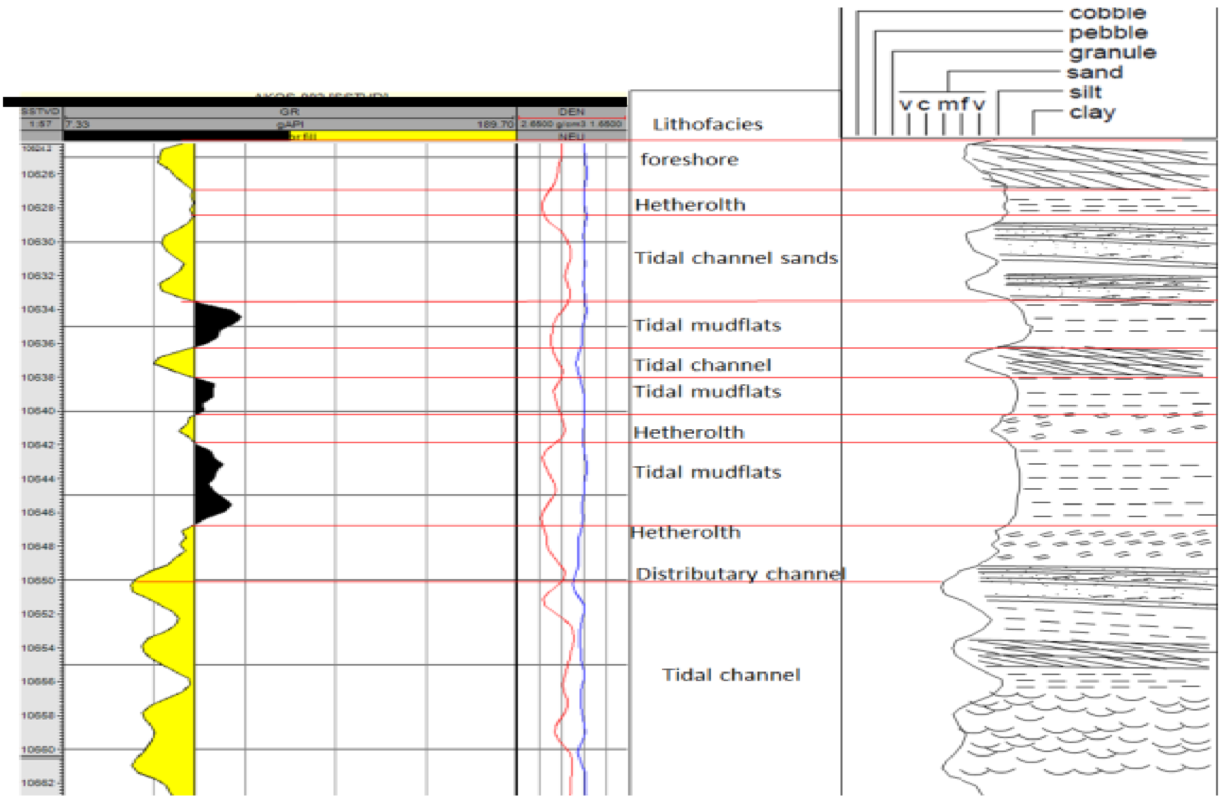


Figure 15: petrophysical analysis using core and well information showing identified facies of the 2nd Lowstand systems tract

Seismic facies analysis showed chaotic and sometimes oblique progradational clinoform configurations (Figure 16) that could be related to deltaic distributary systems. This pattern shows well on depositional strike.

Seismic attributes were generated using spectral decomposition (

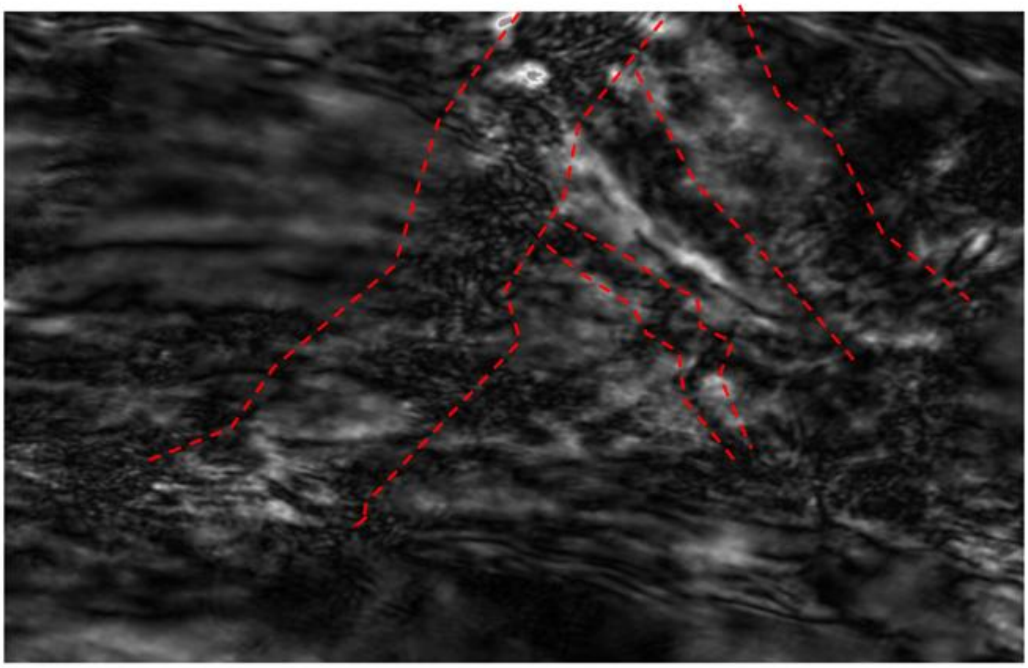


Figure 19) combing main seismic volume with the semblance volume to improve appearance of stratigraphic features. There are several distributary systems trending in a north- south direction as several depocenters may exist.

A two dimensional wheelers diagram (Figure 18) was generated to understand how the depositional systems change temporarily. This diagram depicted the timing and quality of the play elements and is also of value in ascertaining areas for well placement. This model showed areas of sand and seal development which can form reasonable basis for initial litho-type prediction. Onlap- toplap geometries (Figure 17) could indicate some level of sediment bypass from a more proximal environment due to lack of accommodation space to a more distal environment. This onlap geometry shows an increase in coastal accommodation space as depositional topsets aggrade and onlap the inherited depositional profile thus creating a progradational – aggradational stacking. The wheeler diagram showed areas for sand and seal development although net to gross values may be slightly lower. Areas denoted as condensed intervals shows downlap geometries and could be periods of reduced sedimentation rate with potential of being mud prone.

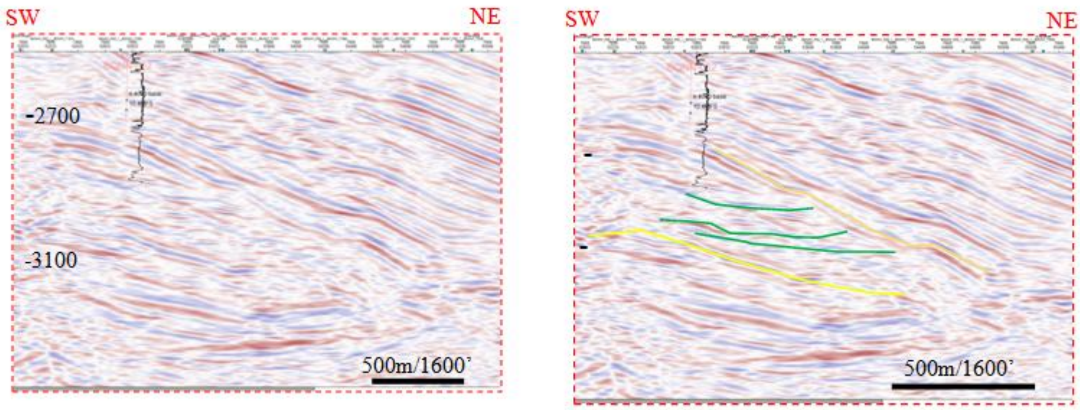


Figure 16: seismic screenshot showing observed oblique clinoforms in Chobie fault block: (A) Un-interpreted (B) Interpreted

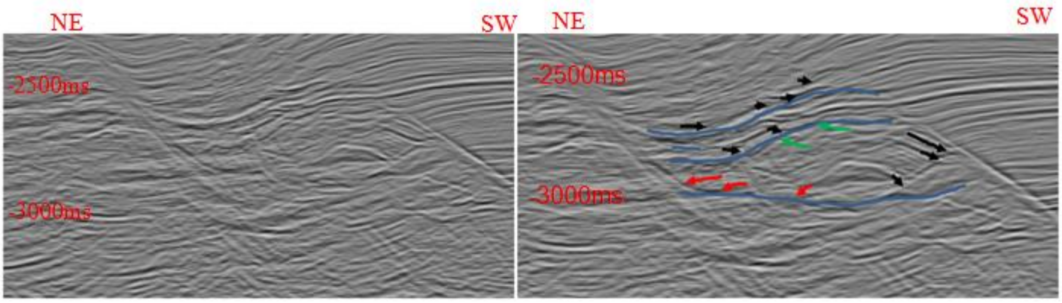


Figure 17: seismic screenshot showing observed wedge like geometry in deep fault block and downlap on 10.4 MFS: (A) Un-interpreted (B) Interpreted

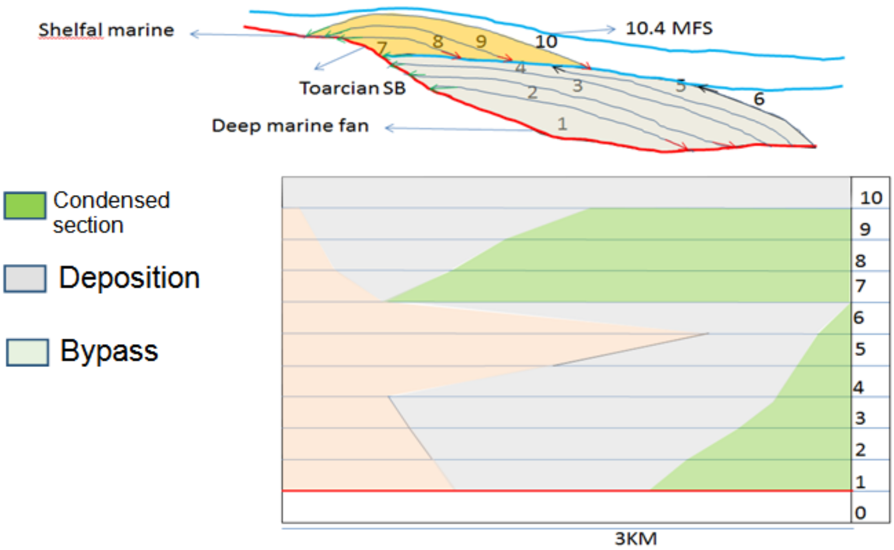


Figure 18:2D Wheelers diagram showing areas of sediment deposition, removal and non-deposition.

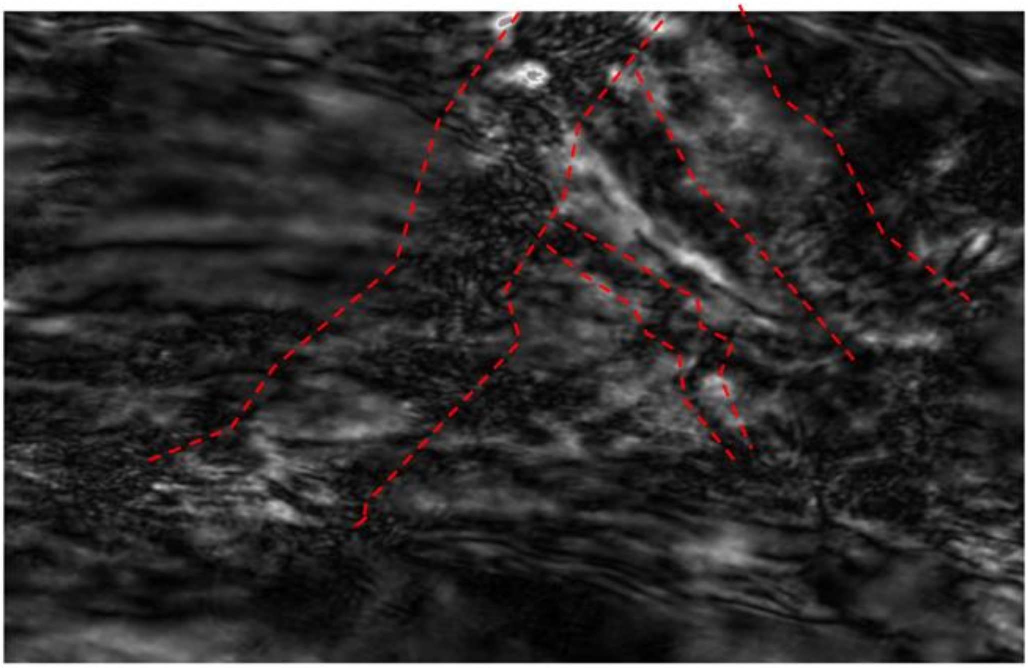


Figure 19: Spectral decomposition extraction showing evidence of possible distributary-tidal channel feature

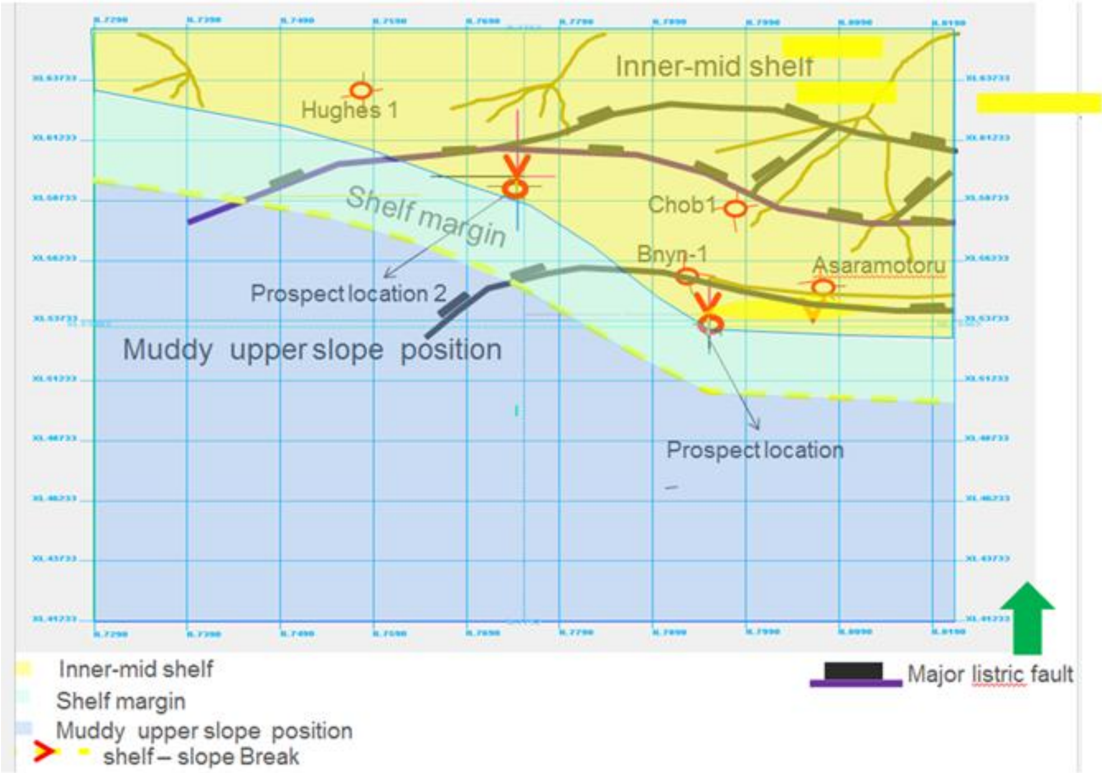


Figure 20: GDE map from 10.4MFS-10.6S

b. Highstand Shelf Margin Deltas

This interval lies below the depositional sequence boundary 2. Seismic evidence at about -3200ms - 3500ms shows shelf margin clinoforms hundreds of metres in amplitude building out into hundreds of metres of deep-water at a high rate. Care should be noted as noise interference/multiples are quite common at that interval as this may also have effect on the generated amplitude extraction. This delta system possesses both stratigraphic and structural characteristics useful in fingerprinting their existence such as significant thickening of section across major outer shelf listric fault, missing sections observed on low angle glide plane faults, rising/ascending shelf edge trajectory, striking stratigraphic facies change and highly overpressure nature of the reservoirs. This outbuilding delta system developed during highstand conditions and has very low potential to deliver huge sands into deepwater areas. The absence of loop scale clinofoms to proof the existence of a shelf edge delta system poses challenges especially in assigning net-gross values as such shelf edge will tend to have low net-gross however recognising lobate patterns from seismic attribute as well as a 3D wheelers diagram generated indicate a delta system at highstand. Seismic attribute generated 20 milliseconds below a surface at time 3200ms on inline 7950 in Chukku block shows arcuate geometries typical of a delta front. This delta front is clearly disconnected from the updip feeder by growth faulting. One interpretation assumes this delta system probably re-established itself at highstand of relative sea level close to the previous shelf edge position. The gross depositional environment interpreted places reservoir facies for this delta on the outer shelf.

Stratigraphic stratascan workflow(Figure 23) attempted on a composite 2D line section shows classic shelf margin geometry with moderate-good sand development on the delta topset and little sand development on the clinoform forset.

Generated 3D wheelers diagram (Figure 22) on the area of interest within Chukku block shows that seismic facies differ on the proximal from the distal part of the delta. The proximal part of the delta system is characterised by pink colour indicating thicker sedimentation rate at late normal regression (HST) which gradually decreases into thin sedimentation rate in a basinward direction shown in light yellow –green colours. Frequent flooding is also present at the delta top after each delta progradation which could be a result of shallower water conditions considerably enough to allow significant mud deposition. Facies have been predicted to consist of delta topset progradational wave dominated shoreface-delta front parasequences less than 150ft thick. Very thin depositional lobes perched on the upper slope may be present and may occur as tempesite layers.

Seismic geometries from a 2D line section shows proper lowstand shelf margin deltas below this highstand shelf margin deltas however interpretation cannot be stretched further at that time interval on the 3D data due to loss of seismic signal probably due to the fact that data was acquired using short cable length

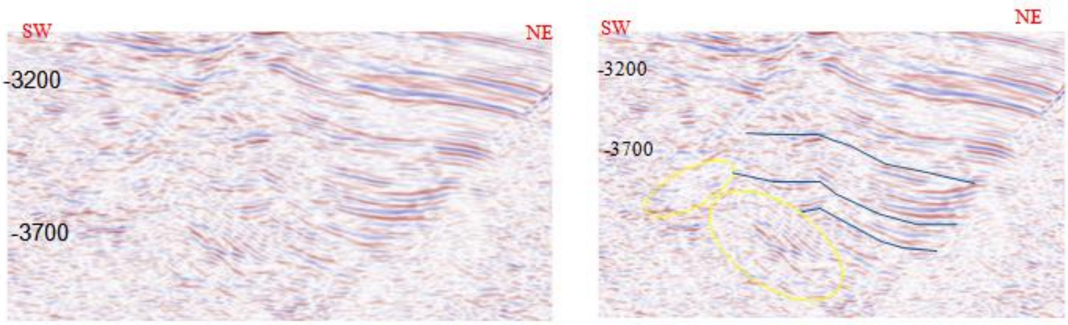


Figure 21: seismic screenshot showing observed highstand shelf margin clinoforms : (A) uninterpreted, (B)interpreted

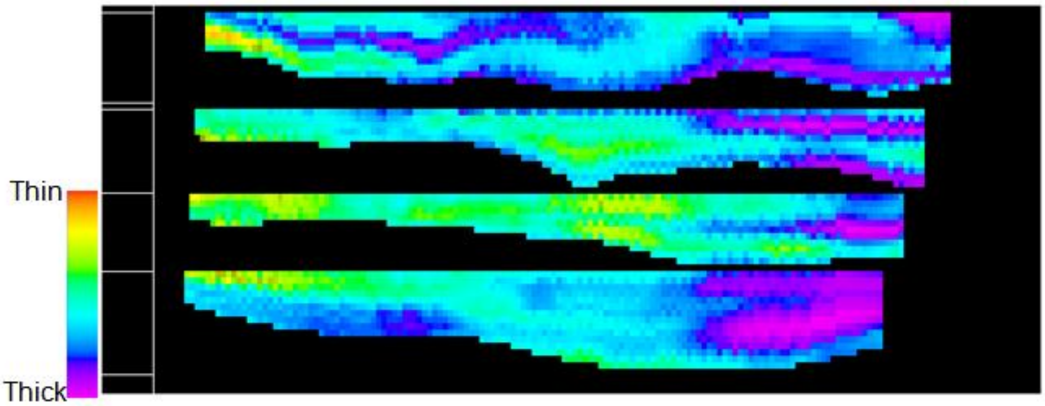
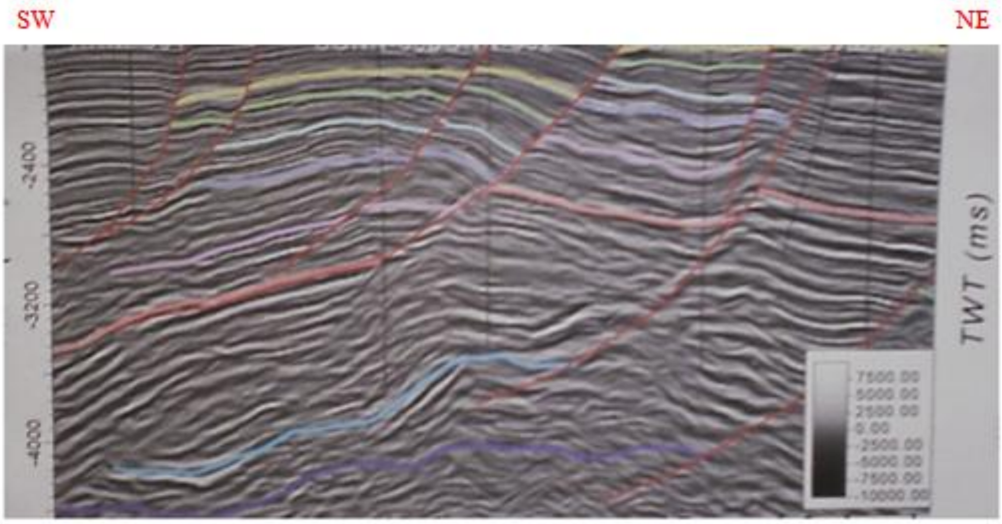


Figure 22: 3D Wheelers model generated using the Geo-leaf thinning attribute, showing increased thickness landwards (to the right)



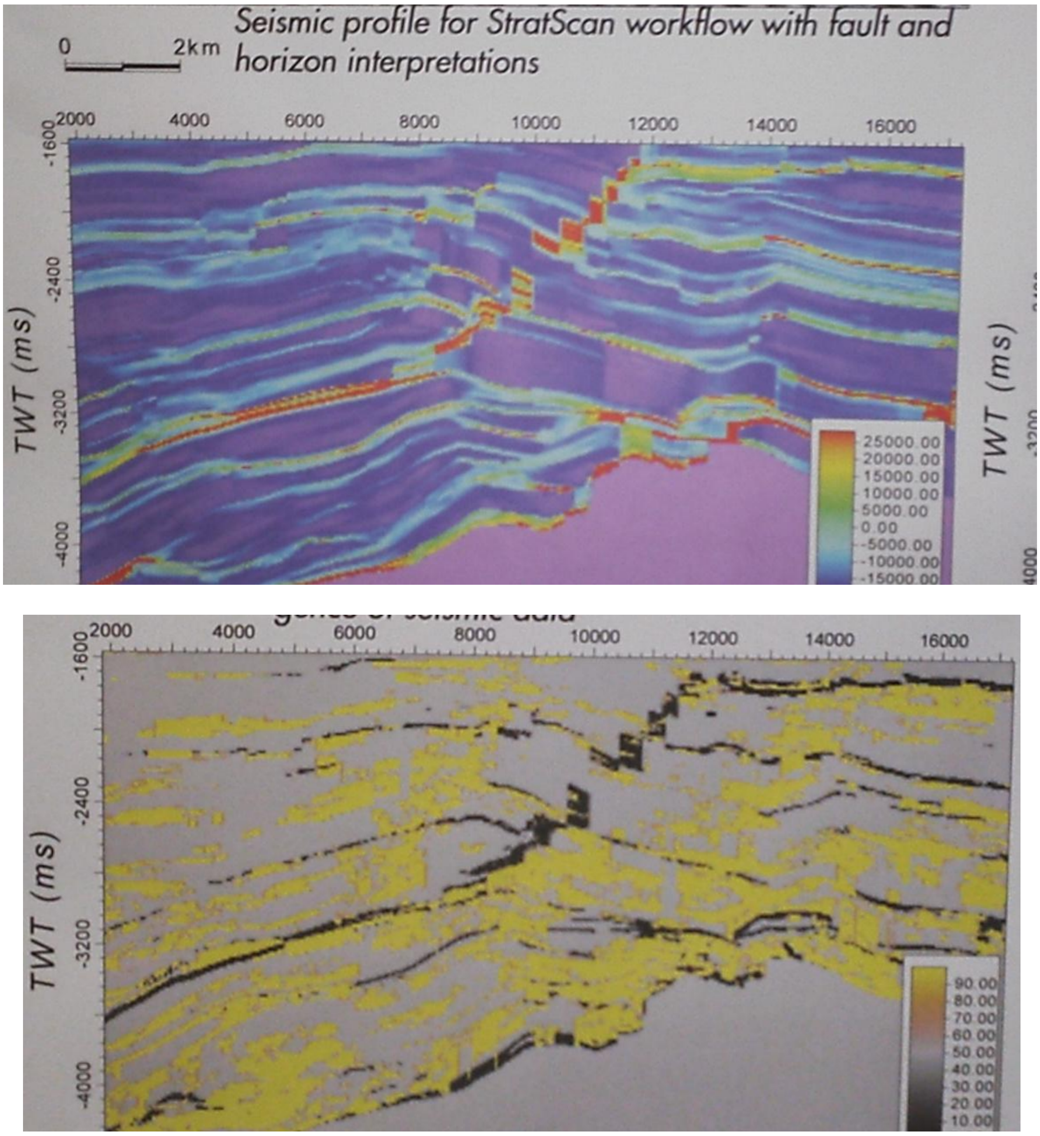


Figure 23: Regional seismic line showing clear geometries of shelf margin deltas below -3200ms: (A) interpreted seismic section with key horizon (B) and (C) are stratscan workflow showing onlap, pinch out geometries, areas of possible sand and shale occurrence

Figure 24: GDE map from 10.6SB-11.5MFS

c. Hydrocarbon Implications of Lowstand Systems Tract 2 and Highstand Systems Tract 2

The lowstand systems tract 2 consists of the 02000 and 03000 reservoir sand. The 02000 sand consist of more than 1000ft amalgamated complex consisting of stacked tidally reworked distributary channel and shoreface sands with a net-gross value of 80-85% while the 03000 sand consist mainly of shoreface parasequences . Such high net-gross values are less likely to have stratigraphic compartmentalization therefore serious connectivity issues may actually not be a problem most especially within the amalgamated channel complex but may pose problems within shoreface zone as flooding shales about 50-80ft thick will act as barriers to gas production. Individual tidal and distributary channels are roughly25-40ft thick having widths less than 1-2km. Architectural style of these channels will be complex as several channel bodies may exist however the possibility of frequent scours could aid connectivity within them. However this channel sands will hold the best potential in terms of volume and permeability. The presence of tidal flats could aid to lateral connectivity between channels. Tidal mudflats show thickness range of about 10-20ft, they are very silty, are not continuous and will not act as barriers for vertical communication in gas charged intervals. However fault seal risk associated with sand- sand juxtaposition in the adjacent hanging wall block may likely have effect on the estimated volumes

The highstand systems tract 2 which contains the shelf margin deltaic succession holds enormous volumes due to the early trapping potential of the fault. It is best to stick to the horizontal delta topset facies which arelikely 120-150ft progradational shoreface-delta front parasequences. In terms of quality this facies will have Net to gross values will like be in the range of 40 -50%, they are likely strike continuous. Fault seal risk will be low as the reservoirs are thin and may likely have good sand –shale juxtaposition. However reservoir development will be a potential problem as frequent flooding intervals will pose vertical communication issues as shales associated with flooding will act as barriers to gas production.

Risk analysis performed on the 02000 and 03000 prospect interval using a matrix diagram based on an observational risk (top down approach) seen on available data and a model risk (bottom up) based on confidence in interpretation places a 55% chance of exploration success for the two prospect interval holding about 250 BCF of gas.

Further prospect believed to be lowstand shelf edge deltas exists below main target, one suggestion is to use the drill bit to de-risk the interval if pressures allow as they could hold enormous hydrocarbon volumes.

IV. Conclusion And Recommendation

Overall this study has shown that sequence and chronostratigraphic framework conducted for the OML 11 block have delineated two 3rd order depositional sequences associated with very thick deltaic reservoirs deposited within 2.0 Ma. The integrated approach taking in making interpretation has aided further

understanding on the processes creating lateral changes in facies and stratigraphic succession of sediments vertically. The study has shown the presence of unexplored deeper stratigraphic play that are aided by structures
The following recommendations are presented as a result of this study:

- It is recommended to farm-in to target the identified deep prospect, however there is need to acquire full set of logging suite such as formation micro-image logs and cores to aid a qualitative facies interpretation and obtain parameters that will be useful in creating realistic geologic model for the subsurface.
- It is recommended to perform long horizontal well completions to allow high rates of production considering the high reservoir heterogeneity of the 02000 sand and the very thin reservoir units predicted below the 03000 sand unit.
- Repeat 3D seismic data acquisition using long offset wide azimuth survey is suggested as some signal exists below actual target but interpretation is limited due to data used was shot with shorter cables.
- If seismic quality at that depth is resolvable more detailed analysis will be required below the main target. This are believed to be shelf edge deltas formed at lowstand
- Further studies should focus on creating numerical models using parameters such as sediment budget and shelf width to create replica image of various case scenarios on shelf edge delta progradation. This information will be quite useful especially when predicting available sand volumes in deep water.

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