SEQUENCE STRATIGRAPHIC ANALYSIS AND POROSITY EVALUATION OF A FIELD USING 3D SEISMIC AND WELL LOGS: AN EXAMPLE FROM THE NIGER DELTA, NIGERIA

BY

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ⓒSanuade, Oluseun Adetola
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Dedication

To my lovely parents for their prayers and support.

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I want to express my heartfelt gratitude to all the people who directly or indirectly contributed to this work. Since the list of names is inexhaustible, I hereby apologize in advance, in case I miss someone in particular.

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THESIS ABSTRACT

NAME: Sanuade, Oluseun Adetola

TITLE OF STUDY: SEQUENCE STRATIGRAPHIC ANALYSIS AND POROSITY EVALUATION OF A FIELD USING 3D SEISMIC AND WELL LOGS: AN EXAMPLE FROM THE NIGER DELTA, NIGERIA

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3*D seismic data and wireline logs from thirteen* (13) *wells were used in this study to understand the sequence stratigraphic evolution and build a sequence stratigraphic model for Otu field in the onshore area of the Niger Delta. The subsurface facies reveals three sequences that are bound by four sequence boundaries (SB*1 *to SB*4*) which are interpreted as erosional unconformities with three maximum flooding surfaces (MFS1, MFS2 and MFS3). Sequence boundaries evolved as the structural collapse of the clastic wedge of the Niger Delta caused steepening of mass flow erosion slopes. The sequences that are delineated were composed of lowstand systems tracts (LST), falling stage systems tracts (FSST), transgressive systems tracts (TST) and highstand systems* *tracts (HST), revealing depositional systems deposited during different phases of base level changes. Sediments identified within the LSTs in Otu field are fluvial channel sands formed at low sea level and when the rate of sediment supply is higher than accommodation space. Sediments within the FSST are offlapping slope deltaic wedge which are formed when the shoreline was forced to regress irrespective of the influx rate of sediment. The TSTs in Otu field capped the low systems tracts facies and consist mainly of marine shales. TSTs are formed during relatively high sea levels and when sediment supply is lower than the accommodation space. HSTs are made up of coarsening and shallowing upward intervals, having deltaic fluvial sands near the top of the units. The sequences that were delineated were deposited in transitional to shallow marine environments. Seismic geomorphological study carried out on all the sequence boundaries and* $MFS3$ *shows a relationship between depositional environments, type of channel and direction of paleo-flow in relation to faults. Channel belts are associated with continental to transitional depositional environment deposits while individual (relatively thin and less sinuous) channels are associated with shallow marine deposits. Channel belts are oriented perpendicular to the fault while individual channels (incised valley) are parallel and rarely affected by the faults. Chronostratigraphic correlation of wells in Otu field revealed that the surfaces that were delineated are not continuous laterally and this could be as a result of syndepositional faults within Otu field. These faults are believed to serve as major traps for the accumulation of hydrocarbon in the field. However, the reservoir rocks of the LST and HST and seals from marine shale of the TST could probably combine together to form stratigraphic traps for hydrocarbon*

accumulation in Otu field.

مستخلص الأطروحة

الأسم: سانا ,اديوليسون اديتول

عنوان الدراسة: تحلي التتابع الطبقي و تقيم المسامية لحقل باستخدام بيانات السيزمية ثلاثية الأبعاد و تسجيلات الآبار: مثال من دلتا النيجر, نيجيريا

مجال ا لتخصص: الجيولوجيا

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في هذه الدراسة تم استخدام كل من بيانات السيزمية ثلاثية الابعاد والمجسات التحلي البئري المستخرجة من 13 بئر لفهم تطور التتابع وبناء قالبه الطبقي لمنطقة حقل اوتو الواقعة على دلتا النيجر القارية.

السحنات الصخرية التحت سطحية اظهرت ثلاثة تتابعات طباقية محاطة بأربعة حدود طباقية والتي فسرت كأسطح عدم توافق نتيجة للتعرية مصاحبة بثلاث اسطح تدفق عليا. الحدود الطباقية تطورت نتيجة للتهدم البنائي لمنخفض دلتا النيجر المتسبب في زيادة إنحدار ميل الانسياب الكتلي الصخري. التتابعات الطبقية تتكون من رسوبيات سطح البحر المنخفض , المنحسر, المتقدم, و المرتفع مظهرة تمثل انظمة ترسيبية في مراحل متغيرة من مستوي سطح البحر. الرسوبيات المتعرف عليها ضمن مستوي سطح البحر المنخفض في حقل أوتو عبارة عن رسوبيات قنوات رملية ترسبت عندما كان إمداد الرسوبيات يفوق سعة الحوض الترسيبي. بينما نجد ان الرسوبيات التي تكونت في فترة انحسار سطح البحر تمثل رسوبيات دلتا تكونت عندما أجبر الخط الساحلي على التراجع, دون اعتبار للامداد الرسوبي. رسوبيات البحر المتقدم تعلو السحنات الترسيبية لمستوي سطح البحر المنخفض, وتتألف في غالبيتها من رسوبيات الطفل البحرية .هذه الترسبات تكونت عندما كان مستوي سطح البحر يرتفع نسبيا" والإمداد الرسوبي أقل من سعة الحوض الرسوبي. رسوبيات سطح البحر المرتفع مكونة من تتابعات طبقية ذات حجم حبيبات يزداد لاعلى في بيئة ترسييبة ضحلة, ورسوبيات دلتا نهرية تعلو كل وحدة طبقية. وهذه التتابعات المتعرف عليها ترسبت في بيئات رسوبية انتقالية وبحرية.

ايضا في هذه الدراسة تم استخدام الطبوغرافية السيزمية في فواصل التتابعات الطبقية والتي بدورها اظهرت علاقة وطيدة بين البيئات الرسوبية ونوع و اتجاه القنوات القديمة وعلاقتها مع الصدوع التركيبةي. تمثل القنوات الموجودة في منطقة الدراسة حزام مصاحب للبيئات الرسوبية القارية والانتقالية, بينما تصاحب القنوات المنفردة (زات مجري رفيع واقل تعرجا) البيئات الرسوبية البحرية. وكذلك مجموعة القنوات المشتركة تتجه عموديا على الفوالق التركيبية, بينما القنوات المنفردة () تتجه متوازية للفوالق التركيبية و غالبا لا تتأثر بها.

مضاهاة الطبقية الزمنية للآبار في حقل اوتو اظهرت أن الاسطح الطبقية غير مستمرة وذلك نتيجة للفوالق المتكونة أثناء الترسيب في حقل اوتو. وهذه الفوالق تمثل مصائد ريئسية لتجميع الهايدروكربون في الحقل. وكذلك تمثل رسوبيات سطح البحر المنخفض والمرتفع و صخور الغطاء المكونة من الطفل البحري المترسب في مستوى سطح البحر التقدمي, تكون مصائد استراتيجرافية لتراكم الهايدروكربونات في حقل اوتو.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Sequence stratigraphy provides the basis for the chronostratigraphic correlation of sediments and a valuable exploration and reservoir development tool for the petroleum industry. An approach of sequence stratigraphy in association with knowledge of depositional environments as well as importance of accommodation space and sediment supply can aid in the reconstruction of paleogeography and prediction of temporal and spatial relationship between source, reservoir and seal facies (Catuneanu et al., 2011). Sequence stratigraphy is used to locate stratigraphic prospects and predict reservoir and seal quality on structural prospects. This approach was applied on Otu field in the Niger Delta.

The Niger Delta is a clastic wedge which is 12 km in thickness with an area of 75, 000 km^2 between southern Nigeria and the Gulf of Guinea. It is known as one of the largest oil provinces in the world having reserves of over 34 billion barrels of oil and 93 trillion cubic feet of gas (Tuttle et al., 1999). The deposits in the Niger Delta are known to be subdivided into three lithostratigraphic units which are the Akata formation, Agbada formation, and Benin formation (Evamy et al., 1978; Whiteman, 1982) (Figure 1.1).

Formations become progressively younger basinward showing long-term progradation of the depositional environments of the Niger Delta into the passive margin of the Atlantic Ocean. The stratigraphy of the Niger Delta is complex as a result of the syndepositional slump of the clastic wedge due to movement of shale of the Akata formation by the influence of the load of the Agbada and Benin formation deposits which are prograding deltaic and fluvial respectively. A network of large-scale, listric normal faults dipping towards the basin formed as a result of diapered upward mobility of the underlying shales. Blocks down dropped across these faults loaded with growth strata, changed the local slopes of deposition, resulting in complex path ways of sediment transport into the basin (Evamy et al., 1978). This has made field evaluation in the basin tedious due to problems associated with imaging of the subsurface in the Niger Delta.

For the purpose of field evaluation or re-evaluation, it is very important to understand detailed relationships between the faulting system in the area as well as the stratigraphic component of the basin. It has been proven that when 3D seismic data is integrated with well log data, it provides a powerful tool to determine the seismic stratigraphic and structural framework of a basin (Nton and Adesina, 2009; Futalan et al., 2012; Amigun et al., 2014). Hence, this study was carried out to understand the tectono-stratigraphic evolution, structural styles, identifying different facies and their depositional environments and establishing a sequence stratigraphic model that will enhance prediction of reservoir quality within Otu field as well as porosity distribution within the field.

1.2 Motivation

The availability of a 3D seismic data and wireline log data encourage detail study for the Niger Delta in field scale. Moreover the wells in Otu oil field were discovered and drilled based on structural traps, hence there is a need to understand the stratigraphic evolution of the field and the relationship between structures and stratigraphic components in the area. This is in addition to the fact that no previous data and/or relationship between stratigraphy and structures were defined.

1.3 Objectives of the Study

The objectives of this thesis are to:

- Identify different facies and their depositional environments
- Establish the tectono-stratigraphic evolution and structural styles of Otu field
- Establish sequence stratigraphic model within the study area
- Evaluate the porosity and predict reservoir quality in field scale

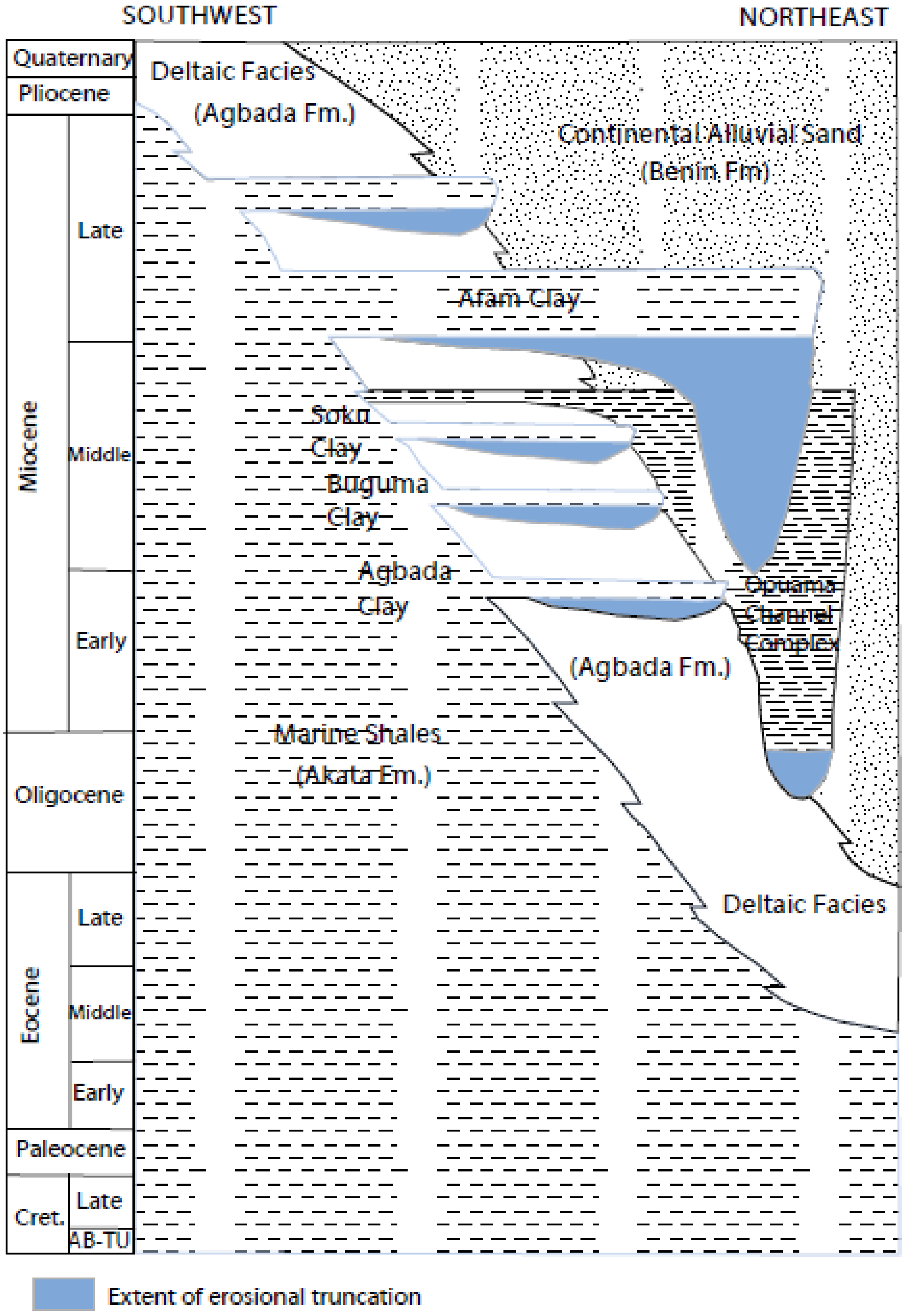


Figure 1.1: Stratigraphic column of the Niger Delta showing Akata, Agbada and Benin formations (Doust and Omatsola, 1990).

1.4 Location and Database

1.4.1 Location

The study area is situated within the Gulf of Guinea off the west coast of the Niger Delta (Figure 1.2) and covers an area of approximately one hundred thousand square miles. The onshore portion covers approximately 30,000 square miles (Chukwu, 1991; Magbagbeola and Willis, 2007). Sediments deposited within the study area consist of marine and fluvial sediments that range in age from Cretaceous to Holocene (Kostenko et al., 2008). Otu field is located onshore in the western part of the Niger Delta.

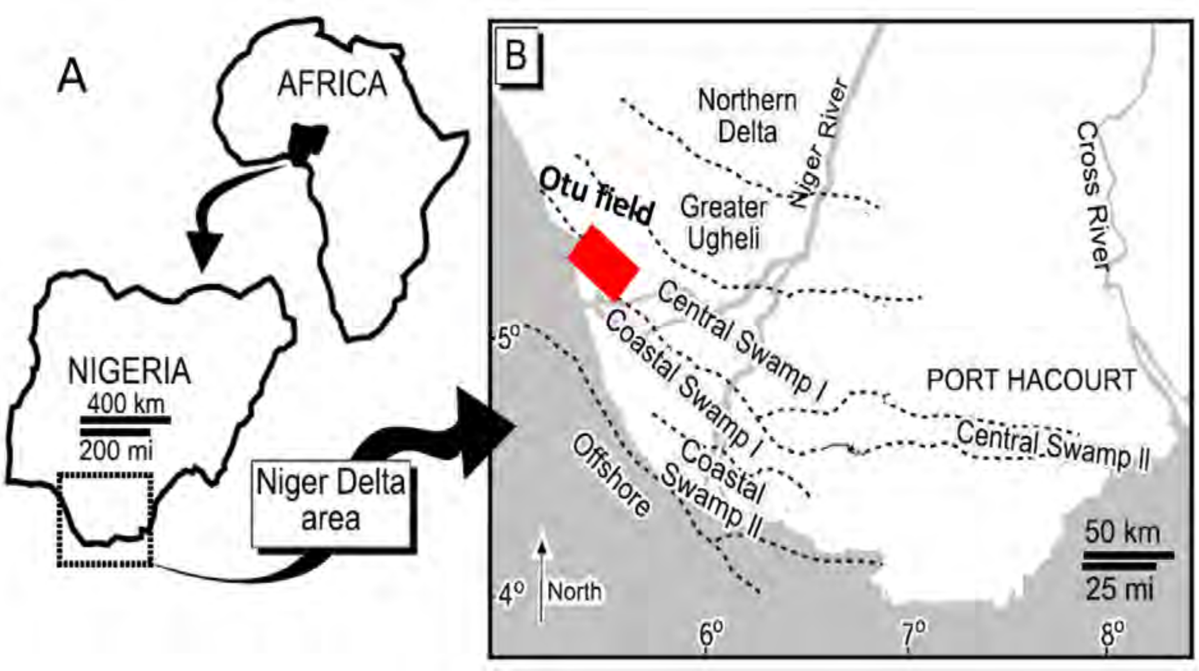


Figure 1.2: Location map of study area (A) Position of Nigeria in Africa and Niger Delta Basin. (B) Otu field location map (Doust and Omatsola, 1990)

1.4.2 Database

The data used for this study include a 3D seismic, thirteen (13) wireline logs, checkshot and deviation survey data. The 3D seismic amplitude data covers an area of about 421 sq. km in the onshore area of the Niger Delta. The bin spacing of the data is 25 by 25 m. The data are available in milliseconds two-way travel time (ms TWTT) with a maximum value of 3000 ms. It has Inline range of 11228 – 12110 and Crossline range of 2673 – 3434 (Figure 1.3). The characteristics of the seismic records were observed to change with depth. The seismic volume generally have series of parallel reflections offsets that have been deformed by major listric normal faults.

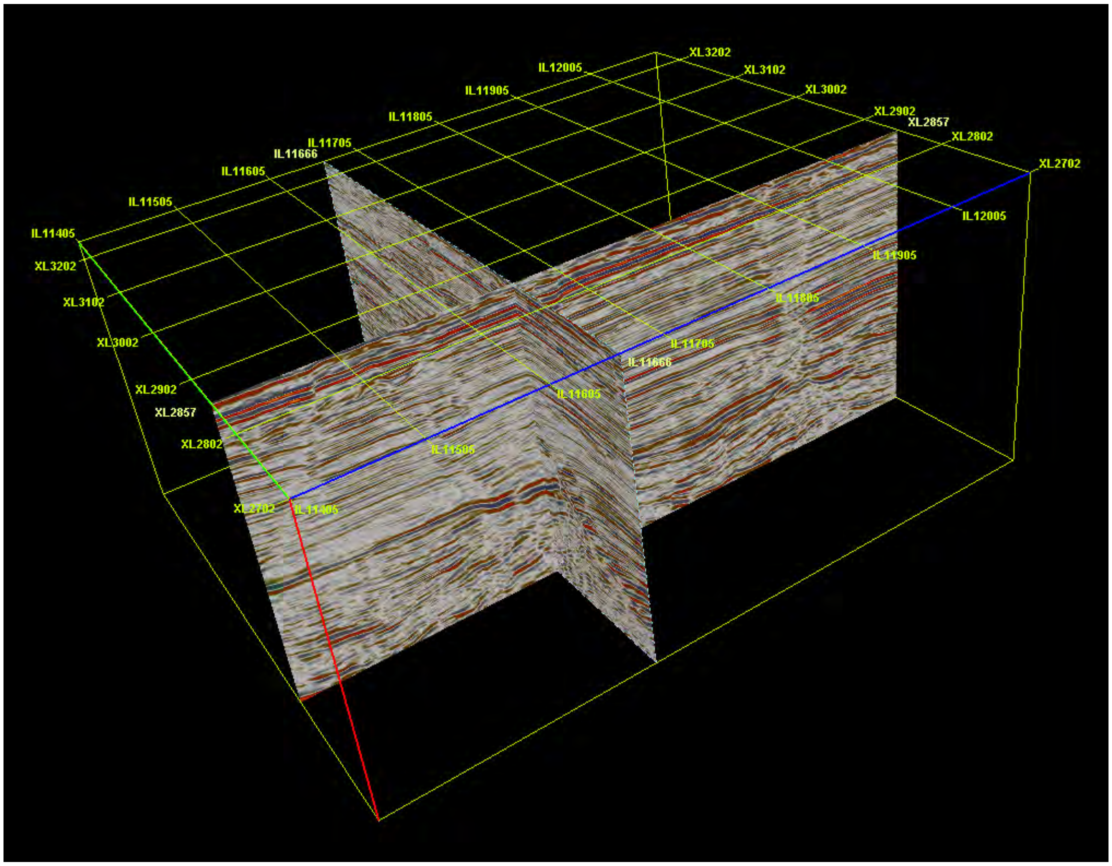


Figure 1.3: Survey line showing inline and crossline in the study area. The inline range from 11228 - 12110 and crossline range has range between 2673 - 3434. The 3D seismic has TWTT between 0 to 3000 ms

Table 1.1: Well log data available for this study

Well	CNLLC	ACAL	RHOCN	GR	LLD	SP	LLS	DT
Otu 4	X	X	X	X	X	X		
Otu 5	X	X	X	X	X	X		
Otu 6	X	X		X	X	X	X	
Otu 8	X	X	X	X	X	X	X	
Otu 11	X	X	X	X	X	X	X	
Otu 19	X	X	X	X	X	X	X	
Otu 21	X	X	X	X	X	X	X	
Otu 29	X	X	X	X	X	X	X	
Otu 32	X	X	X	X	X	X	X	
Otu 36	X	X	X	X	X	X	X	
Otu 38	X	X	X	X	X	X	X	
Otu 46	X	X	X	X	X		X	X
Otu 56	X	X	X	X				

Note: ACAL: caliper, LLD: laterolog deep resistivity, LLS: laterolog shallow resistivity, CNLLC: neutron porosity, RHOCN: bulk density, DT: sonic, GR: gamma ray, (X): available type log

The well data include time depth curves and digital well curves. Well log types available are shown in Table 1.1. These wells were drilled spatially in the study area. The basemap in Figure 1.4 shows the distributions of the wells in the study area.

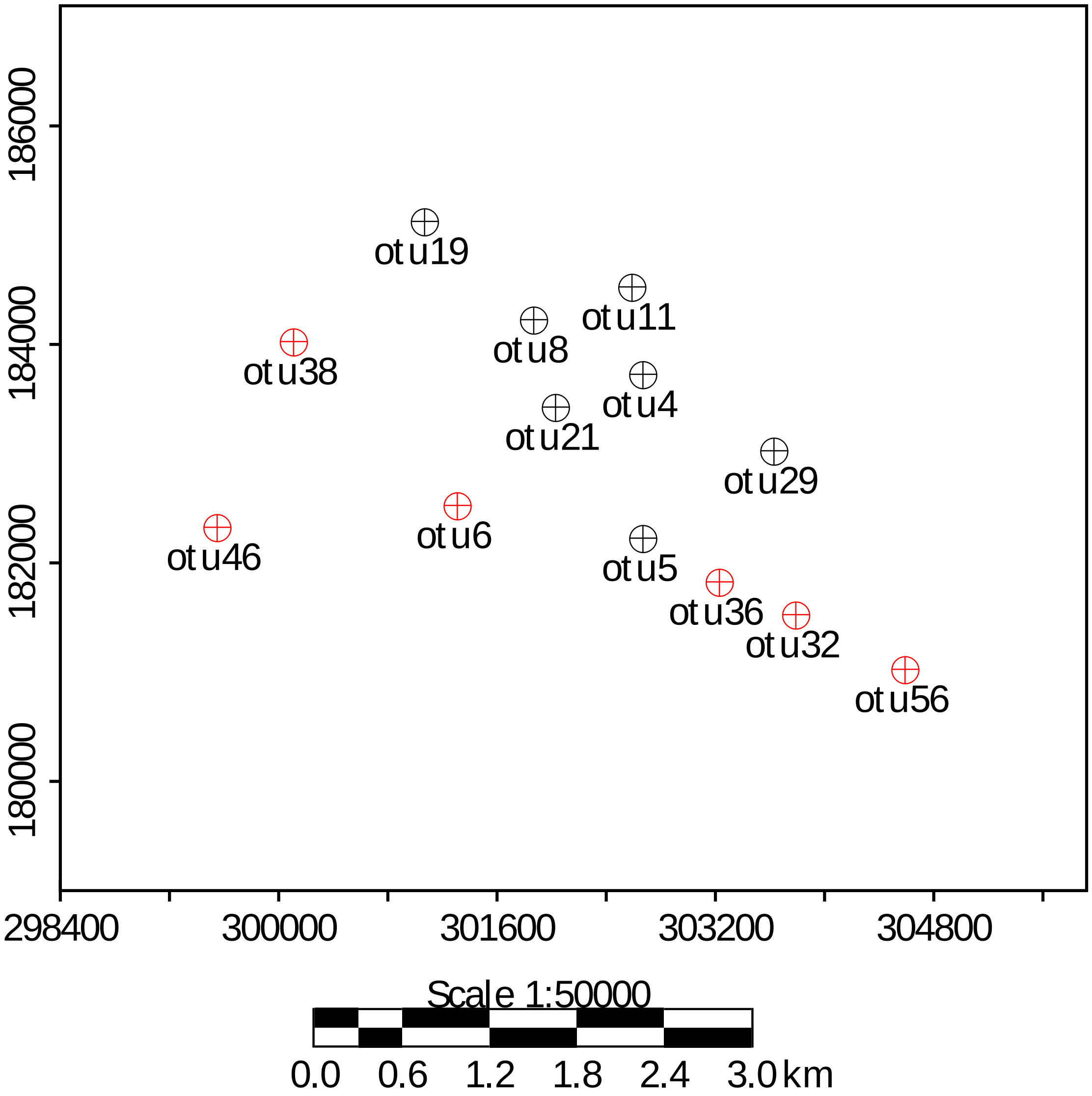


Figure 1.4: Distribution of wells in the study area. The wells in red are deviated wells while those in black are vertical wells

1.5 Methodology

Wireline logs (gamma ray, resistivity, density and neutron) and a 3D seismic data were studied, analyzed and interpreted to identify facies and their depositional environments, establish the tectono-stratigraphic evolution and structural styles of Otu field, establish sequence stratigraphic model, evaluate the porosity and to predict reservoir quality in field scale.

1.5.1 Lithostratigraphy Identification

Gamma ray (GR) logs from all the thirteen wells were employed to delineate the lithology in Agbada formation of Otu field. The sand bodies were identified by the deflection of the GR log to the left while shale was identified by the deflection to the right. Gamma ray log cut-off of 35 API was used for the lithostratigraphic analysis (i.e. shale: $> 80API$, shaly sand: $35 - 80$ and sand: $< 35API$). The hydrocarbon bearing sands were identified using GR and resistivity logs. The results of lithostratigraphy was compared with that of chronostratigraphy in order to establish the relationship between the two.

1.5.2 Identification of Facies and Depositional Environments

Gamma ray (GR) log patterns were used for the identification of facies and their depositional environments (Beka and Oti, 1995). 'Blocky' log pattern was interpreted to depicts uniform deposition that is peculiar to channelized region and typical of fluvial channel deposits. Pattern showing coarsening upward units (progradational pattern) was interpreted to be a feature of deltaic fluvial environment (Channel point bar). 'Serrated' (aggradational log pattern) with uniform bandwith shows limited coastline variability and was interpreted to be typical of tidal flat environment. 'Bell-shaped' GR log pattern (upward fining, retrogradational log pattern) was interpreted to be tidal channels or sands.

1.5.3 Stacking Patterns and Parasequences

The stacking patterns and parasequences of the facies were also established. The stacking of parasequences (vertical occurrence of repeated cycles of sequences that are fining upward or coarsening upward) produced progradational, retrogradational and aggradational sets of parasequences.

1.5.4 Stratigraphic surfaces, systems tracts and depositional sequences

The delineation of maximum flooding surface (MFS) was done on the wireline logs. MFS was identified as the boundary between progradational and retrogradational parasequence sets as well as the units that have shale peaks and were well developed on GR, resistivity and neutron logs. The criteria for the recognition of sequence boundaries (SBs) included low GR and high resistivity responses that occurred within the shallow section. SBs were described at the base of the thickest and coarsest sand units between two adjacent MFSs (Williams, 1997) and base of a progradational stacking pattern. The depositional (IV) model of Hunt and Tucker (1992, 1995) and Helland-

Hansen and Gjelberg (1994) was used for the identification of the systems tracts and depositional sequences within the Otu field.

1.5.5 Chronostratigraphic correlation of wells

Wells were correlated along strike and dip line for the development of a chronostratigraphic framework. The correlation was carried out to build a holistic sequence stratigraphic framework in Otu field. This was done to establish the lateral continuity or discontinuity of facies and depositional sequences in order to aid reservoir studies in the field.

1.5.6 Structural Interpretation

Major and minor faults were identified and mapped appropriately on the 3D seismic to establish the structural styles and framework within Otu field and to clarify the main structural elements that affect the hydrocarbon-bearing reservoir.

1.5.7 Seismic Stratigraphy

Stratal terminations such as truncation, toplap, onlap, downlap, and offlap (Catuneanu, 2002) were incorporated into sequence stratigraphy to describe the stacking patterns of stratal units and to provide diagnostic features for the recognition of the various surfaces and systems tracts (Posamentier and Vail, 1988; Van Wagoner et al., 1990; Christie-Blick, 1991).

1.5.8 Synthetic Seismograms

Seismic to well tie was carried out using checkshot data and sonic log of well number 46 to link the well data to the seismic for more reliability.

1.5.9 Seismic Geomorphology

Seismic geomorphology may be defined as the application of analytical techniques pertaining to the study of landforms and to the analysis of ancient, buried geomorphological surfaces as imaged by 3D seismic data. Seismic geomorphology, when used in conjunction with seismic stratigraphy, represents the state of the art approach to extracting stratigraphic insights from 3D seismic data (Posamentier et al., 2007). The seismic geomorphology was applied to the subsurface facies of the Agbada formation. The patterns observed from the 3D seismic images were described to be diagnostic of depositional environment(s). Sequence boundaries were mapped as horizons and attributes such as spectral decomposition and similarity (coherency) were draped on the surfaces to enhance the identification and interpretation of the structural and stratigraphic features.

1.5.10 Porosity Evaluation

Porosity was evaluated in Otu field by cross-plotting both density and neutron logs using techlog software developed by Schlumberger. The two logs were guided by both gamma ray and resistivity logs to know the lithology and fluid contents. The quality of each reservoir rock was established using the results of the porosity that was evaluated from both density and neutron logs.

1.5.11 Reservoir Quality

Reservoir potential in Otu field was analyzed based on the results of sequence stratigraphic analysis and the evaluation of some petrophysical parameters in Otu field.

1.6 Previous Work

Although the title of this study is describing the Niger Delta, this thesis focuses on Otu field as it is a representative in the Niger Delta region. The outcome of this study can be applied in other areas in the Niger Delta. The Tertiary Niger Delta is known to have reservoirs that are stacked together in an oil rich shale and the best approach to understanding these fields is to study them on a field scale. The present study addresses the sequence stratigraphic analysis of Otu field and develops a sequence stratigraphic model using 3D seismic data and well logs as this information is absent in the field.

However, it is important to discuss what previous authors have studied in some other fields located in the Niger Delta.

Hooper et al. (2002) explained the influence of deformation in the control of the patterns of deposition in the south-central part of Niger Delta. Their work was however focused mainly on the compressional toe of the delta, and they concluded that the elements of structures in the area are the main control of accommodation changes on the slope and toe of the delta.

Morgan (2004) examined the relationships between mobile shale structure and channel formation above the compressional toe of Niger Delta and highlighted the importance of transfer zones within the toe thrust belt as a control on the underlying structural framework.

Corredor et al. (2005) related styles of structures in the deep-water fold and thrust belts of the Niger Delta and concluded that there are two complex, imbricate fold and thrust belt systems (the inner and outer fold and thrust belts) that are produced by contraction which are formed as a result of extension driven by gravity on the shelf.

Nton and Adesina (2009) worked on structural interpretation and environment of deposition of sand bodies within tomboy field, offshore western Niger Delta. They showed that the field is made up of sand bodies deposited in different environment across normal, growth faults and associated rollover anticlinal structures.

Rotimi (2010) worked on application of 3D seismic interpretation of structures and seismic attribute analysis to hydrocarbon prospect in a field called "'X'" in the Niger Delta. Closures found in the field were fault assisted closures which corresponds to the crest of rollover structures and the amplitude map revealed high amplitude zones. He identified some prospects which are hydrocarbon bearing.

Opara (2010) worked on 3D seismic interpretation and structural analysis of Ossu oil field, northern depobelt, situated in the onshore area of the Niger Delta. He revealed a complex subsurface structures, predominant with simple rollover structures that are widely spread bounded by growth faults. He also examined for hydrocarbon prospects and found that the field is hydrocarbon bearing.

Daramola et al. (2011) made use of integration of 3D seismic and data from well logs to evaluate subsurface geology as well as the potentiality of hydrocarbon of an oil field in the onshore Niger Delta by identifying and mapping faults and horizons. They produced time and depth structural maps of the top of the reservoir that they analyzed. The maps showed that the structure that bears hydrocarbon is dependent on networks of fault in the area. They also generated amplitude map of the top of the reservoir which is consistent with structural maps.

Amigun et al. (2014) used well logs and seismic data to determine the lithology, lithofacies, sequence stratigraphy, seismic facies and depositional environment of Holu field, in the Niger delta. They analyzed wireline logs and identified five depositional sequences having six sequence boundaries that are in association. They also identified sand and shale to be the dominant lithologies. By analyzing the seismic facies of the area using seismic amplitude extraction, continuity of reflections, frequency and reflection configuration, the environment of deposition of the field was suggested to belong to fluvial systems to marine environments.

Futalan et al. (2012) mapped the seismic facies in the Sandakan Sub-basin, in the Philippines and the results of their analysis showed that there is a relationship between lithofacies and depositional environment of the sub-basin. They identified the depositional environment to be fluvio-deltaic system. They also performed the structural analysis of the sub-basin and provides information about the timing of deformation in the sub-basin as well as the present of some related structural maps.

Tamannai et al (2013) carried out a detailed 3-D interpretation of seismic in Pict Field, in the Central North Sea, United Kingdom. The interpretation was carried out with the aim of identifying different seismic facies types in the field and also to determine hydrocarbon potential in the Tay Sandstone. They recognized three seismic facies types using maximum seismic amplitude maps. They then confirmed the results from the seismic interpretation with the available information from the well log.

Oyedele et al. (2013) in their work entitled "‘Sequence stratigraphic approach to hydrocarbon exploration in Bobsaa field, onshore Niger Delta"’ used data from seismic, well logs, paleobathymetric and biostratigraphic to evaluate the field with a view to determine the lithology, reservoir sands and the depositional environment of the study area. Their results showed that the lithology is mainly alternation of sand and shale with sand having the highest ratio. The environment of deposition was recognized using integration of available data to be fluvial to shallow marine mainly shallow inner neritic, inner neritic and middle neritic.

Obaje (2013) mapped the structures of Tomboy field using seismic interpretation method. He recognized some strata terminations including onlaps, toplaps and truncations. He concluded that the styles of structures style in the area is characterized by two systems of antithetic and growth faults and that the overall reflectors geometry is parallel or sub-parallel.

John et al. (2014) integrated well logs and 3D seismic data to perform facies analysis and to determine the environment of deposition of RAY field in Onshore, Niger Delta, with the aim to know the hydrocarbon potential of the field. They however identified four lithofacies shale, heterolithic, shaly-sand and sandstone facies. The facies were subjected to electrosequence analysis which showed five depositional systems. The sandstone facies of the distributary channels revealed good potential for hydrocarbon reservoir having thickness of 40 m and 60 m.

Adewoye et al. (2013) used information from well logs, check-shot and 3D seismic data in the delineation of sand reservoirs that are oil bearing, determination of petrophysical parameters and also analysis of geologic structures in Maiti field, Niger Delta. They used three wells for the evaluation and delineated three hydrocarbon reservoirs within the study area (R1, R2 and R3).

Alao et al. (2013) also made use of the combination of 3D seismic volume and well log data to characterize reservoirs of ALA field in the Niger Delta. They evaluated petrophysical parameters of the reservoirs and obtained time-depth structural maps. The authors also used seismic attributes in the characterization of those reservoirs. In their study, they delineated seven hydrocarbon-bearing reservoirs having thicknesses that vary from 9.9 to 71.6 m. They also generated structural maps of horizons in six wells having hydrocarbon-bearing zones with tops and bottoms at range of 2,453 to 3,950 m. They concluded the trapping mechanism in the study to be mainly fault-assisted anticlinal closures. The identified prospective zones have good porosity, permeability, and hydrocarbon saturation. The depositional environment was determined from shapes of available logs which indicate a transitional-to-deltaic depositional environment.

CHAPTER 2

THE NIGER DELTA

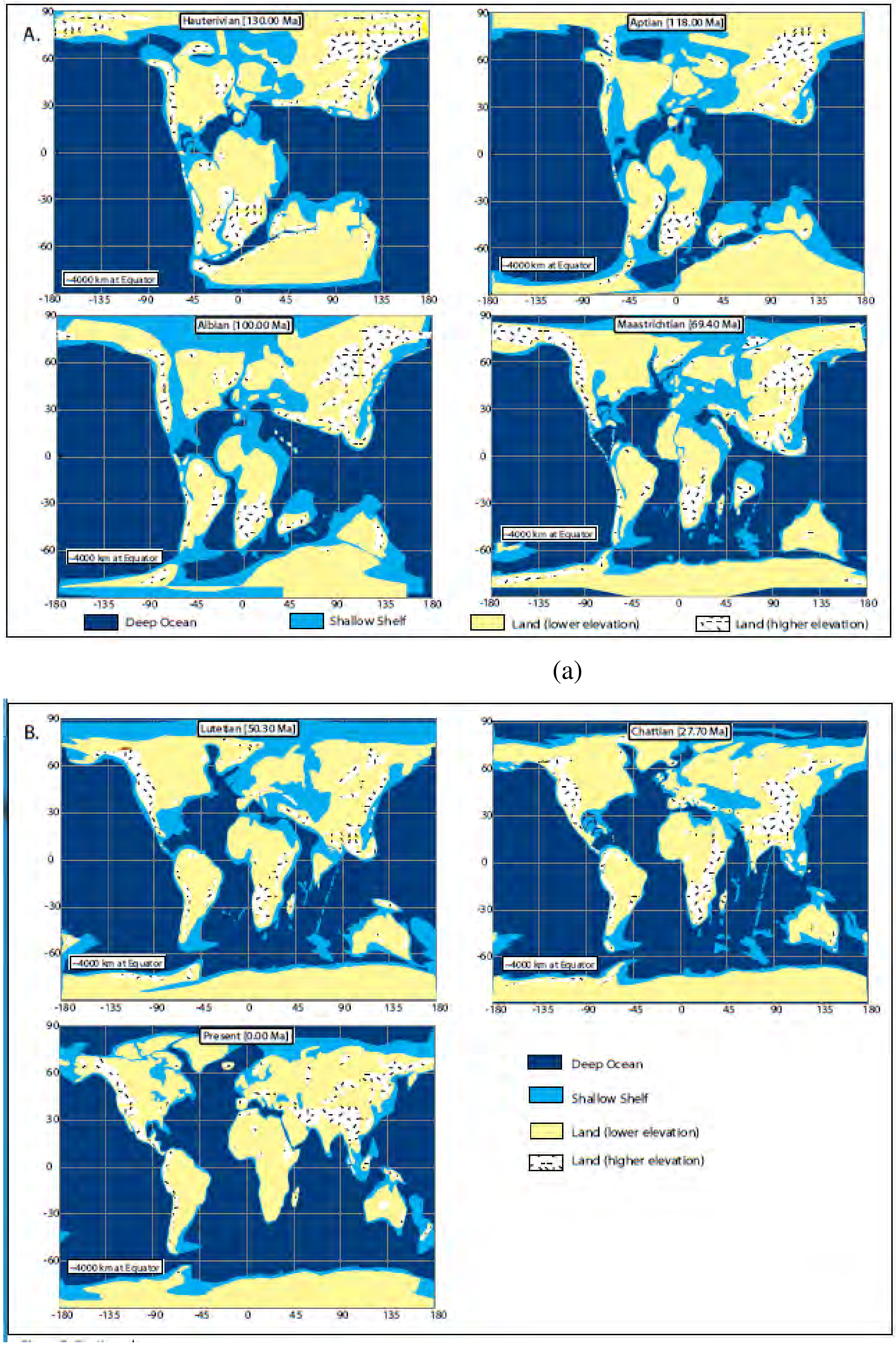
2.1 Introduction

This chapter describes the geologic setting of the Tertiary Niger Delta, its structural and stratigraphic settings as well as the petroleum systems within the Niger Delta.

2.2 Geologic Setting

The Niger Delta is situated in the Gulf of Guinea, in West Africa. It represents the southern margin of a triple junction rift system that triggered the separation of the African continent from the South American continent during the Jurassic through the Early Cretaceous. Rifting started around Late Jurassic and continued to the Middle Cretaceous (Lehner and De Ruiter, 1977). During the Late Cretaceous, rifting reduced. Figure 2.1 depicts the gross paleogeography of the Niger Delta and the relative positions of the African and South American plates from the period of rifting.

At the end of rifting, gravity tectonism occurred as the main process of deformation.



(a)

(b)

Figure 2.1: Paleogeography revealing the opening of the South Atlantic, and development of the region around the Niger Delta (a) Cretaceous paleogeography (b) Cenozoic paleogeography (Tuttle et al., 1999).

Internal deformation was induced by the mobility of shale. This occurred as a result of the response to two major processes as explained by Kulke (1994). The first process is the formation of shale diapirs from the loading of Akata formation which is poorly compacted, over-pressured, pro-delta and delta-slope clays, by the more densely delta front sands which is the Agbada formation. The second process involved the instability of slope which occurred as a result of lack of lateral, basinward, and support for the Akata formation (Figure 2.2).

There was completion of gravity tectonics for any depobelts in the Niger Delta before Benin formation was deposited. These are shown in complex structures such as roll-over anticlines, shale diapirs, collapsed growth faults, back-to-back features and steeply dipping closely spaced flank faults (Evamy et al., 1978).

2.3 Stratigraphic Setting

The River Niger, which drains much of West Africa south of the Sahara, is the main supplier of sediments to the Niger delta (Allen, 1965). River Benue, which is the second prominent fairway of sediment supply to the Niger delta, merges with River Niger in the confluence town of Lokoja, Nigeria. River Niger subsequently branches into a network of tributaries that deposit their fluvial loads into the Niger delta. Sediment supply to the Niger Delta is sourced from the Northern Nigerian massif, the West African massif, Adamawa Massif, Oban massif, Benue trough, Bida basin, Anambra basin, and Abakaliki trough (Figure 2.3). The Niger delta lithology is predominantly siliciclastic, and the direction of current at discharge to the Niger Delta is approximately north-south

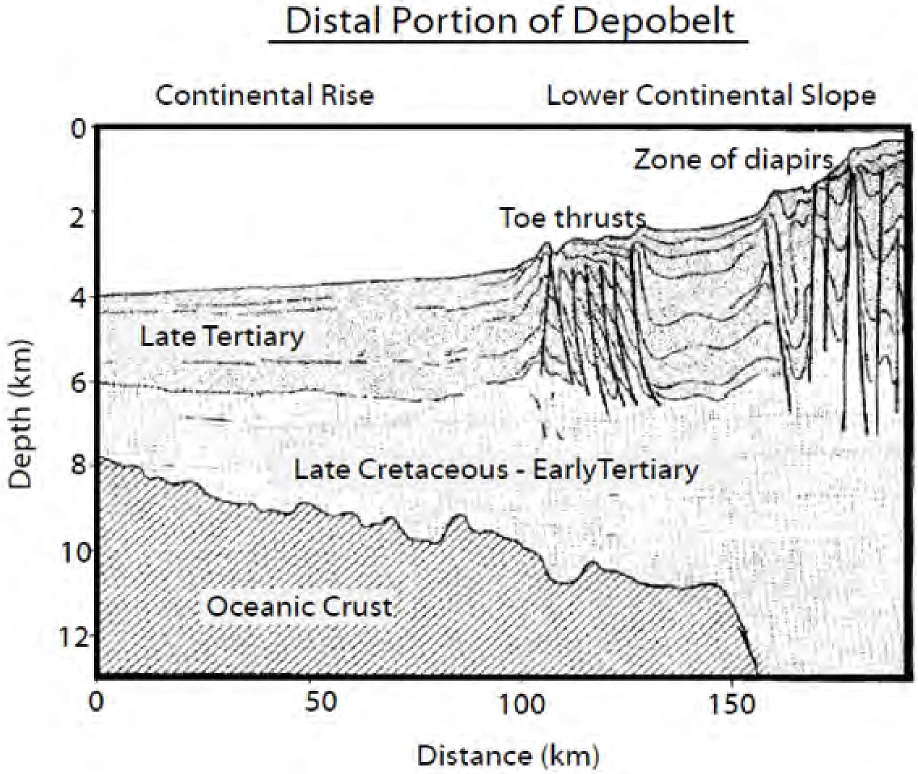


Figure 2.2: Schematic of a seismic section from the Niger Delta continental slope/rise depicting the result of internal gravity tectonics on sediments at the distal portion of the depobelts (Doust and Omatsola, 1990).

(N-S). The Niger Delta is believed to have been prograding into the Atlantic Ocean for the last 35 Ma. Each formation records a different part of a linked non-marine to delta to offshore depositional system.

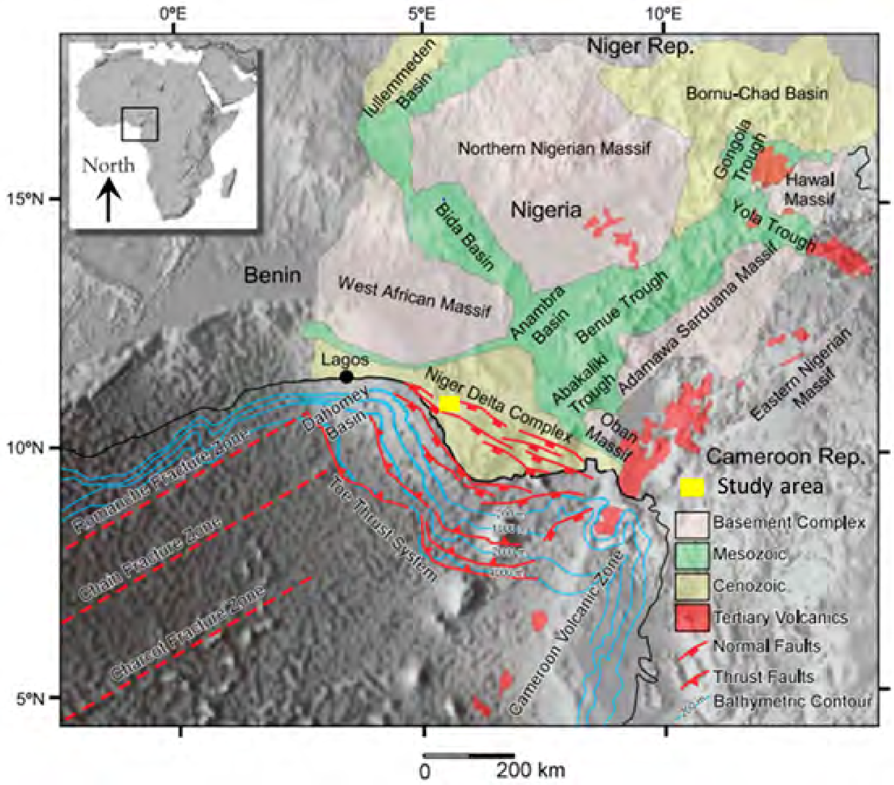


Figure 2.3: The bounding geologic features of the Niger delta depicting the northern sources of fluvial supply (Whiteman, 1982).

2.4 Regional Stratigraphy

Short and Stauble (1967) subdivided the Niger delta into three lithostratigraphic units, ranging in age from Paleocene to Recent. They include the Akata, Agbada and Benin formations (Figure 2.4). These formations are coeval. The Akata formation is marine in origin and is made up of thick shale sequences. The Akata formation is situated at the base of the Niger Delta and consists of prodelta, hemipelagic, and pelagic shales that were deposited in marine environments (Figures 2.4, 2.5, 2.6). The formation is late Paleocene to early Pliocene in age. The Akata formation is characterized by high plasticity and overpressure, especially at depth. All major faults and counter-regional faults merge into a plane (or detachment surface) in the lower part of the Akata formation. Though little of the Akata formation has been drilled with the availability of only top structure map of the formation, estimations show that the formation is about 23,000 ft. (7,000 m) in thickness (Doust and Omatsola, 1990; Tuttle et al., 1999) (Figure 2.7).

The Agbada formation consists of a paralic sequence of interbedded sands and shales. The sandstones were deposited in prograding transitional or coastal environments comprised the fluvio-deltaic and barrier islands of the delta front, lagoon, brackish-water bays, beaches, and the shoreface. Shales are prodeltaic to hemipelagic in origin. The Agbada formation is Eocene to Pleistocene in age and about 3,700 m thick (Figure 2.7).

The Benin formation consists of continental sandstones that were deposited in a delta plain as point bars by meandering streams or as channel fills with natural levees (Doust and Omatsola, 1990). The massive fresh-water bearing Benin formation occurs widely across the Niger Delta, with thicknesses ranging between 300 and 3,000 m. The Benin formation does not play any important role in the evolution of the Niger delta petroleum system, except serving as overburden.

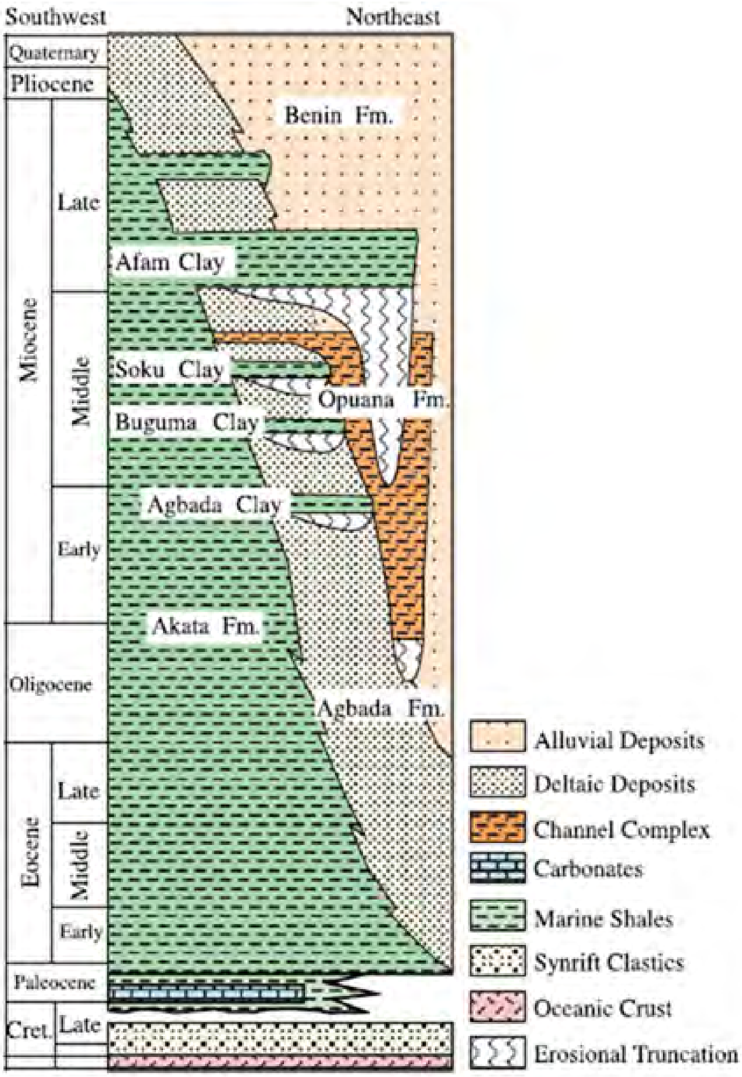


Figure 2.4: Stratigraphic column depicting the three formations in the Niger Delta (Doust and Omatsola, 1990).

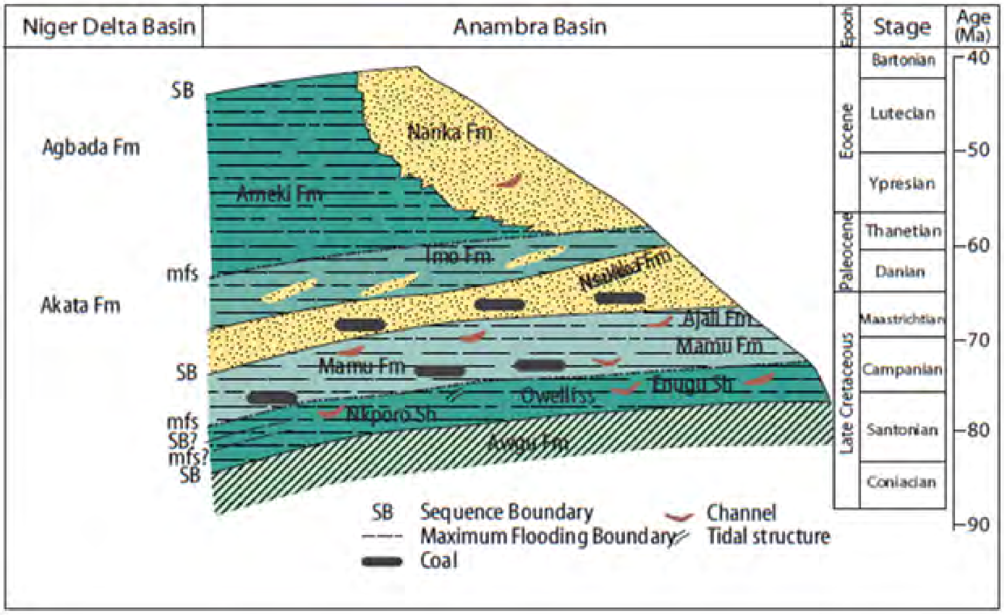
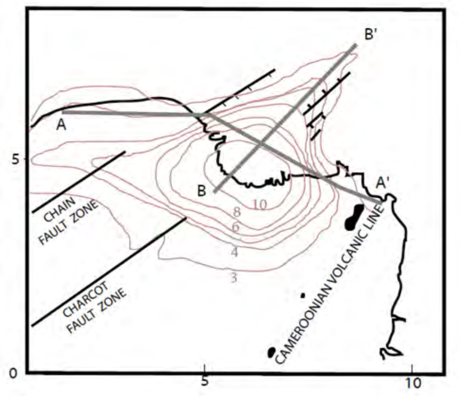
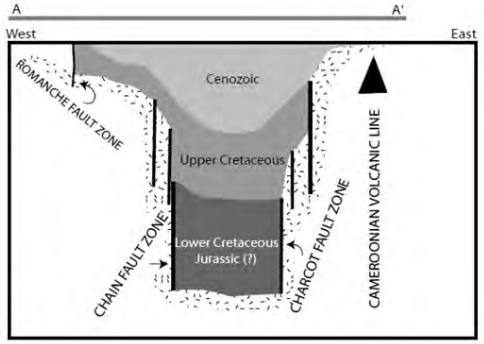


Figure 2.5: Stratigraphic column of Anambra basin from the Late Cretaceous through the Eocene as well as time equivalent formations in the Niger Delta (Reijers et al., 1997).



(a)



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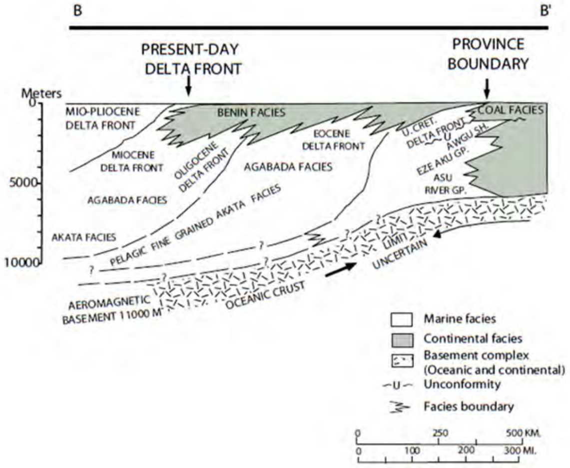
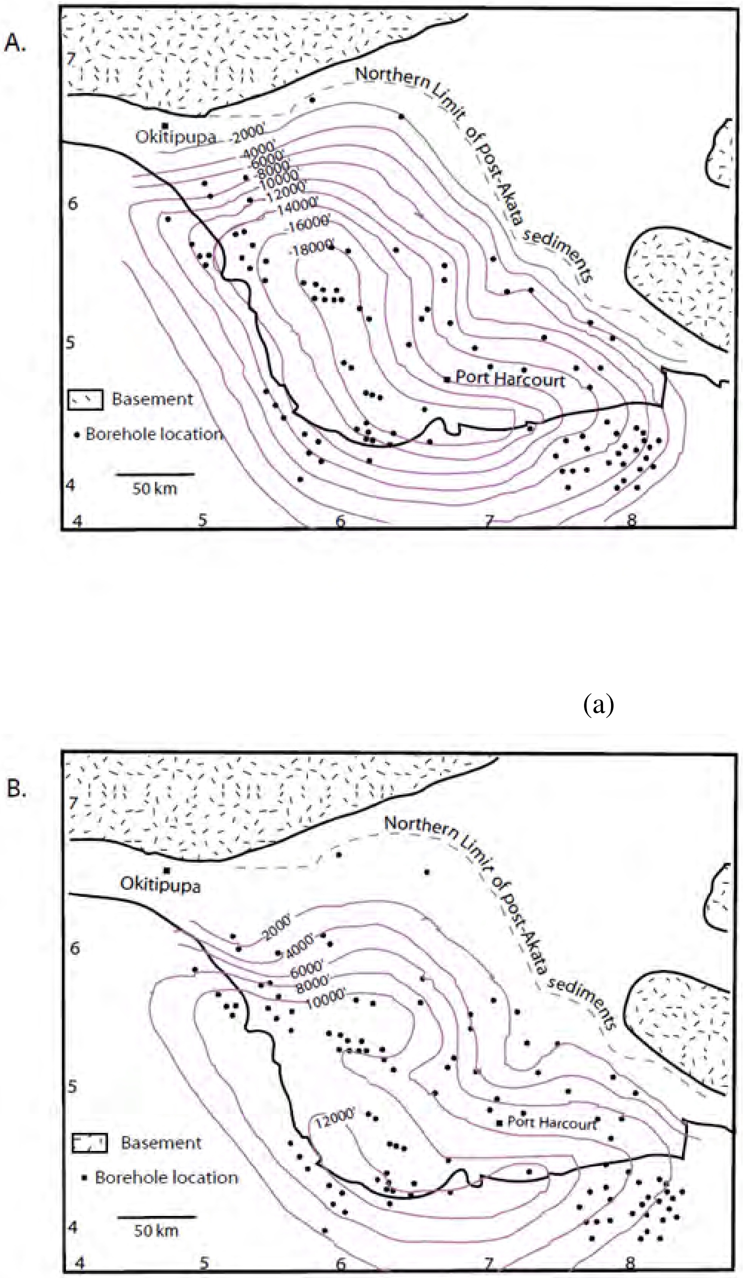


(c)

Figure 2.6: (a) Isopach of total sedimentary thickness (in km) in the Niger Delta (b) Cross section (East - West) A-A through the Niger Delta region and Cross section (Southwest-Northeast) (c) B-B depicting the three formations of the Niger delta (Whiteman, 1982).



(a)

(b)

Figure 2.7: (a) Top structure map of Akata formation (b) Isopach map of Agbada formation (Avbovbo, 1978).

2.5 Structural Setting

Otu field is located in the south-west Niger delta, within the extensional fault province that is associated with growth faults and rollover anticlines.

2.5.1 Regional Structure

The Niger Delta system, the Anambra basin, the Benue trough, and the Chad basin, are believed to have been triggered by the triple-junction rifting that is responsible for the splitting of Africa from South America during the Jurassic through the Cretaceous; with a relict in the present-day West African Gulf of Guinea. The system extends from the north in the present onshore, prograding southwestward into the present offshore deep waters. Paleo-depositional environment is believed to range from the onshore deltaic fluvial systems to the offshore marine systems. The separation of the African plate from the South American plate gave rise to the opening of the South Atlantic and the Early Cretaceous incursion of marine sediments in the basin (Doust and Omatsola, 1990).

Corredor et al. (2005) subdivided the delta into five structural zones (Figure 2.8), based on seismic interpretation which include: (a) extensional province defined by listric basin-dipping faults, as well as counter-regional normal growth faults and associated rollovers, (b) a zone of mud diapirs made up of passive, active, and reactive mud diapirs (c) the inner fold and thrust belt, made up of basinward-verging thrust faults and associated folds, (d) a transitional detachment fold zone beneath the lower continental slope, and (e) the outer folds and thrust belts characterized by both basinward and hinterland-verging thrust faults and associated folds. The extensional province commences from the onshore Niger delta, including the field to be studied. Otu field is situated within the extensional province defined by basin-dipping listric faults.

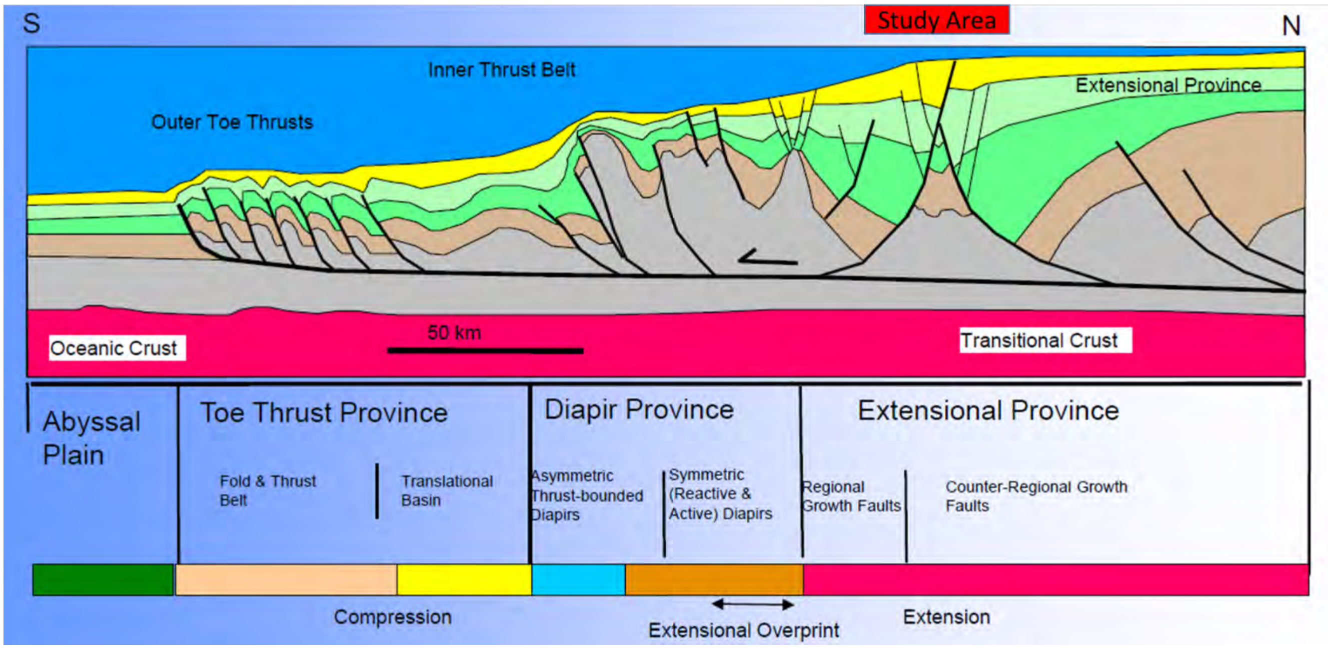


Figure 2.8: Structural styles of the deepwater Niger Delta. The three provinces in the Niger Delta are the toe thrust, diaper and extensional province. Otu field falls within the extensional province (Corredor et al., 2005).

2.6 Petroleum Geology of the Niger Delta

There are three critical factors that are important in the Niger Delta regarding the petroleum system in the basin. These include the source, reservoir, and seal. These critical factors are believed to have occurred during the Middle Eocene (Figure 2.9)

2.6.1 Petroleum System

. The main source rock of the Niger Delta petroleum system is the Akata formation (Evamy et al., 1978; Ejedawe, 1986; Nwachukwu and Chukwura, 1986; Bustin, 1988). The organic contents and kerogen type of the shale in the younger Agbada formation was evaluated and believed to have contributed towards the generation of hydrocarbon in the basin (Evamy et al., 1978). Oil-bearing type III kerogen is the predominant kerogen in the petroleum system of the Niger Delta .

The Niger Delta has low total organic carbon (TOC), having a range of 1.4 percent and 1.6 percent according to Bustin (1988). As a result of the synchronous occurrence of the reservoir rocks, traps, and seals, the Niger Delta is thus believed to provide a prolific oil province, irrespective of the relatively low TOC

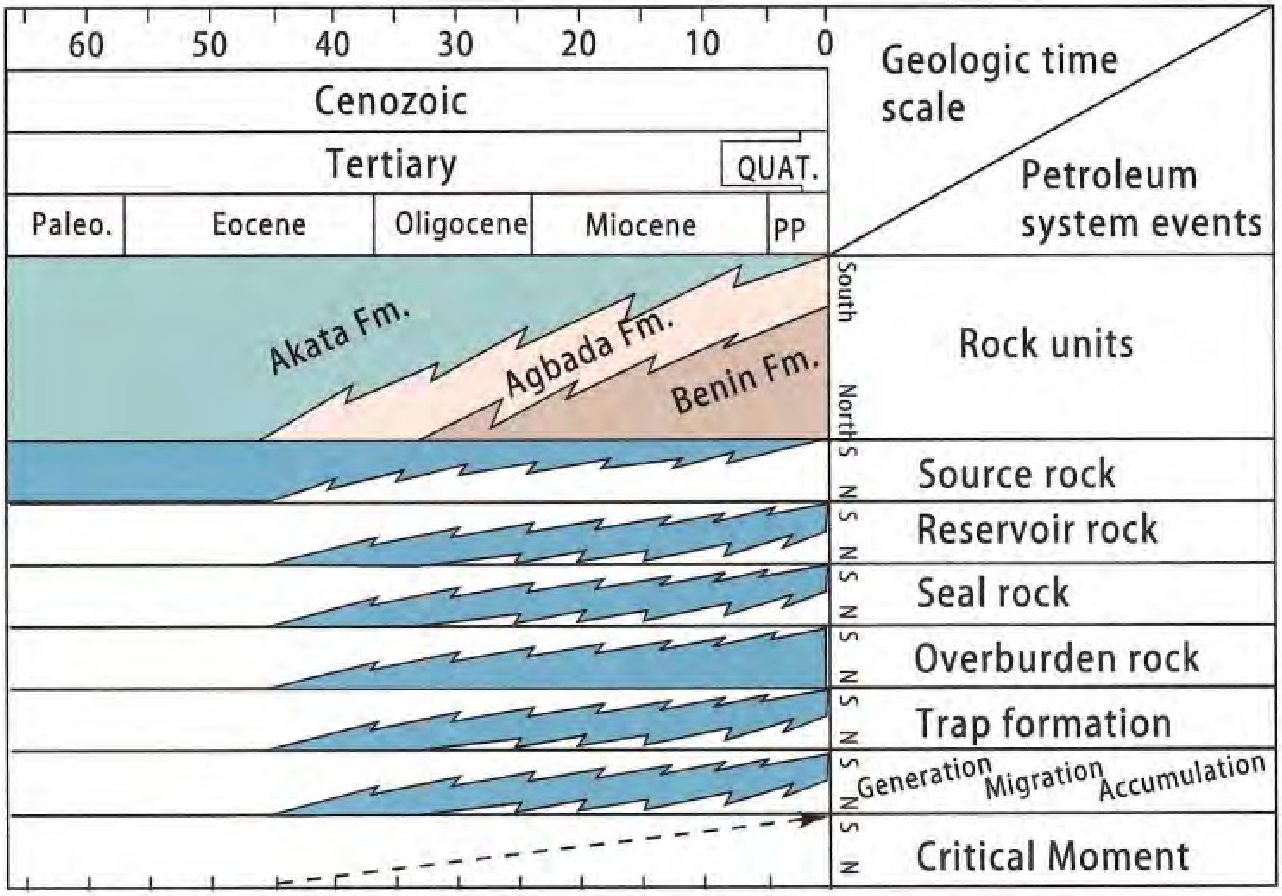


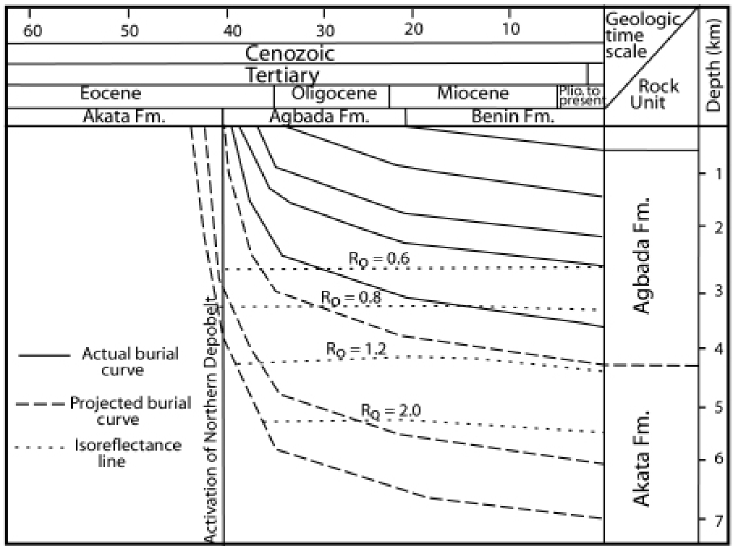
Figure 2.9: Event chart of the Niger Delta showing Akata/Agbada petroleum system (Tuttle et al., 1999).

2.6.2 Source Rock

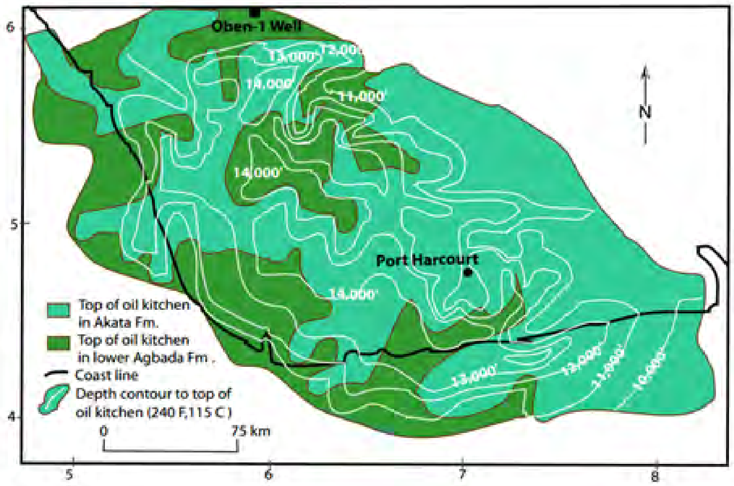
Akata formation, which is the oldest formation in the basin is the established formation that served as source rock of the petroleum system of the Niger Delta. The Akata formation is comprised mainly of mobile shale on which growth faults detach and propagate basinward, thereby creating more accommodation space in the Niger Delta basin (Evamy et al., 1978; Doust and Omatsola, 1990; Tuttle et al., 1999). The deposition of this formation started during the Paleocene.

2.6.3 Petroleum Maturation and Migration

During the Middle Eocene to the Present, there is deposition of overburden rock in the Niger delta. The generation of petroleum in the delta started in the Eocene and continues up till present (Tuttle et al., 1999). Petroleum generation started from the north to south as progressively younger depobelts entered the oil window (Tuttle et al., 1999). The top of the Niger delta oil window is presently at the 240°F (115°C) isotherm (Evamy et al., 1978). The oil window in the northwestern portion of Niger Delta (where Otu field is located) is in the upper Akata formation and the lower Agbada formation (Figure 2.10). The top of the oil window is stratigraphically lower in the southeastern portion of the Niger delta: about 4,000 ft (1,247 m) below the upper Akata/lower Agbada sequence (Evamy et al., 1978). The distribution of the top of the oil window depends on the thickness and sand/shale ratios of the overburden rocks of Agbada and Benin formations (Nwachukwu and Chukwura, 1986; Doust and Omatsola, 1990; Stacher, 1995). The sandy continental Benin formation has the lowest thermal gradient of 1.3 to 0.125°C/321 ft (100 m); the paralic Agbada formation has an intermediate gradient of 2.7°C/321 ft (100 m); and the marine, over-pressured Akata formation has the highest thermal gradient of 5.5°C/321 ft (100 m) (Ejedawe, 1986).



(a)



(b)

Figure 2.10: (a) Burial history chart of the northern portion of the Niger delta petroleum system, derived from data collected in Oben-1, northwest Niger delta (b) Top Niger delta oil kitchen, contour interval is 1,000 ft (312 m) (Ekweozor and Daukoru, 1994).

The boundary of the Akata and Agbada formations in the vicinity of Oben-1 entered the oil window during the Late Eocene at approximately 0.6 Ro (Stacher, 1995), (Figure 2.10). The current depth of the Akata/Agbada boundary in the northwestern Niger Delta is about $4,300m$, with the upper Akata formation in the wet gas/condensate generating zone of vitrinite reflectance value greater than 1.2 (Tissot and Welte, 1984; Tuttle et al., 1999). The lowermost part of the Agbada formation in the northwestern Niger Delta entered the oil window during the Late Oligocene.

Stacher (1995) assumed that migration overlapped in time with the burial and structural development of the overlying reservoir and that hydrocarbon migration occurred mainly through the fault gaps. Migration distances were believed to be short, as evident in the wax content, API gravity, and the chemistry of the Niger Delta oils (Short and Stauble, 1967; Reed, 1969). Migration from matured, over-pressured shale in the more distal portion of the Niger Delta may be similar to that described from over-pressured shale in the Gulf of Mexico (Tuttle et al., 1999). Beka and Oti (1995) predicted a bias towards lighter hydrocarbons (gas and condensate) from the over-pressured shale as a result of down-slope dilution of organic matter as well as differentiation associated with expulsion from over-pressured sources.

2.6.4 Reservoir and Seal

Both structural and stratigraphic traps are present in the Niger Delta, although structural traps are more pronounced in the basin. Examples of such oil fields are given in Figure 2.11. The Agbada formation in the Niger Delta serves as the hydrocarbon reservoir. It is described as an intercalation of sand and shale (Doust and Omatsola, 1990). Growth faults that detach on the Akata formation provide the pathways through which the porous and permeable sandstones of the Agbada formation are interconnected. The shales of the Agbada formation serve as the local seal, in combination with the appropriate fault framework as seen in Figure 2.12.

Benin formation (continental sands) is believed not to play an important role in the generation and the preservation of hydrocarbon in the Niger Delta. The Benin formation is, however, thick enough (300 m - $3,000$ m) to serve as a significant overburden rock.

About 65 percent of the crude oil produced from the Niger Delta fall within the category of the sweet (low-Sulfur-content), 30 degrees to 40 degrees API gravity range.

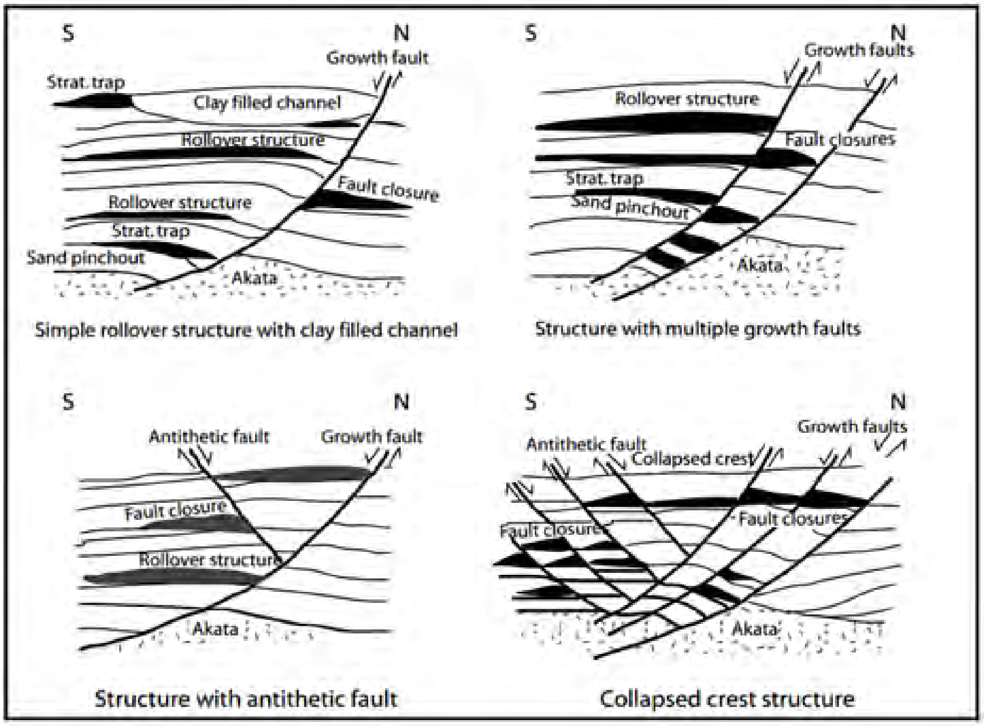


Figure 2.11: Examples of Niger Delta oil field structures and associated trap types (Stacher, 1995).

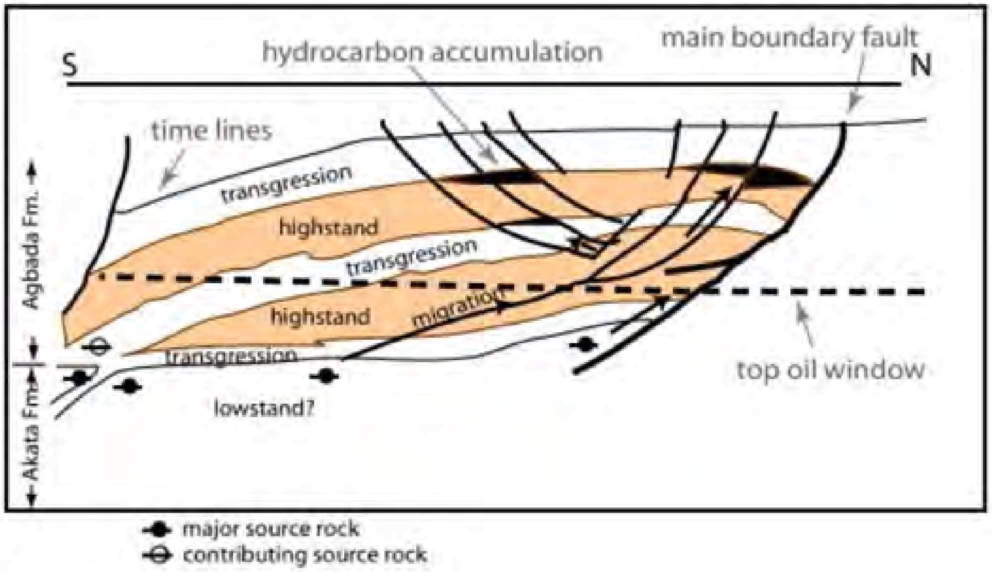


Figure 2.12: Sequence stratigraphic model of the Niger Delta showing the relationships between the source rock, migration paths, and traps (Stacher, 1995).

CHAPTER 3

DATA ANALYSIS AND INTERPRETATION

3.1 Introduction

This chapter describes the analysis and interpretation of data in Otu field. The analysis involves the results of well logs and seismic data. The chapter also describes reservoir potential and porosity evaluation within Otu field.

3.2 Well Log Data

3.2.1 Lithostratigraphic Analysis of the Wells

Gamma ray (GR) logs from all the thirteen wells were used to delineate the lithology in Otu field. The sand bodies were identified by the deflection of the GR log to the left while shale was identified by the deflection to the right. Gamma ray log cut-off of

35 API was used for the lithostratigraphic analysis (i.e. shale: $> 80API$, shaly sand: $35-80$ and sand: $< 35API$). Sand reservoirs were identified in the field.

The result of the lithostratigraphic analysis for the subsurface facies of the Agbada formation penetrated by the wells in the Niger Delta is given in Figure 3.1. Fourteen sand reservoirs were identified in Otu field. Sand N is the deepest sand whose top was encountered at different depths in almost all the wells except in wells Otu 19, Otu 21, and Otu 46 whose total depths were shallower. Sand A is the shallowest sand reservoir that was penetrated by all the wells at different depths. Some sand units occurred at greater depth than their adjacent units and this could be the result of faulting.

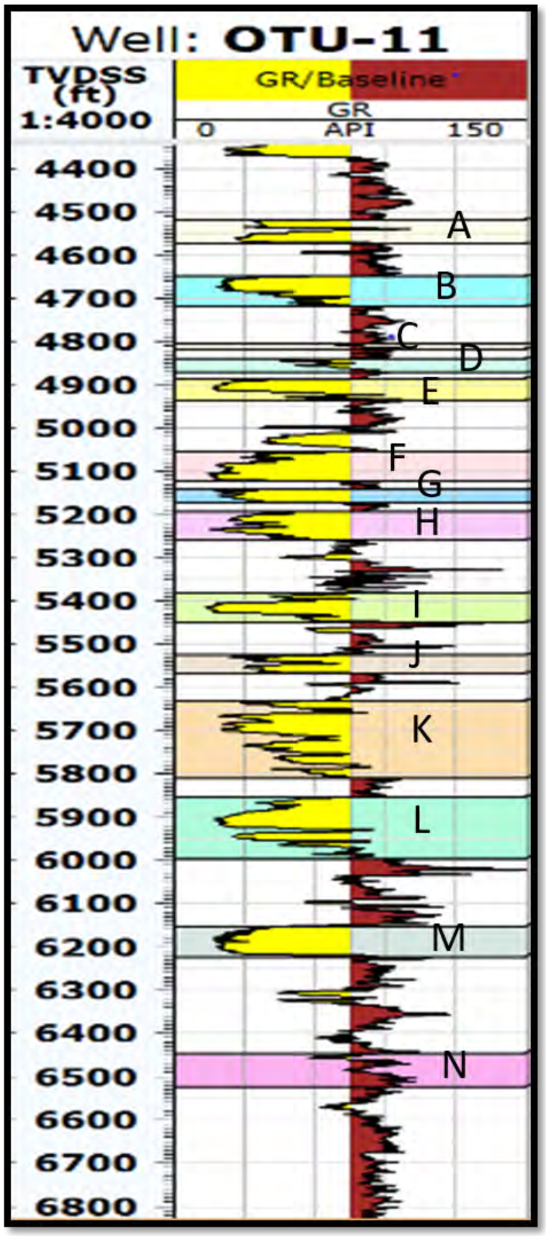


Figure 3.1: Lithostratigraphic analysis of the wells showing fourteen reservoir sands in Otu field. Sand A is the shallowest while Sand N is the deepest which was not penetrated by all wells within the field.

3.2.2 Lithofacies

Four lithofacies and their depositional environments were delineated in Otu field using the gamma ray log motifs.

Facies One: Shaly Sandstone Facies

This facies is made up of fine grained sandstone with intercalations of shale. It is coarsening upward unit GR log pattern (Figure 3.2). This pattern is a common feature of deltaic fluvial environment. This facies is interpreted to be channel point bar deposits based on these characteristics.

Facies Two: Sandstone Facies

This facies is composed of bodies of sand that are characterized by blocky-shaped GR log motif (Figure 3.3). This log pattern depict uniform deposition and the facies are peculiar to channelized region. This facies is interpreted to be fluvial channel deposits. The presence of serration may indicate the presence of tidal influence.

Facies Three: Mudrock Facies

This facies is made up of units of shale having intercalations of thin shaly sandstone displaying a retrogradational parasequence pattern. It is characterized by serrated GR log character with uniform bandwidth depicting limited coastline variability (Figure 3.4). Based on these characteristics, it is interpreted to be tidal flat.

Facies Four: Heterolith Facies

This facies consist of sandstone and shale heteroliths and characterized by bell-shaped GR log character (Figure 3.5) depicting a fining upward sequence. The serrated edges may signifies tidal influence. It is interpreted to be tidal channel or sands based on the GR log pattern.

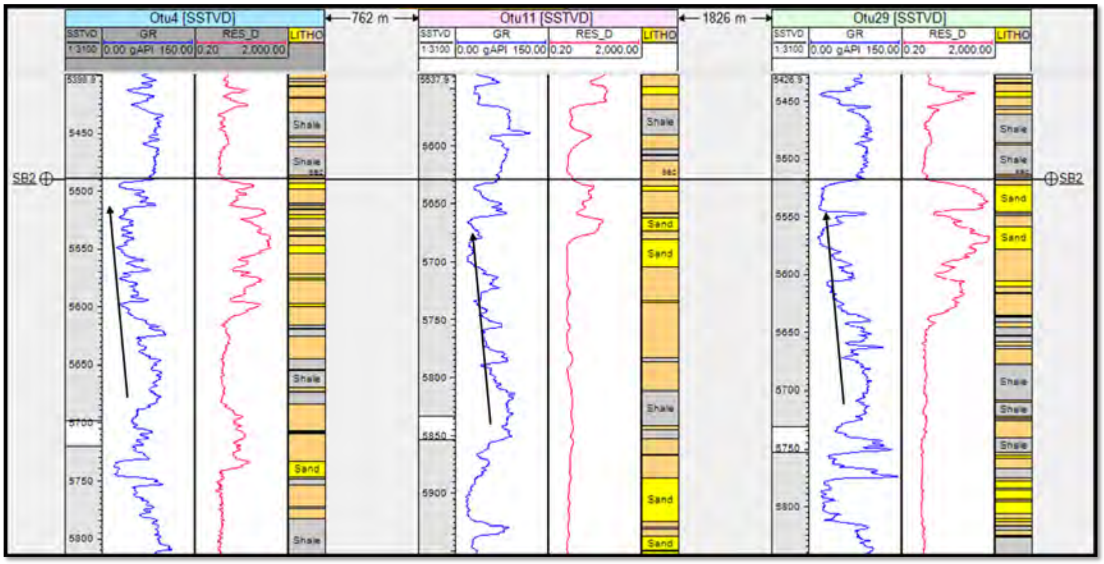


Figure 3.2: Shaly sandstone facies represented by coarsening upward unit GR log pattern. SB means sequence boundary.

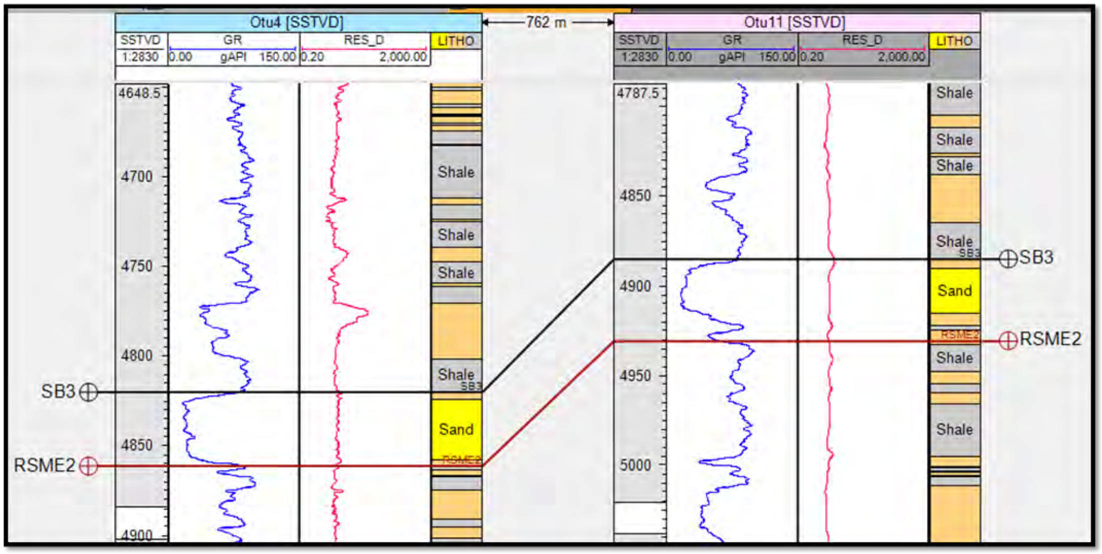


Figure 3.3: Sandstone facies represented by blocky-shaped gamma ray log pattern. SB means sequence boundary and RSME is regressive surface of marine erosion

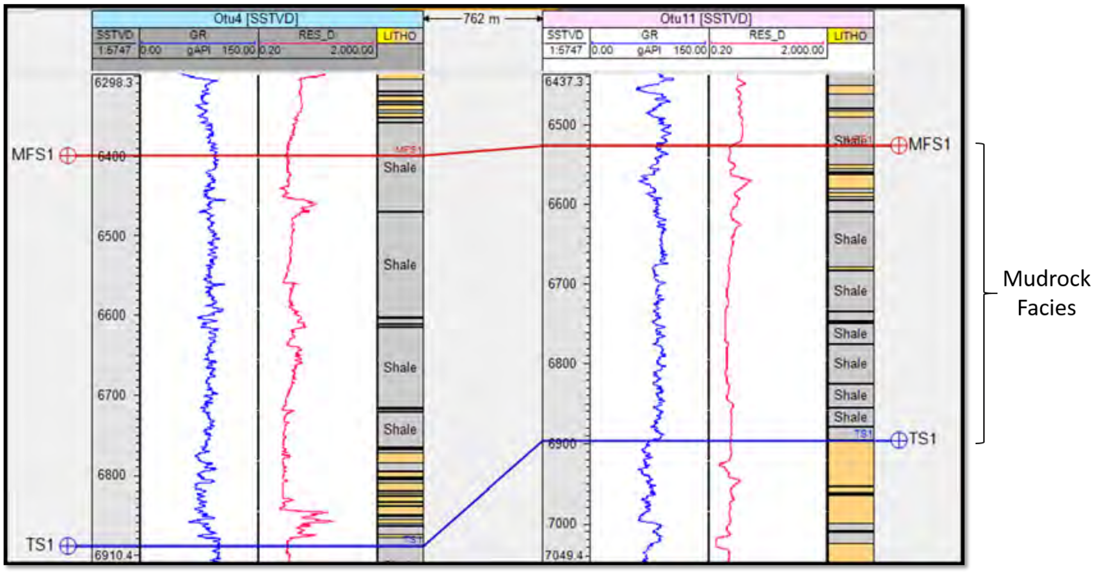


Figure 3.4: Mudrock facies represented by serrated GR log pattern. MFS and TS are maximum flooding surface and transgressive surface respectively.

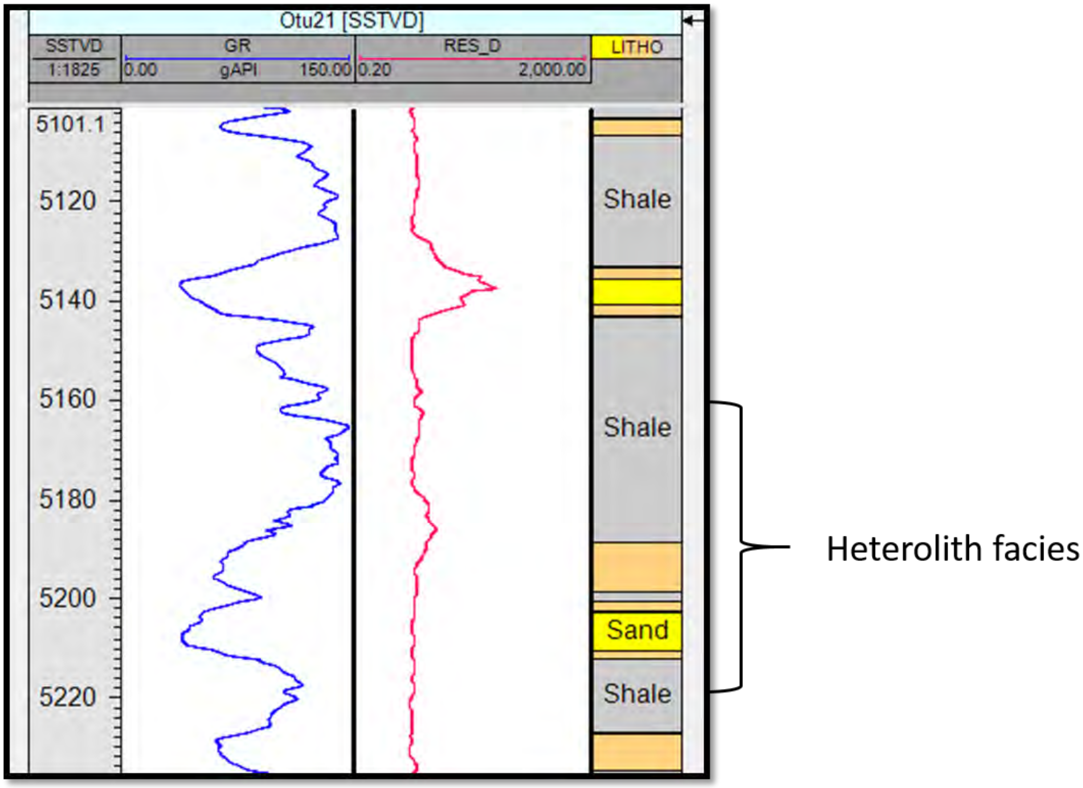


Figure 3.5: Heterolith facies represented by bell-shaped GR log pattern

3.2.3 Chronostratigraphic Correlation of Wells

Chronostratigraphic correlation of time significant surfaces was performed using available well logs and carried out the well log sequence stratigraphic interpretation of individual wells using the stacking patterns such as progradation, retrogradation and aggradation which aided the delineation of the lateral continuity of facies within the systems tract. The depositional (IV) model of Hunt and Tucker (1992, 1995) and Helland-Hansen and Gjelberg (1994) was employed for the subsurface facies within the Agbada formation. The chart in Figure 3.6 was used for the well log sequence stratigraphy and the prediction of the depositional environment.

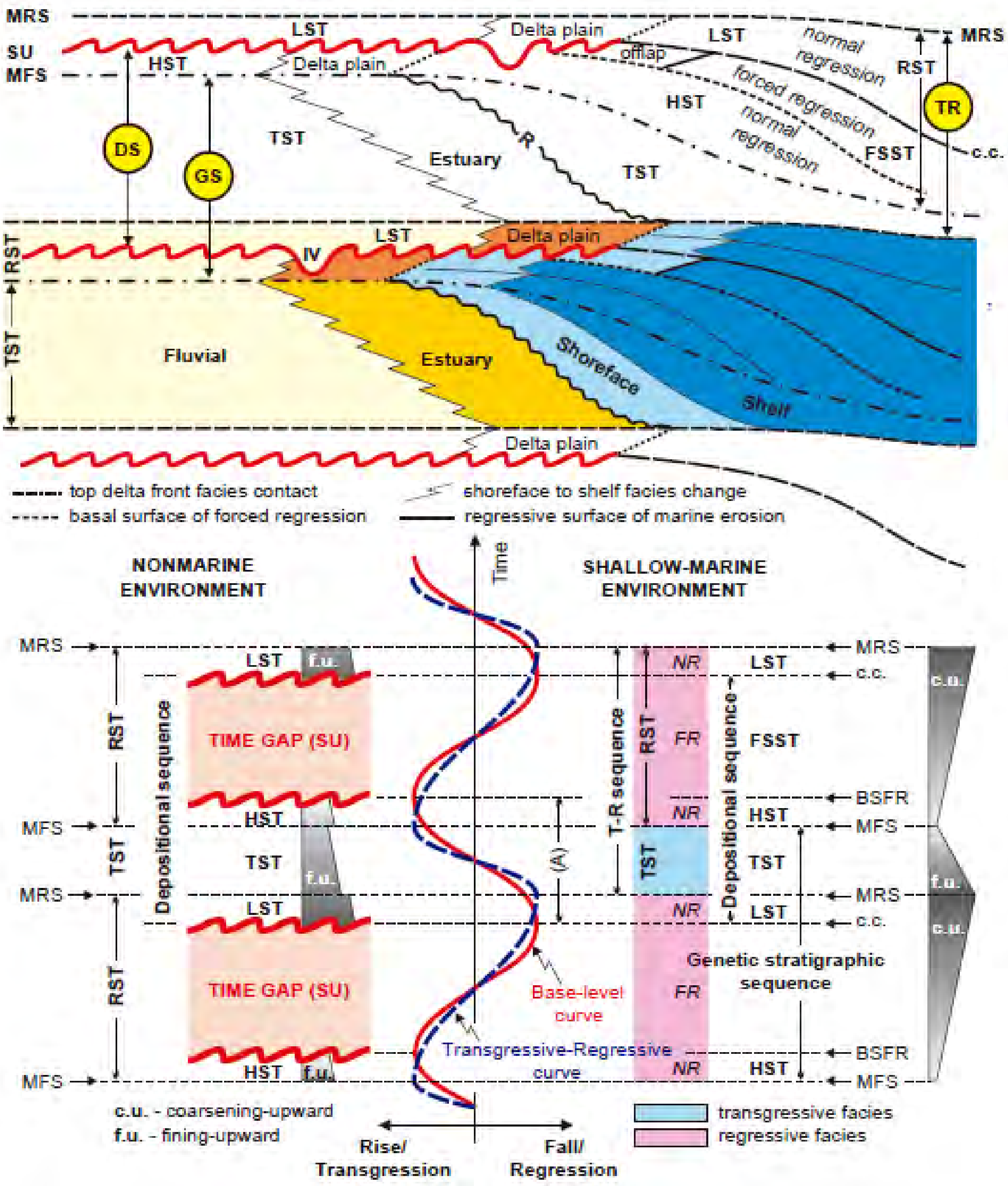


Figure 3.6: Sequences, systems tracts, and stratigraphic surfaces defined in relation to the base-level and the transgressive —regressive curves (Catuneanu, 2002)

The interpretation of the sequence stratigraphic interpretation carried out for the subsurface facies of the Agbada formation penetrated by the wells revealed three depositional sequences based on the depositional (IV) model of Hunt and Tucker (1992, 1995) and Helland-Hansen and Gjelberg (1994) used. Sequence one is an incomplete sequence due to the depth at which logging terminated. Although, sequence boundary one ($SB-1$) was not penetrated by all the wells, nonetheless transgressive systems tracts one ($TST-1$) and highstand systems tracts one ($HST-1$) were identified and delineated. $SB-1$ was penetrated by Otu 4, Otu 6, Otu 8, Otu 11, Otu 29 and Otu 32 wells. Sequence two is a complete sequence with a lowstand prograding wedge (LPW) as its youngest systems tracts and falling stage systems tracts two ($FSST-2$) as the oldest systems tract. FSST is sharp based suggestive of forced regression in the more distal portion of the shallow marine environment. The event of $SB-3$ marks the end of sequence two and the beginning of sequence three. Sequence three extends from the Agbada formation to the Benin formation in the field. Maximum regressive surface three ($MRS-3$) marks the end of sequence three LPW with maximum flooding surface three ($MFS-3$) (Base of Benin formation) capping the underlying $TST-3$ sealing facies. Sequences and stratigraphic surfaces were also correlated within the wells of Otu field along the strike and dip in the field. This was achieved by matching similar well log patterns in the adjacent wells (Figures 3.7, 3.8, 3.9, 3.10, 3.11 and 3.12).

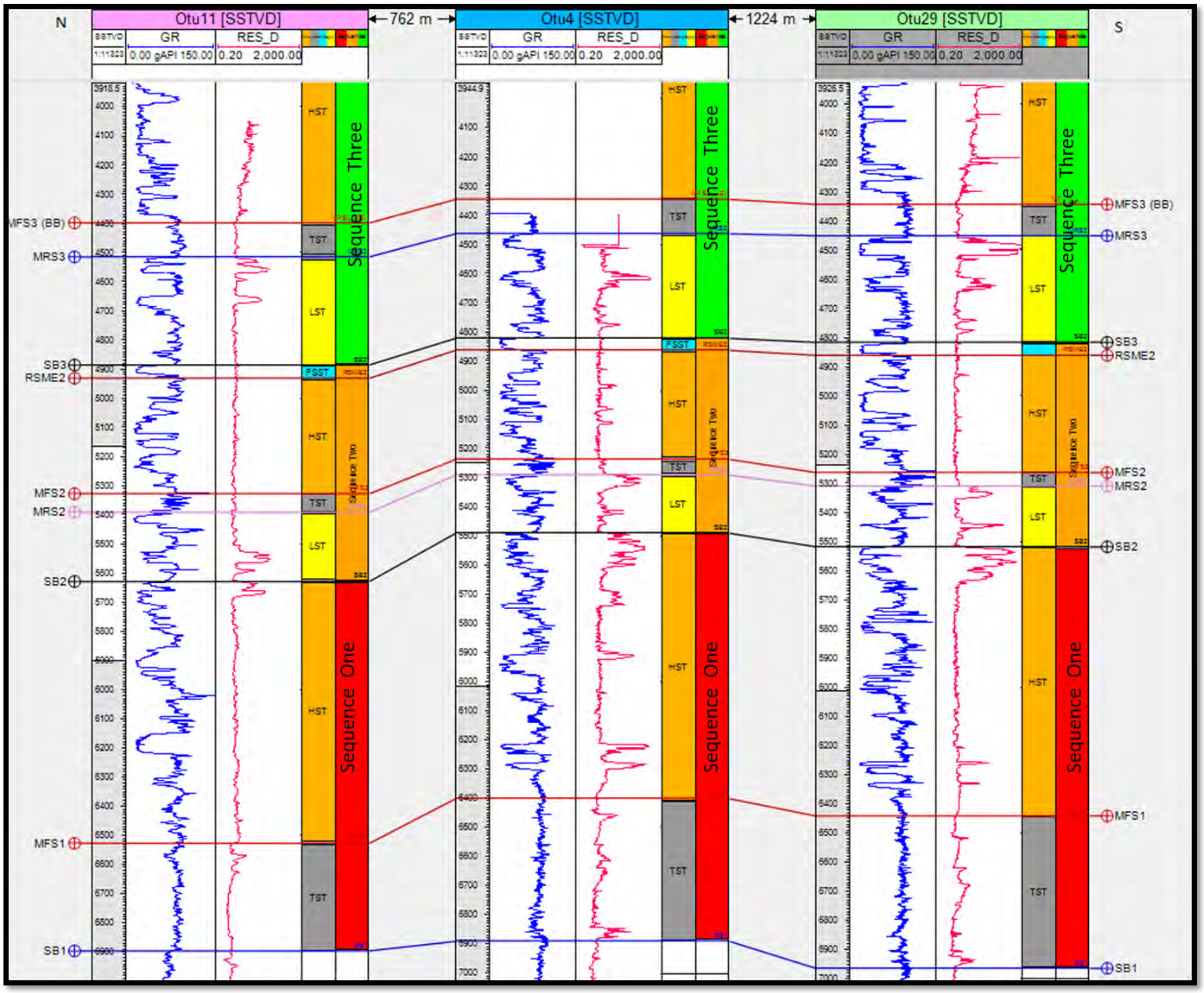


Figure 3.7: Chronostratigraphic correlation log panels for wells 11, 4 and 29 indicating a coarsening upward sequence. Serrated log character are interpreted to be tidal flat, blocky patterns are interpreted to be fluvial channel deposits. MFS3 is the base of the Benin formation.

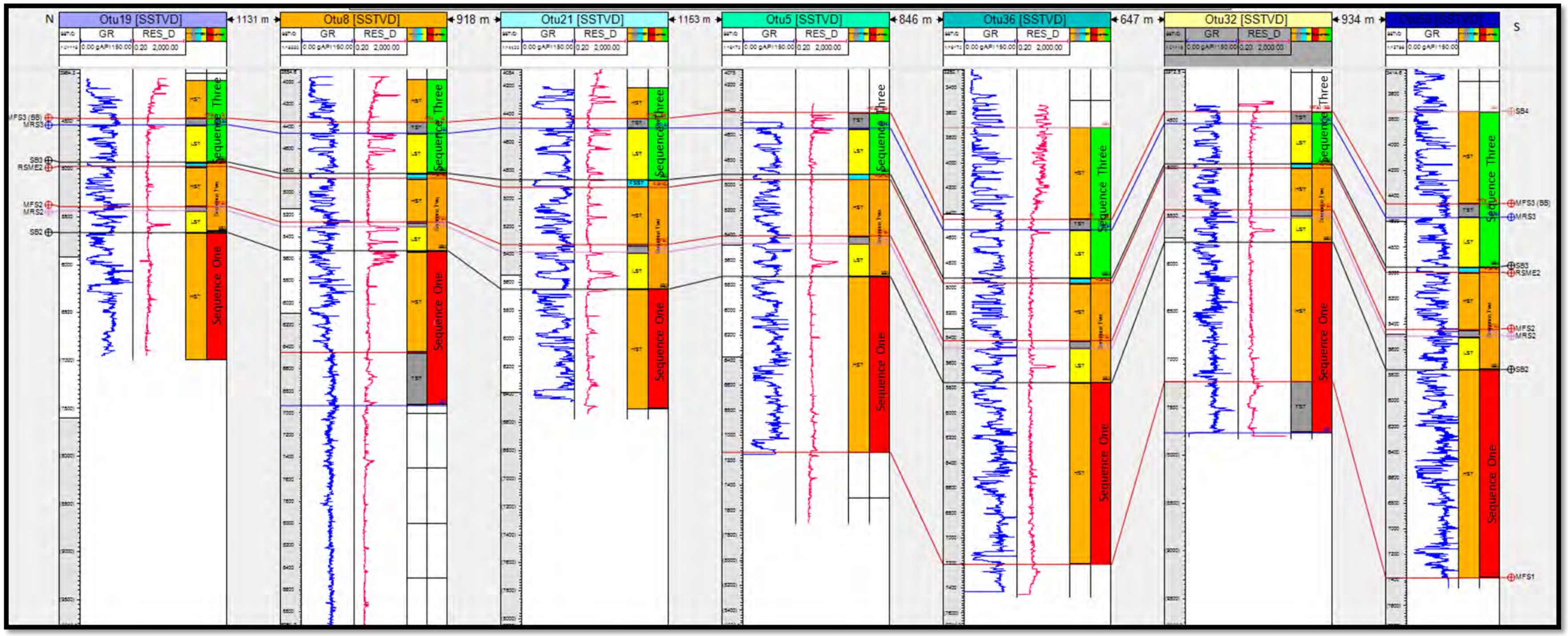


Figure 3.8: Chronostratigraphic correlation log panels for wells 19, 8, 21, 5, 36, 32 and 56 indicating a coarsening upward sequence. Serrated log character are interpreted to be tidal flat while blocky patterns are interpreted to be fluvial channel deposits. HSTs are inferred to be prograding clinoforms.

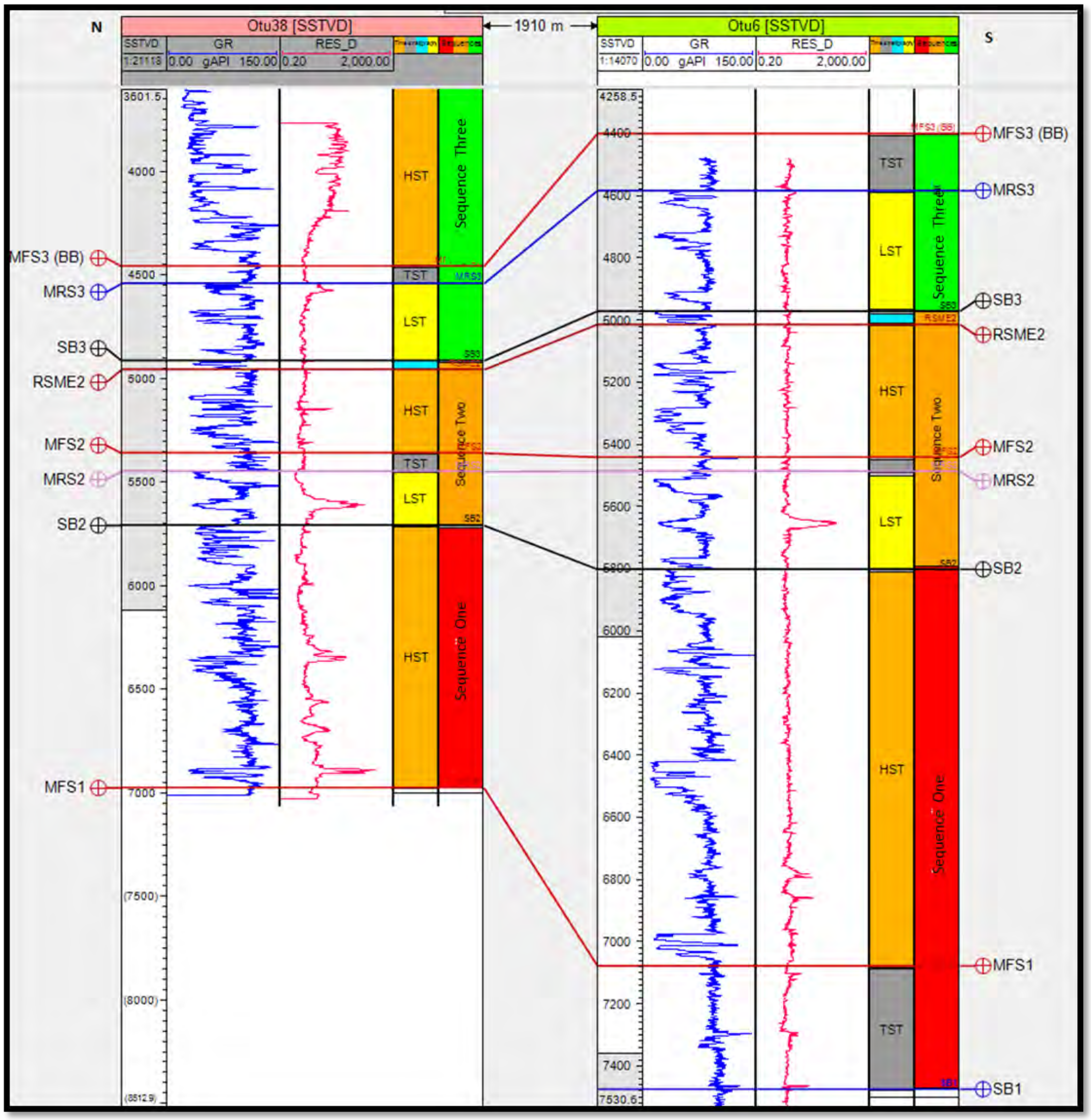


Figure 3.9: Chronostratigraphic correlation log panels for wells 38 and 6 indicating a coarsening upward sequence. SB-1 was not penetrated by Otu 38. Serrated log character are inferred to be tidal flat deposits and HST are prograding clinoforms. Sequences and tracts are thicker in the southern part of the field

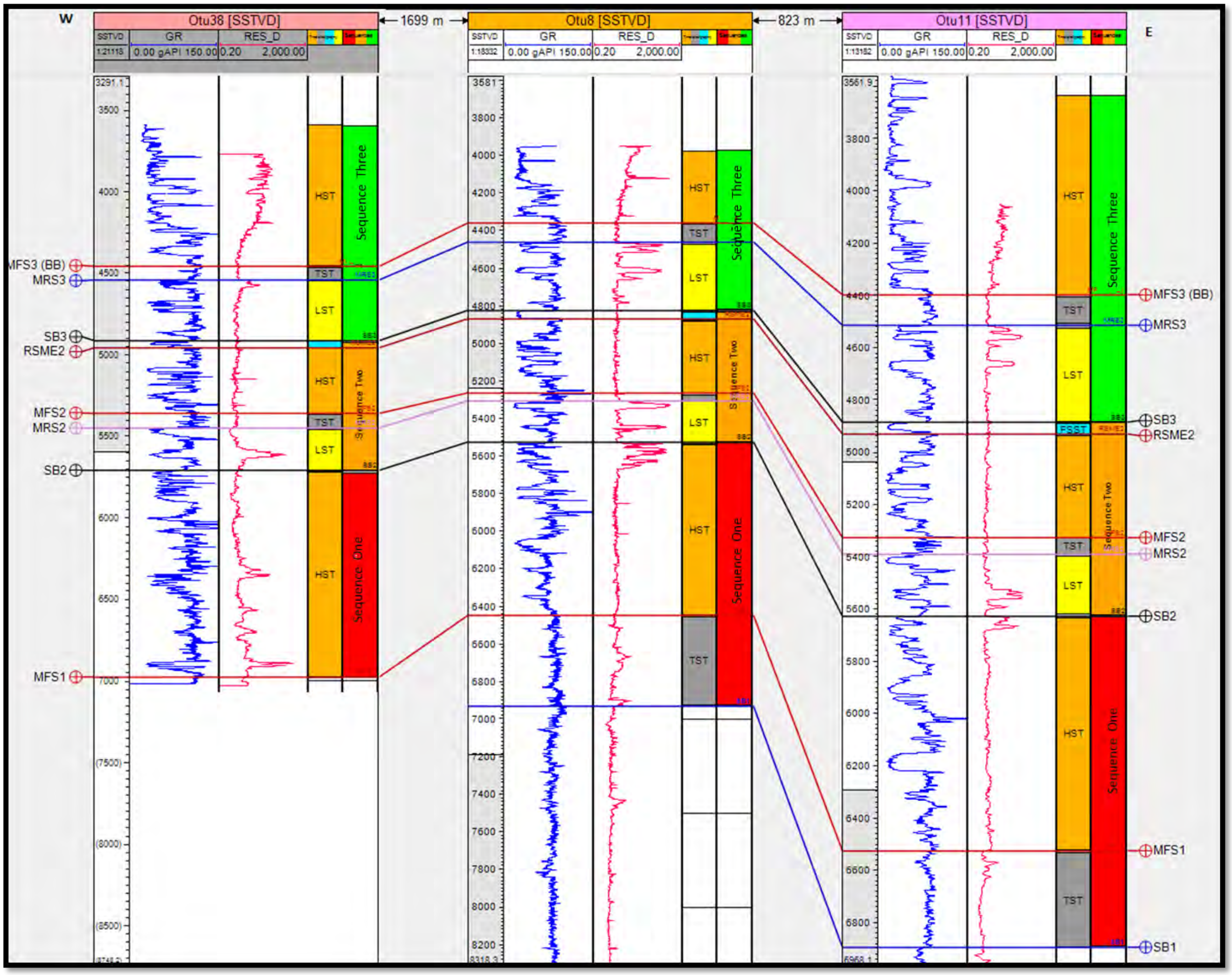


Figure 3.10: Chronostratigraphic correlation log panels for wells 38, 8 and 11 indicating a coarsening upward sequence. Serrated log character are interpreted to be tidal flat deposits and blocky patterns are inferred to be fluvial channel deposits. Small scale coarsening upward units are interpreted to be point bar deposits.

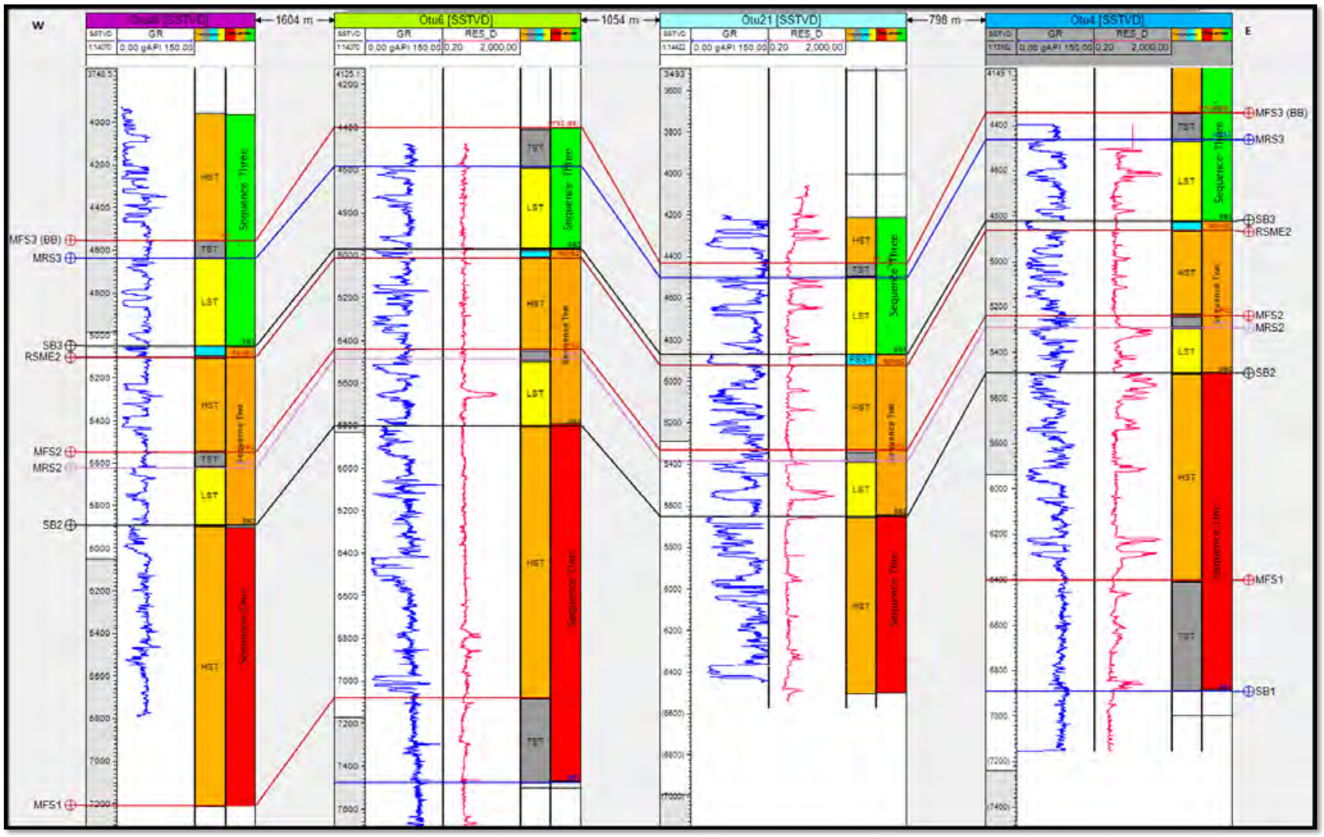


Figure 3.11: Chronostratigraphic correlation log panels for wells 46, 6, 21 and 4 indicating a coarsening upward sequence. Small scale coarsening upward units are interpreted to be point bar deposits.

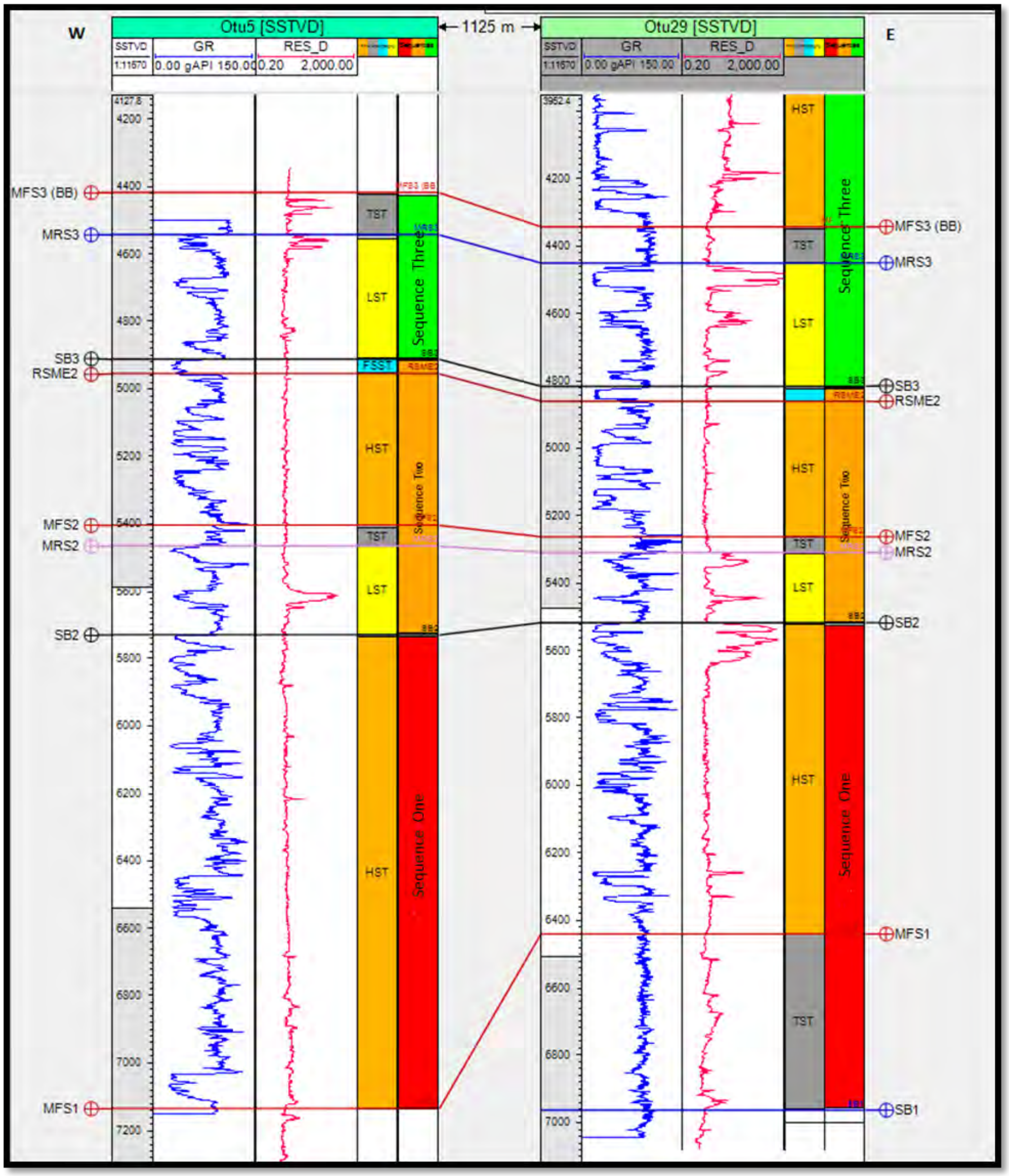


Figure 3.12: Chronostratigraphic correlation log panels for well 5 and 29 indicating a coarsening upward sequence. Serrated log character are interpreted to be tidal flat while blocky patterns are interpreted to be fluvial channel deposits. HSTs are inferred to be prograding clinoforms. Sequence two is thicker at the eastern part of the field.

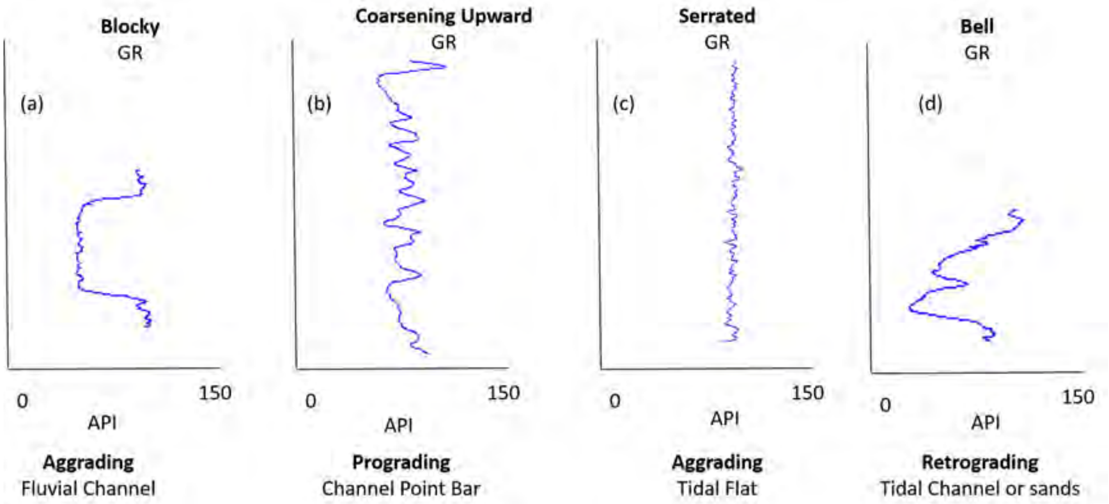


Figure 3.13: Types of well log patterns in Otu field. (a) Blocky log pattern. (b) Upward-coarsening, progradation log pattern. (c) Serrated, aggradational log pattern. (d) Bell shaped, upward-fining, retrogradational log pattern

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3.3 Interpretation of Stratigraphy of Otu Field

The variations of stratigraphy in the Agbada formation of Otu field reflect the regression of depositional environments within the Niger Delta basin by changing broadly from fine-grained deposits in deeper wells directly above underlying the shales of Akata formation (high GR log values) to progressively coarser-grained deposits in shallower wells below the overlying Benin formation (lower GR log values). With the use of standard interpretations of the Agbada formation, successions of logs that gradually decrease in GR value and then rapidly increase are interpreted to be prograding delta deposits. On the other hand, log successions that abruptly decrease in GR value and have "'blocky"' or gradually increasing trends are interpreted to be channel deposits (Figure 3.13).

"'Serrated"' high GR value intervals are known to be dominated by shale with different amounts of thin beds of sandstones. It should be noted, however, that varying trends of log related to prograding shorelines are not always different from those of prograding deeper water mass flow fans, and that no core samples from Otu field are available. Faulting, formations of growth strata over down thrown blocks, and structural deformations that are related with upward movement of underlying Akata formation always makes the stratigraphy of the Agbada formation to be more complex.

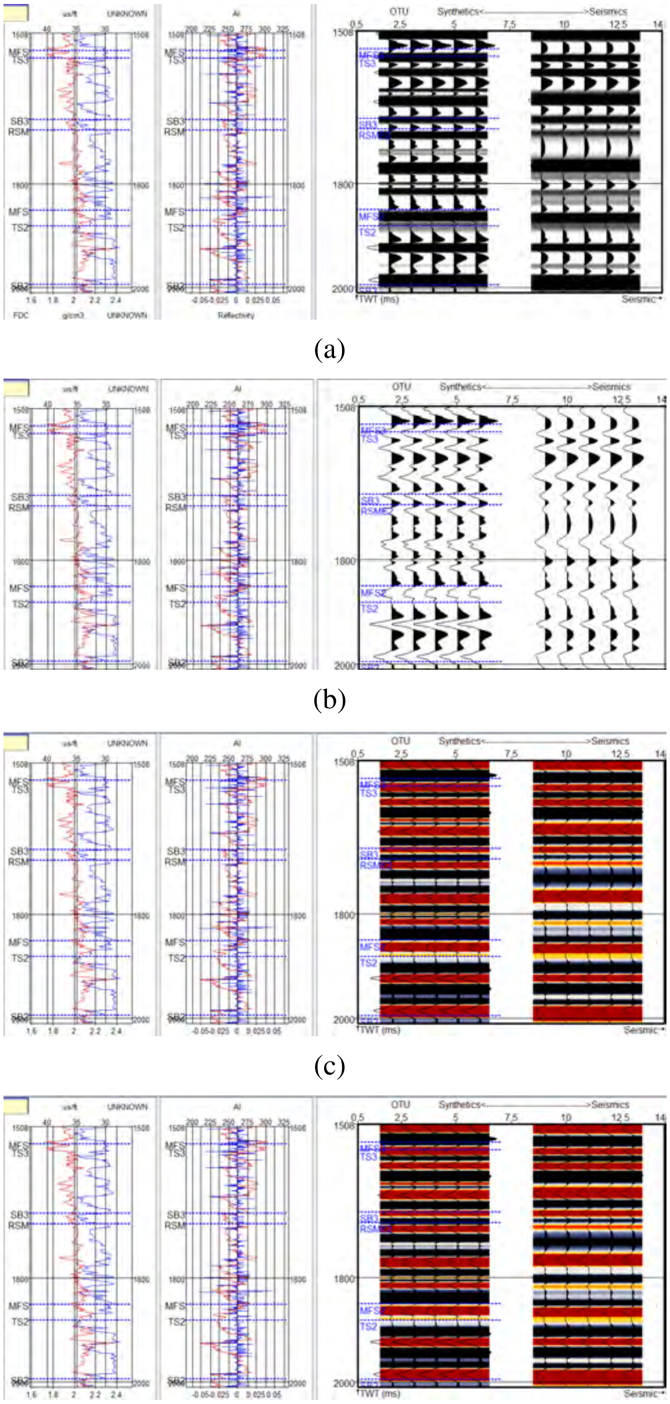
3.3.1 Interpretation of Sequences within Otu Field

Although wells of Otu field penetrate only part of the area documented by the seismic record, they provide critical information for interpreting lithic variations associated with changes in seismic reflector character, sequence boundary incision depth, and depositional patterns across major faults. The four sequence boundaries and stratigraphic surfaces were correlated between well logs by viewing adjacent log parallel to their deviated paths. Correlations of these surfaces between gamma ray well logs and resistivity logs are shown in Figures 3.7, 3.8, 3.9, 3.10, 3.11 and 3.12.

Vertical well log patterns between sequences are complex and laterally variable. These patterns suggest that vertical grain size changes observed in individual well logs cannot be related directly to regional patterns of regression and transgression. Vertical trends rather record more complicated changes in accommodation and sediment supply related to the rapid aggradation of sediments above down-dropped blocks and shifts in the position of coarser-grained sediment transport pathways along topographically complex and structurally-faulted sea beds. Lithic patterns observed in well logs (Figures 3.7, 3.8, 3.9, 3.10, 3.11 and 3.12) thus can only be understood within the context of patterns of structural deformation and sediment thickness changes mapped in the three dimensional seismic volume (Figures 3.15 and 3.16). The depositional environment of the subsurface facies penetrated by the wells was therefore suggestive of the shallow marine environment (inner neritic —outer neritic) for sequence two and three while sequence one was predicted to consist predominantly deposits of the transitional environment.

3.4 Seismic to well tie: Otu 46 Synthetic Seismograms

Seismic-to-well tie was carried out for only Otu 46 due to the availability of sonic logs. Density (Blue) and sonic logs (Red) were integrated into impedance (Red) and reflectivity (Blue), depth time converted (includes an upscaling) and convolved with the wavelet. This resulted in synthetic seismic traces for the well (samples 1-4) (Figure 3.14). This trace was compared with composite seismic trace that was extracted in the volume along the (deviated) well path, on the nearest trace. The synthetic and composite seismic traces were then cross correlated, and the output value shows the alignment and matching quality. The alignment was carried out by shifting the synthetic trace up or down and also by selecting several locations in both seismic traces, specifying and applying a shift function which varies with the travel time. The applied changes were then validated before being converted into a new time-depth function that replaces the previous one. This was used to link the well data to the seismic data with higher degree of accuracy.



(a)

(b)

(c)

(d)

Figure 3.14: Synthetic seismogram (a) Sample 1 (b) Sample 2 (c) Sample 3 (d) Sample 4 showing the integration of density (Blue) and sonic logs (Red) into impedance (Red) and reflectivity (Blue) and was depth time converted (including an upscaling) and convolved with the wavelet. The red color means peak (+) while the black color means trough cores (-)

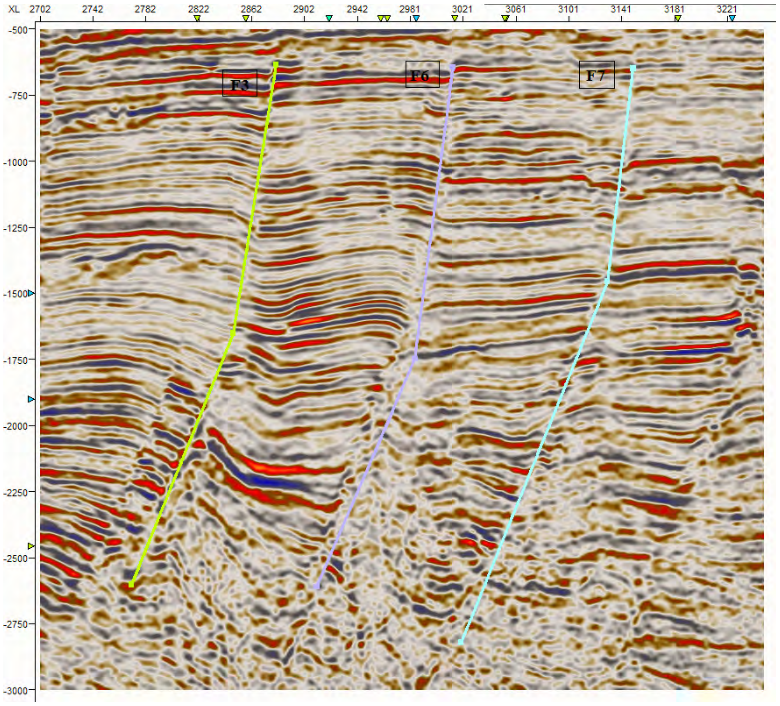
3.5 3D Seismic Volume

3.5.1 Structural Elements and Framework

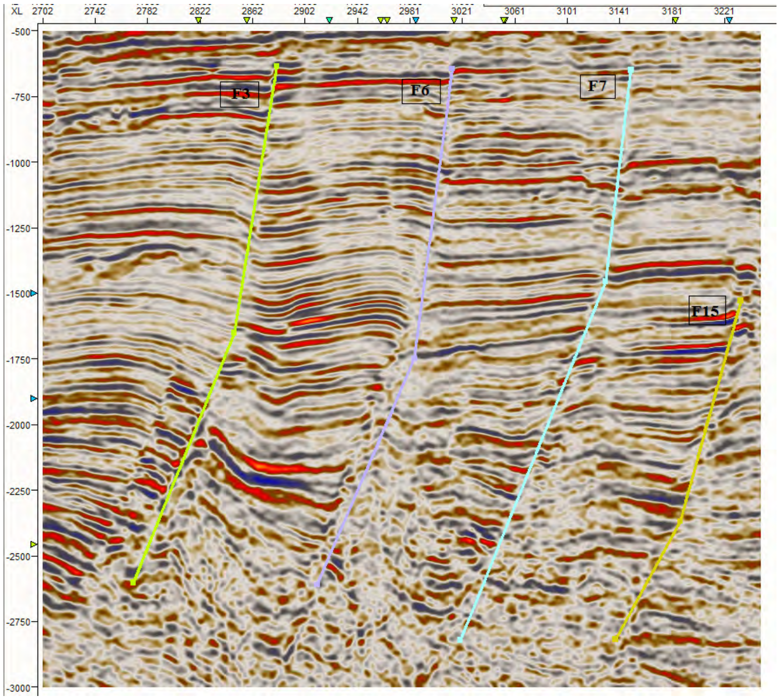
Major and minor faults observed from the 3D seismic were mapped appropriately to identify the structural styles within the field and to clarify the main structural elements that affect the hydrocarbon-bearing reservoir. The structure in Otu field is dominated by three major listric normal faults, trending northwest-southeast (NW-SE) and dip toward the south which corresponds to gravity tectonics that occurred as a response to variable rates of subsidence and sediment supply. The faults are labeled F3, F6, and F7 as seen on seismic cross sections in Figures 3.15 and 3.16.

Synthetic, antithetic and counterregional faults of small scale radiate from anticline crests, which makes those observed structures to be more complicated. The antithetic faults include F4 and F8 while synthetic faults include F1, F2, F5 and F15 (Figure 3.15b and Figure 3.16). The counterregional faults identified within Otu field include F10 and F14 (Figure 3.16b). Although several smaller faults were also delineated within the seismic volume, only those faults with the highest offsets are shown in the seismic cross sections in Figures 3.15 and 3.16. The presence of these complex structures such as collapsed growth faults, back-to-back features in Otu field suggested that there was completion of gravity tectonics before Benin formation was deposited (Evamy et al., 1978).

Structural analysis framework of the study area also reveals NW-SE trending of the faults (Figure 3.17). These major faults are believed to act as conduits for the migration of hydrocarbon from the Akata formation to the overlying Agbada formation. The accumulation in the field is defined by a hanging wall structural closure associated with F6 (Figure 3.18), which appears to demarcate the field into NE and SW block. The Otu wells targeted this closure and encountered about fourteen hydrocarbon bearing sands proving that F6 is sealing.

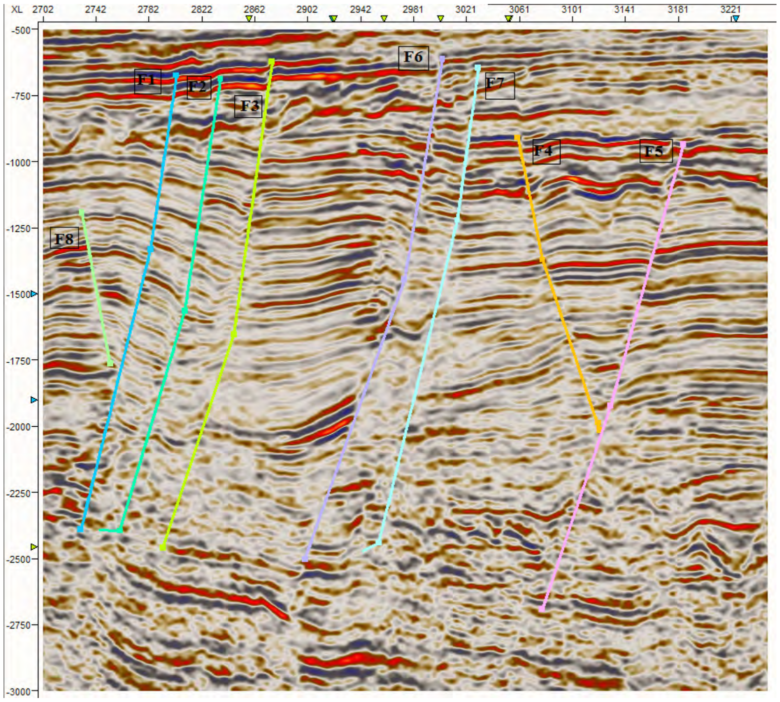


(a) Seismic cross sections on Inline 11686.

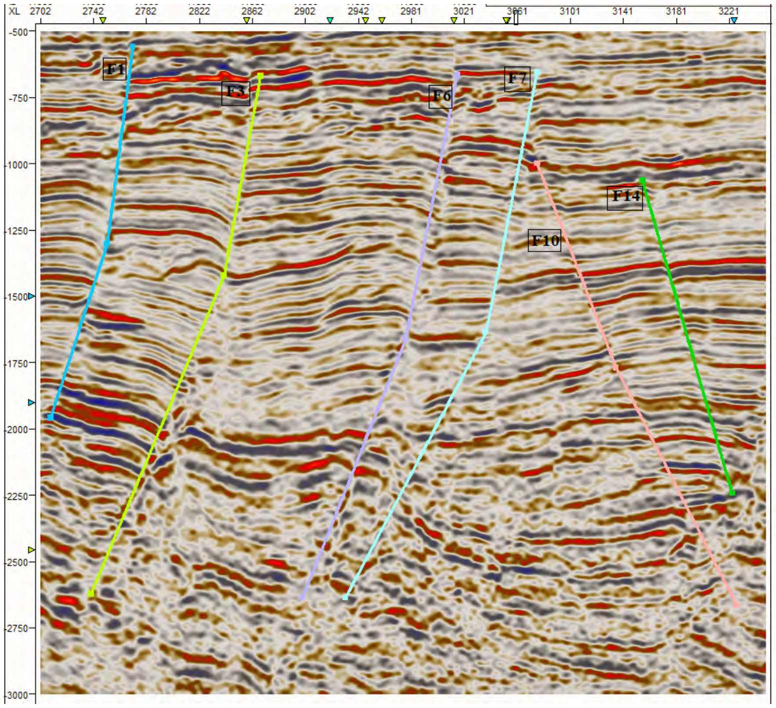


(b) Seismic cross sections on Inline 11666.

Figure 3.15: Structural interpretation of Otu field showing inlines 11686 and 11666. The figures reveal three major listric faults in the field (F3, F6 and F7) and a synthetic fault (F15)



(a) Seismic cross sections on Inline 11466



(b) Seismic cross sections on Inline 11586.

Figure 3.16: Structural interpretation of Otu field showing Inline 11466 and Inline 11586. It reveals antithetic faults (F4 and F8), counter regional faults (F10 and F14), major listric faults as well synthetic faults within the Otu field.

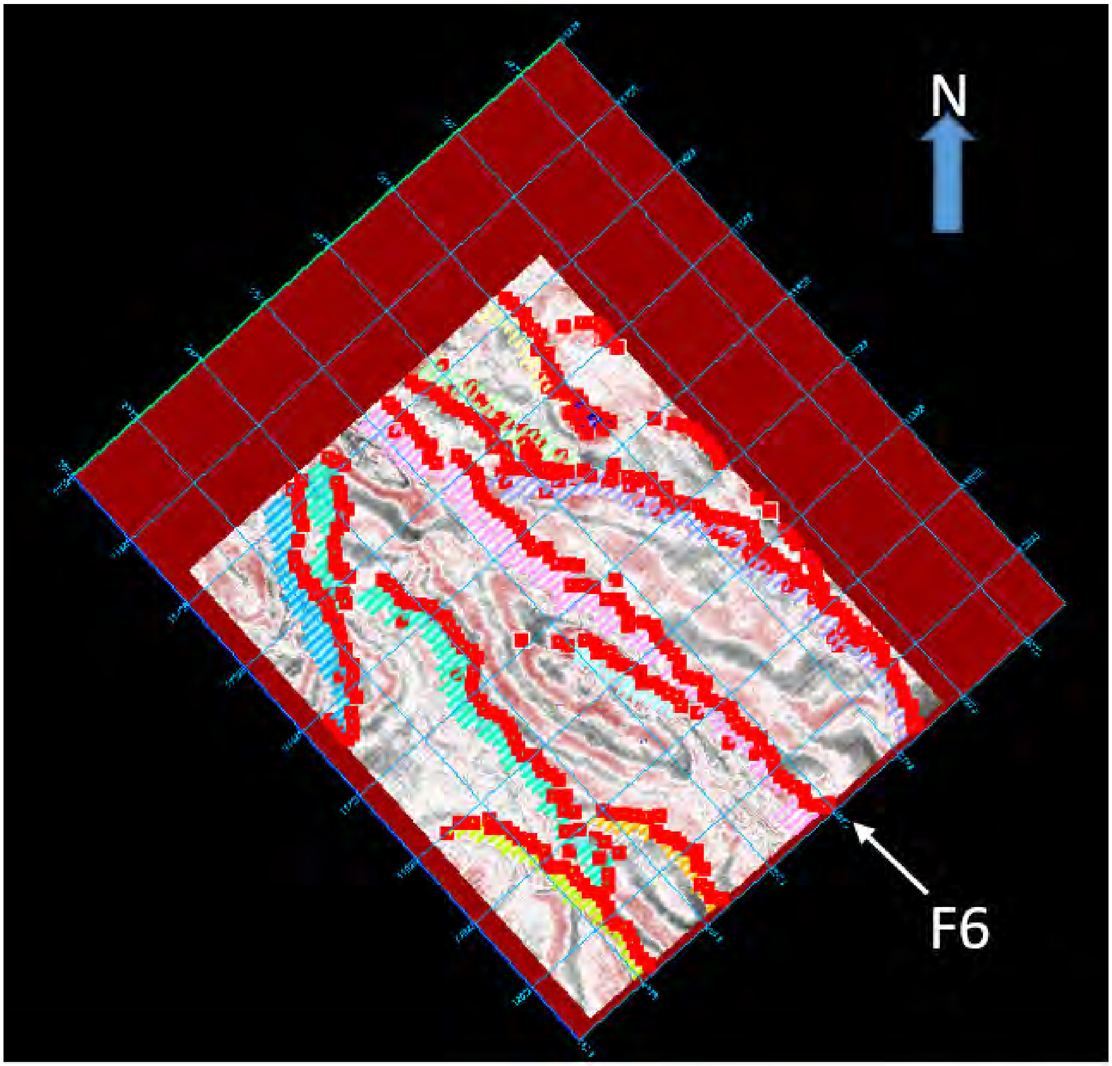


Figure 3.17: Time slice at 1500 ms showing NW-SE trending faults

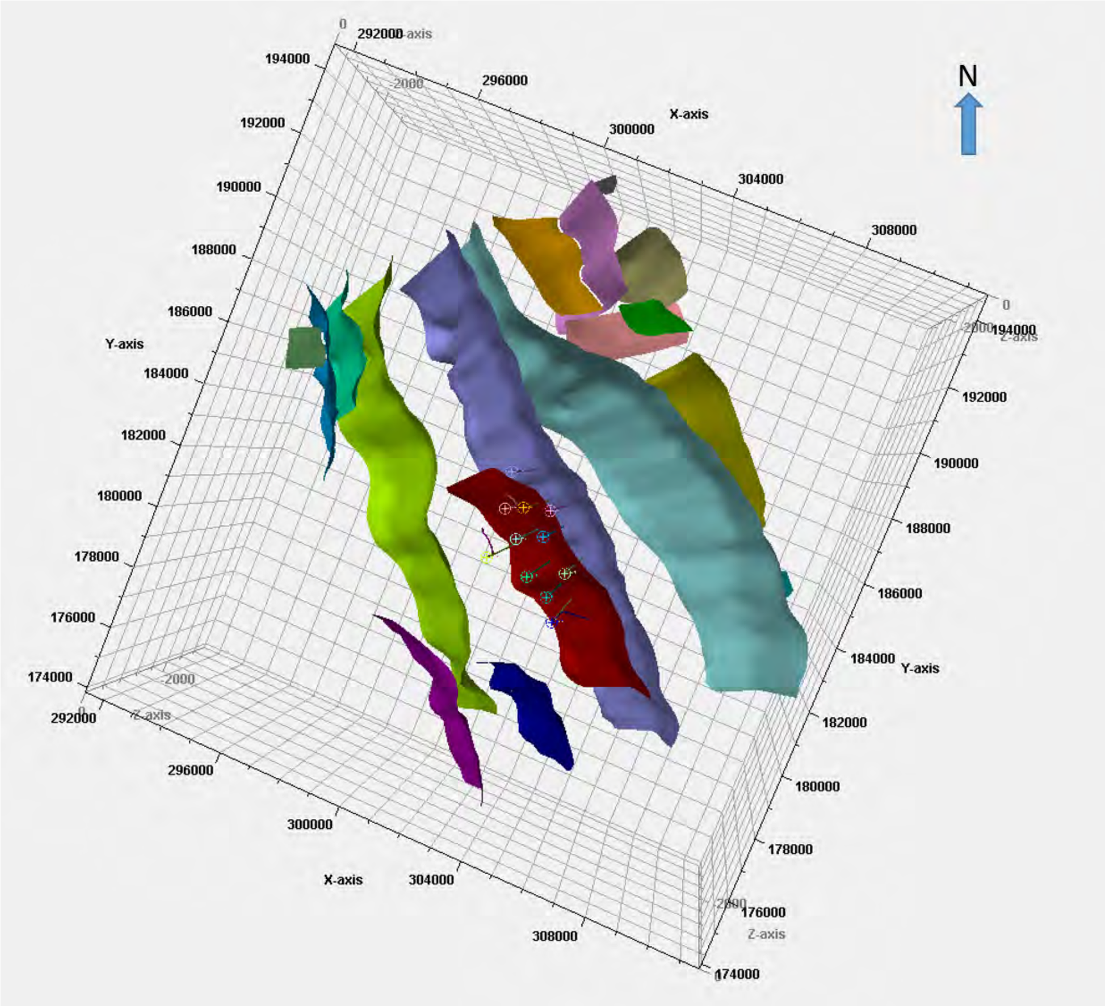


Figure 3.18: 3D Fault model. The Otu wells targeted the hanging wall closure and encountered about fourteen hydrocarbon bearing sands

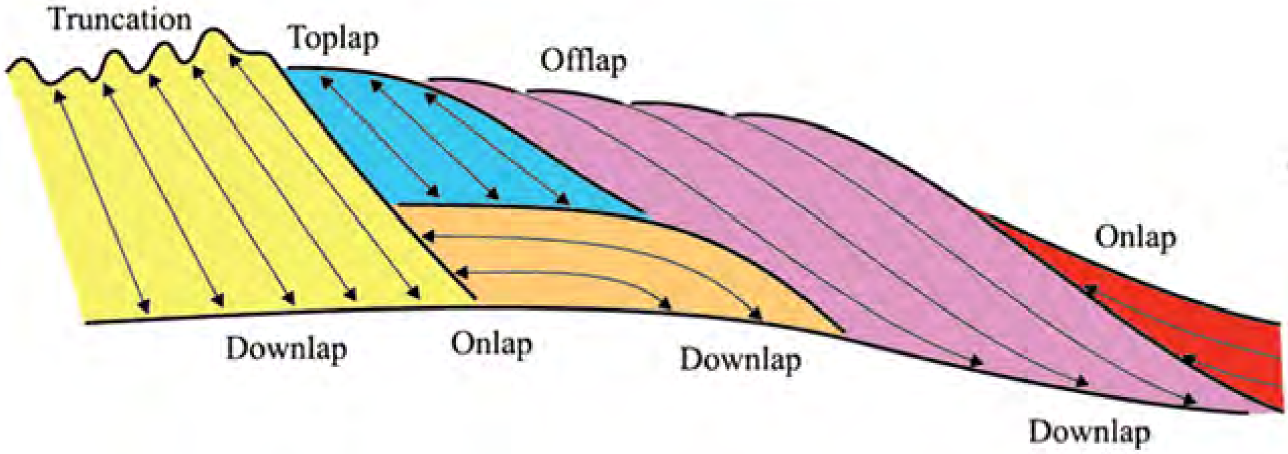


Figure 3.19: Types of stratal terminations (Catuneanu, 2002)

3.6 Seismic Stratigraphy Analysis

The identification of stratal terminations aided the identification of time significant surfaces. Stratal terminations are defined by the geometric relationship between strata and the stratigraphic surfaces against which they terminate. The main types of stratal terminations are described by truncation, toplap, onlap, downlap, and offlap (Catuneanu, 2002). These terms have subsequently been incorporated into sequence stratigraphy in order to describe the stacking patterns of stratal units and to provide diagnostic features for the recognition of the various surfaces and systems tracts (Posamentier and Vail, 1988; Van Wagoner et al., 1990; Christie-Blick, 1991) (Figure 3.19).

The result of seismic stratigraphy analysis carried on the available 3D seismic data is shown in Figure 3.20. The stratal terminations were used to infer the various shoreline shifts such as transgression and regression (normal regression and forced regression) and their respective diagnostic depositional trends such as progradation, retrogradation and aggradation. Having successfully integrated the well data to the seismic, consistency was established between the stratigraphic surfaces independently interpreted from both data sets as recommended by Vail et al. (1977).

The prevalence of incised valleys accompanied by seismic reflections truncating at the base of the channels serves as evidence for sequence boundaries in most cases. Fluvial down-cutting and the formation of incised valleys are typically formed during a major fall in sea level at the shoreline.

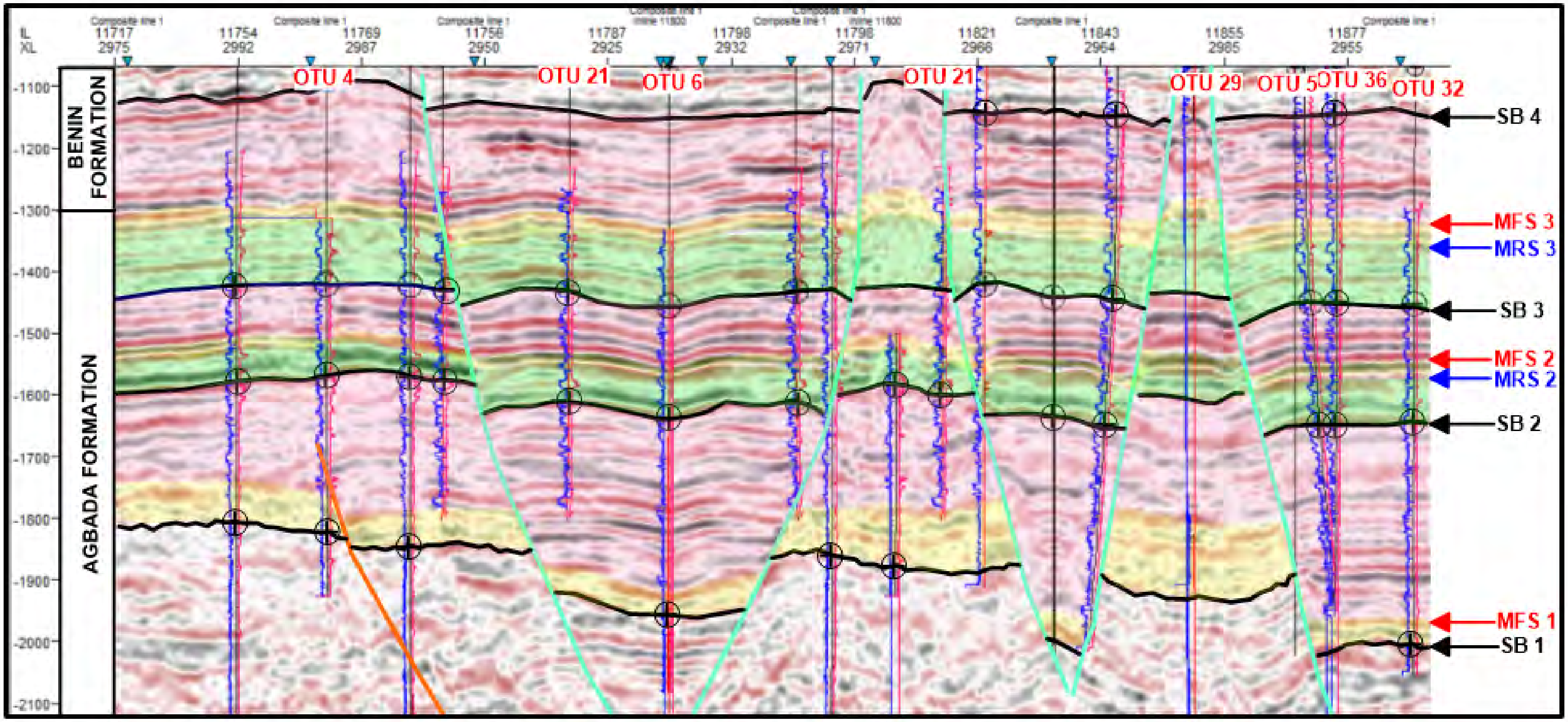


Figure 3.20: Sequence stratigraphy architecture with the horst and grabenal structure within Otu field showing sequence boundaries and stratigraphic surfaces mapped.

3.6.1 Sequence Boundary One ($SB-1$)

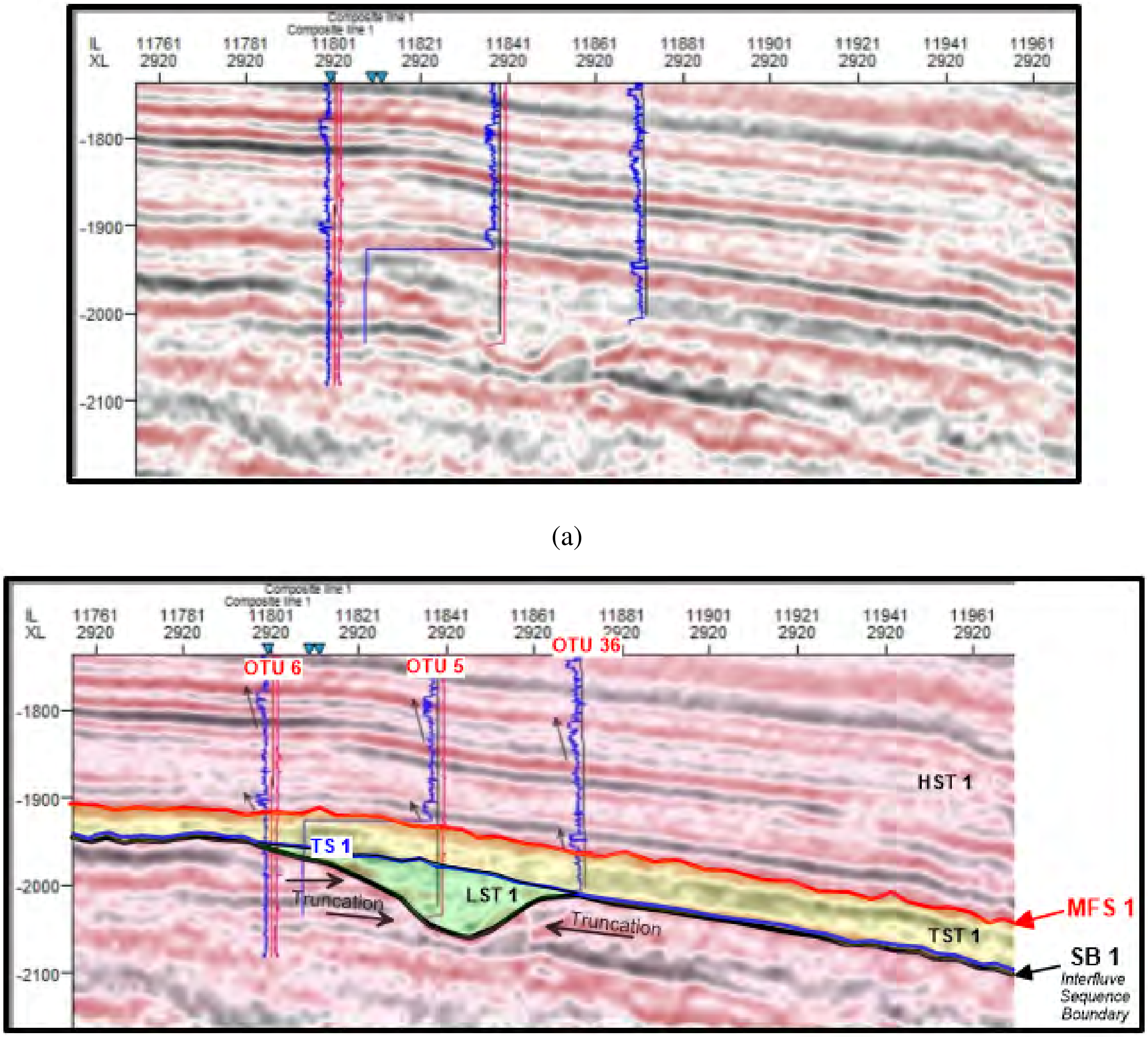
Sequence boundary one is the deepest sequence identified and it has an interfluve sequence boundary ($SB-1$) which shows a merging of $SB-1$ and $TS-1$ allowing $LST-1$ to be localized within the channel. No well was observed to penetrate the channel although Otu 6 was observed to penetrate the margin of channel margin (Figure 3.21).

3.6.2 Sequence Boundary Two ($SB-2$)

Sequence boundary two ($SB-2$) separates the underlying sequence one from the overlying sequence two. The underlying $HST-1$ is characterized by inclined beds which are prograding clinoforms terminating at the base of $SB-2$ (Figure 3.22).

3.6.3 Sequence Boundary Three ($SB-3$)

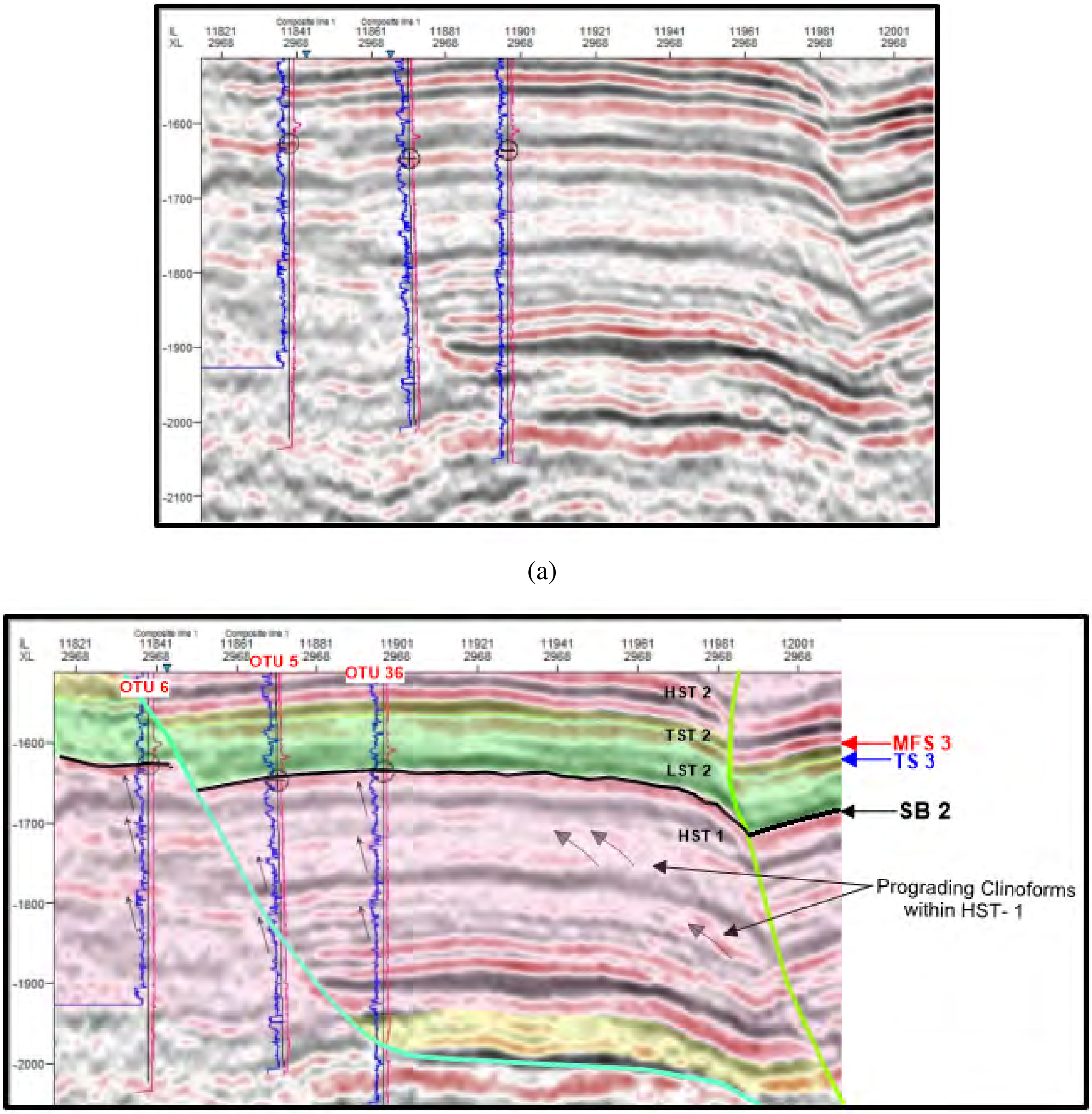
The shallowest sequence boundary three extends from the Agbada formation into the Benin formation. $SB-3$ separates the underlying sequence two from the overlying sequence three. $SB-3$ bounds the base $LST-3$. The overlying channel fill within $LST-3$ has a complex geometry which characterizes the channel fill. In this case, the $TS-3$ does not merge with the $SB-3$, therefore the lowstand deposit within $LST-3$ should be widespread and not localized (Figure 3.23).



(a)

(b)

Figure 3.21: Sequence Boundary one ($SB-1$) (a) Trace 2920 uninterpreted section (b) Trace 2920 interpreted section revealing interfluve sequence boundary one (SB1)



(a)

(b)

Figure 3.22: Sequence Boundary two ($SB-2$) (a) Trace 2968 uninterpreted section (b) Trace 2968 interpreted section showing prograding clinoforms within HST-1

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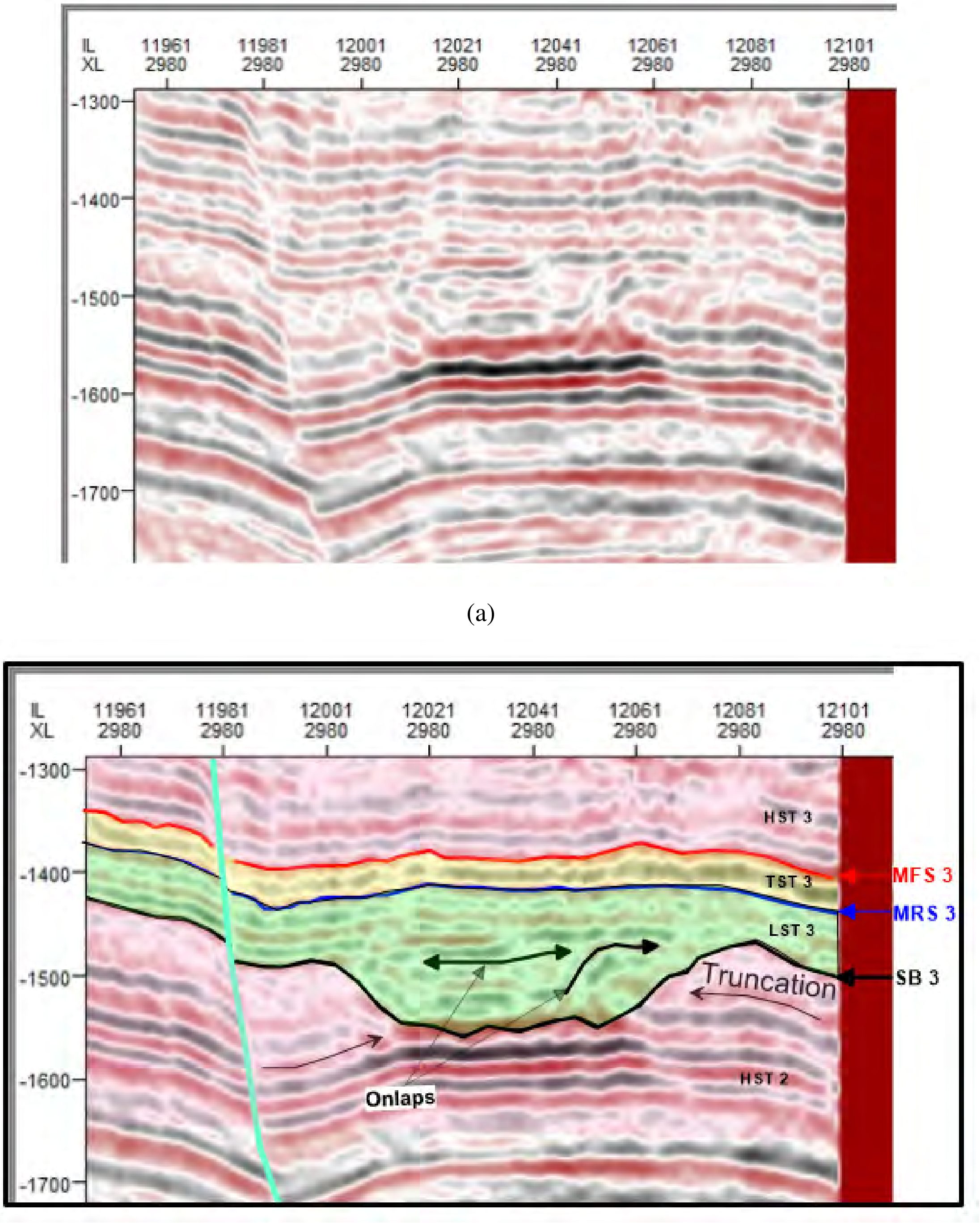


(a)

(b)

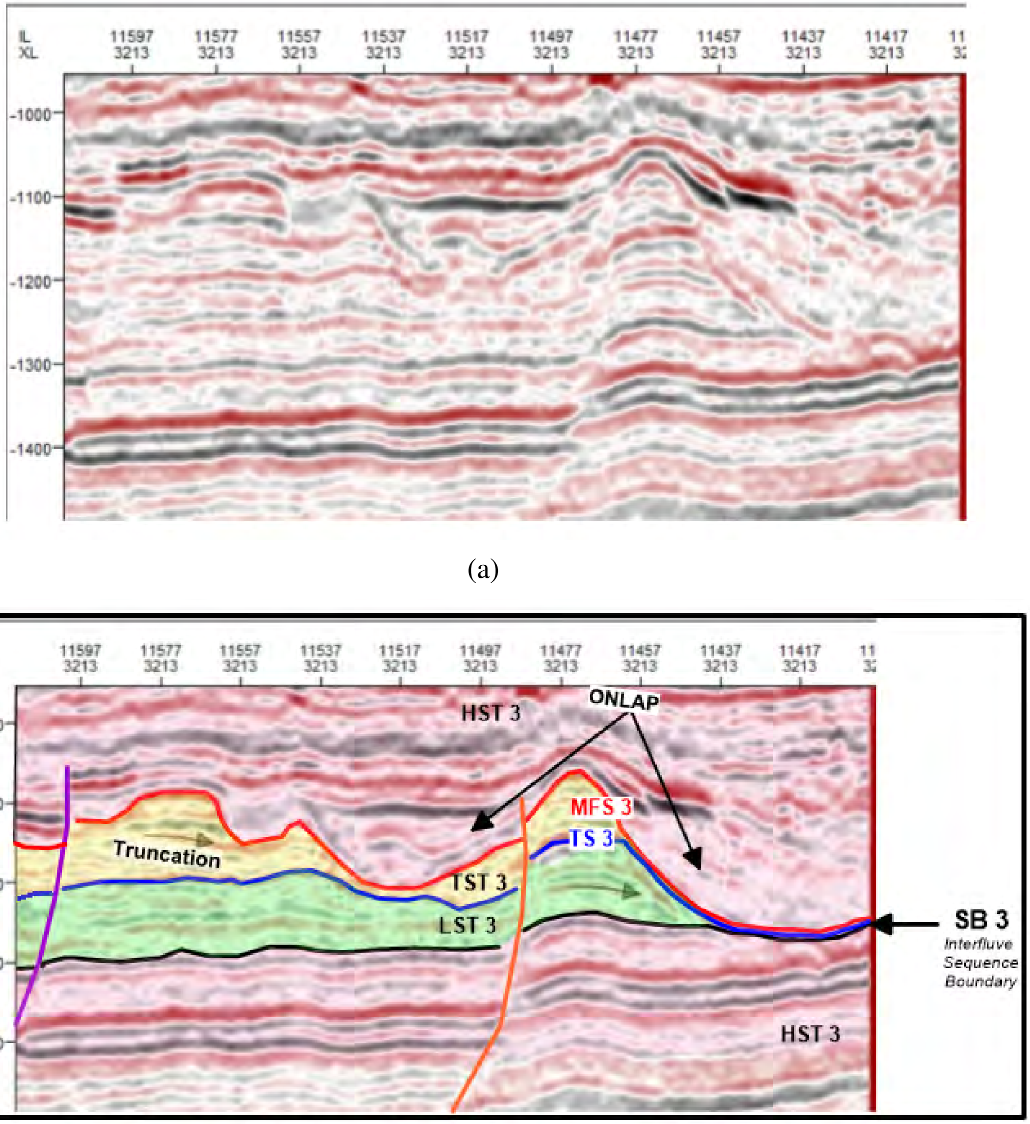
Figure 3.23: Sequence Boundary three ($SB-3$) (a) Trace 2980 uninterpreted section (b) Trace 2980 interpreted section. LST-3 has a complex geometry and its deposits should be widespread and not localized because TS-3 does not merge with SB-3

3.6.4 Maximum Flooding Surface Three ($MFS - 3$)

Several channelized systems exist between the Benin formation and the Agbada formation such as the Soku clay, Buguma clay, Agbada clay and Opuama channel complex (Figure 2.4). Such channels are well pronounced within Otu field as it extends all through the 3D seismic sections. Figure 3.24 reveals more perspectives of $SB - 3$ which separates the underlying sequence two from the overlying sequence three. The figure shows that the channel is bounded at its base by $SB - 3$ which merges with $TS - 3$, $MFS - 3$ and $SB - 3$; hence, revealing the interfluve nature of $SB - 3$. Furthermore, in some other areas this channel is bounded at its base by $MFS - 3$. These variations show that the intensity of the erosional event led to the down-cutting of the underlying $TST - 3$ and $MFS - 3$ is not the same all through. This therefore led to the presence of these systems tracts in some areas and their absence in some others.

3.6.5 Sequence Boundary Four ($SB - 4$)

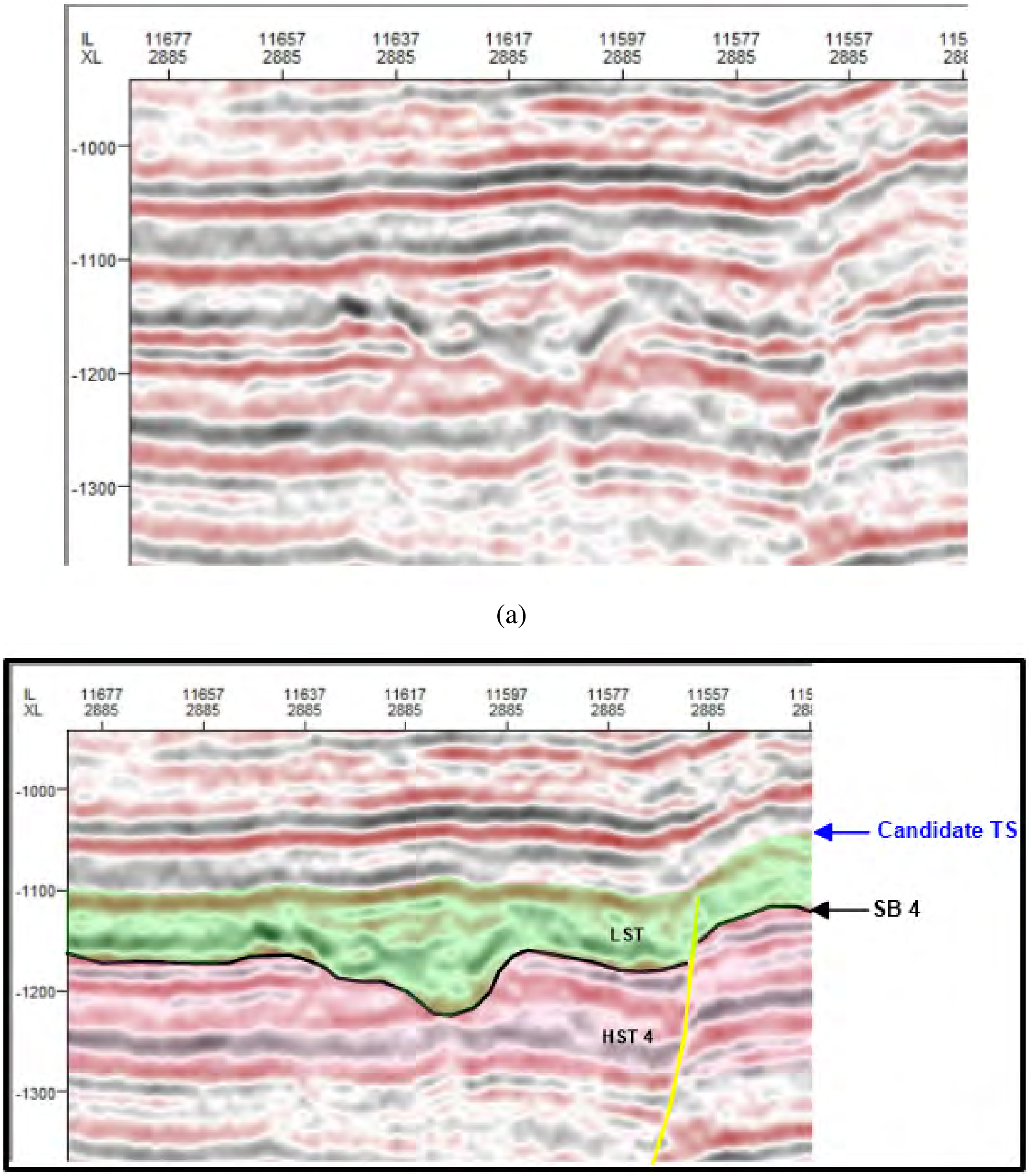
The truncation of reflections below the channel is also found to be consistent with the $SB - 4$ independently identified from well logs. The channel associated with this event is within the continental Benin sands. $SB - 4$ separates the underlying sequence three from the overlying sequences (Figure 3.25).



(a)

(b)

Figure 3.24: Maximum Flooding Surface three (MFS-3) (a) Trace 3213 uninterpreted section (b) Trace 3213 interpreted section. SB-3 is an interfluve sequence boundary.



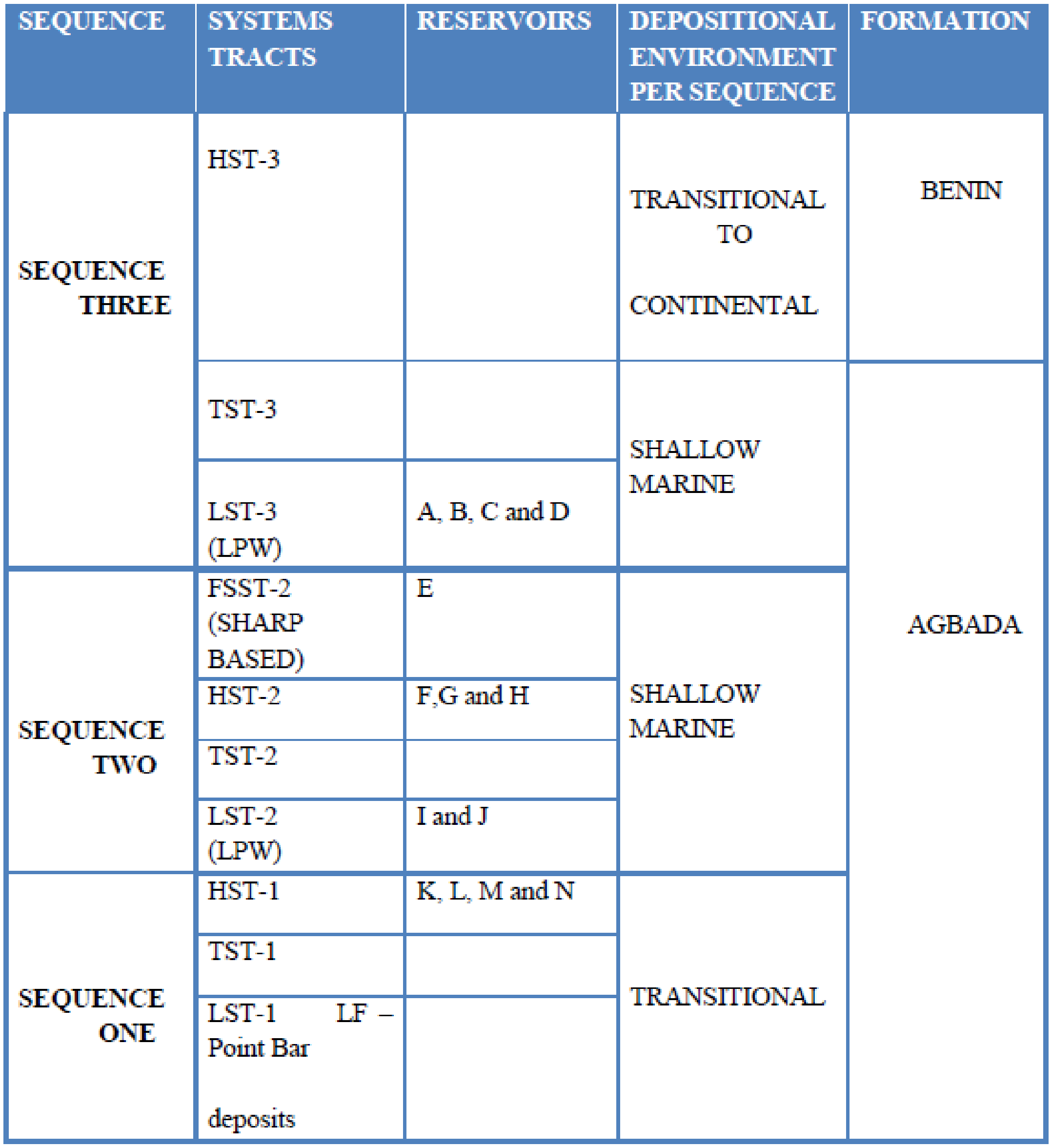
(a)

(b)

Figure 3.25: Sequence Boundary four ($SB-4$) (a) Trace 2885 uninterpreted section (b) Trace 2885 interpreted section. SB-4 separates the underlying sequence three from the overlying sequences

The relationship between systems tracts, reservoirs and their respective depositional environments (Table 3.1) shows that sequence one which extends from the Agbada formation to Benin formation belongs to transitional to continental and shallow marine environment. Sequence two in the Agbada formation is shallow marine based on the associated system tracts while sequence three belongs to a transitional environment.

Table 3.1: The relationship between systems tracts, reservoirs and their respective predicted depositional environments



SEQUENCE	SYSTEMS TRACTS	RESERVOIRS	DEPOSITIONAL ENVIRONMENT PER SEQUENCE	FORMATION
SEQUENCE THREE	HST-3		TRANSITIONAL TO CONTINENTAL	BENIN
	TST-3		SHALLOW MARINE	AGBADA
	LST-3 (LPW)	A, B, C and D		
SEQUENCE TWO	FSST-2 (SHARP BASED)	E	SHALLOW MARINE	
	HST-2	F,G and H		
	TST-2			
	LST-2 (LPW)	I and J		
SEQUENCE ONE	HST-1	K, L, M and N	TRANSITIONAL	
	TST-1			
	LST-1 LF – Point Bar deposits			

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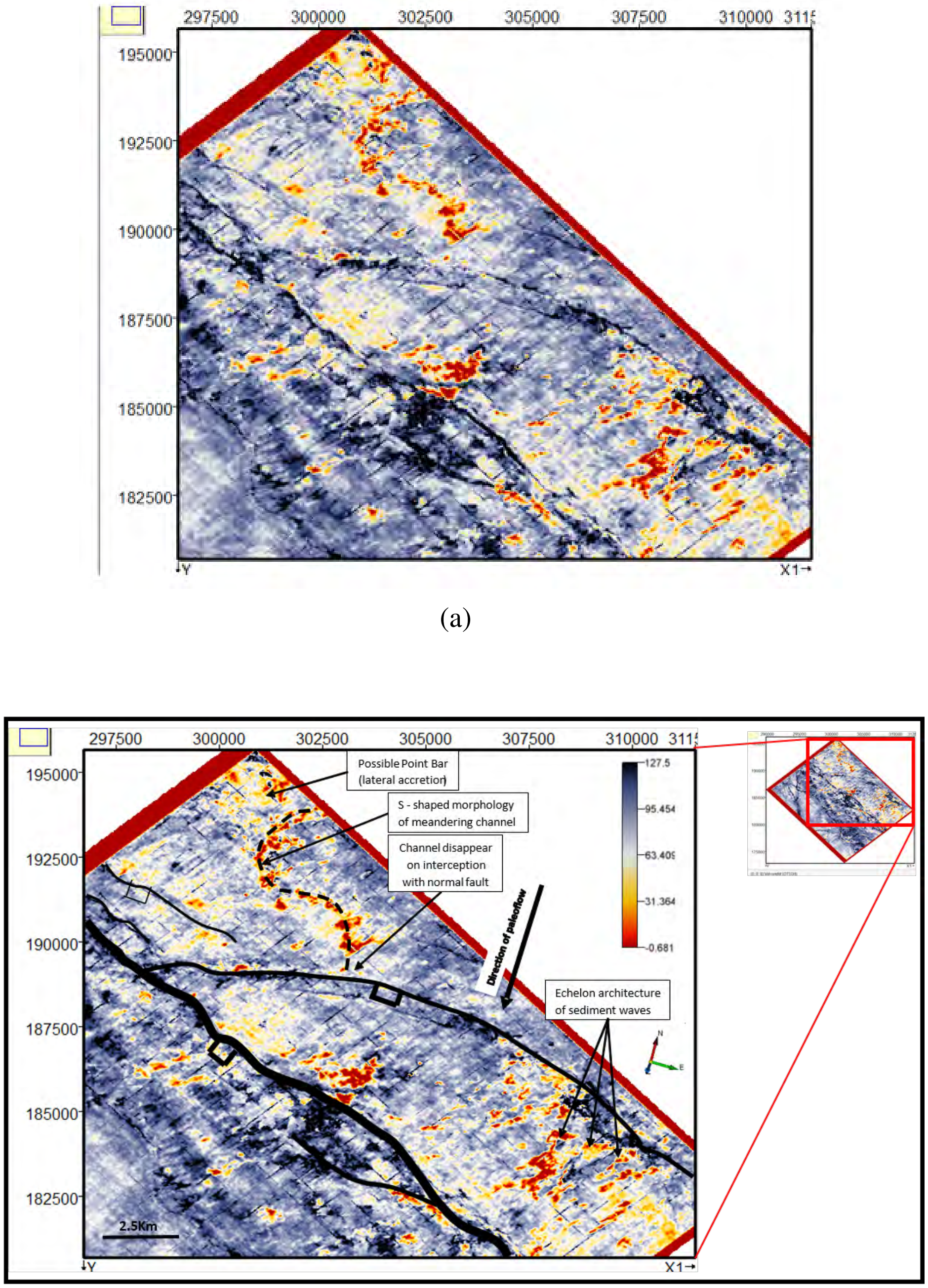
3.7 Seismic Geomorphology

A seismic geomorphological approach was applied to the subsurface facies of the Agbada formation. The patterns observed from the 3D seismic images are diagnostic of depositional environment. The study provides an indication of the reservoirs internal and external architecture which furthers our understanding of depositional processes that "‘gave birth’" to the various stratigraphic features. The structural analysis revealed a complex faulting system which plays a major role in the trapping of hydrocarbons. The wells in the study area are concentrated within a prominent hanging wall closure at the central portion of the field. The outputs of the seismic geomorphology studies reveal the structural framework for some of the sequence stratigraphic significant surfaces of interest. Seismic geomorphological interpretation on stratal slices along sequence stratigraphic significant surfaces provides an understanding of the geological events that occur as a result of interplay of sea level changes and the rate of sedimentation. Seismic geomorphology provides a clear cut relationship between stratigraphic elements such as channels and structural elements such as faults. The sequence stratigraphic surface of interest includes $SB-1$, $SB-2$, $SB-3$, $MFS-3$ and $SB-4$ in order of decreasing depth. The stratigraphically mapped horizon were auto-tracked and several attributes such as spectral decomposition and similarity (coherency) were draped on the auto-tracked surfaces in order to enhance the identification and interpretation of the structural and stratigraphic features. Spectral decomposition outputs the amplitude at discrete frequencies. It unravels the seismic signal into its constituent frequencies, which allows the interpreter to see phase and amplitude tuned to specific wavelengths.

The amplitude component excels at quantifying thickness variability and detecting lateral discontinuities while the phase component detects lateral discontinuities. For this study, it provides a useful tool for ”below resolution” seismic interpretation, sand thickness estimation, and enhancing channel structures. Coherency/similarity together with color blended spectral images help better illustrate geological information.

3.7.1 Sequence Boundary Four ($SB-4$)

Sequence boundary four ($SB-4$) is the shallowest stratigraphic surface mapped within the Benin formation with an overlying lowstand deposit $LST-4$. The direction of paleoflow of the S-shaped meandering channel is northeast-southwest (NE-SW) (Figure 3.26). The channel is visible at the footwall of the east-west (E-W) trending normal fault but was not observed at the hanging wall area. However, sediment waves were observed at the hanging wall area. There is an evidence of a possible point bar in this sequence boundary. It was observed that the channel disappears on interception with normal faults (Figure 3.26).



(a)

(b)

Figure 3.26: Section (a) Uninterpreted section (b) Interpreted section. A point bar was observed here and the channel disappears on interception with normal faults. Scale bar is amplitude values.

3.7.2 Maximum Flooding Surface Three ($MFS-3$)

A relatively pronounced sinuous channel was observed in the northeastern part of the field. The direction of paleoflow is NE-SW and perpendicular to the fault trace (Figure 3.27). The strength of incision is perturbed by the faulting event causing the channel to be pronounced at the footwall of the normal fault.

3.7.3 Sequence Boundary Three ($SB-3$)

The individual channel observed on $SB-3$ is subtle and directed along the hanging wall of the fault, running parallel along the fault trace (Figure 3.28).

3.7.4 Sequence Boundary Two ($SB-2$)

The individual channel observed on $SB-2$ is subtle and directed along the hanging wall of the fault, running parallel along the fault trace (Figure 3.29).

3.7.5 Sequence Boundary One ($SB-1$)

The meandering channel belt in this sequence boundary shows characteristics point bar which flow at an obtuse angle in the direction of NE-SW (Figure 3.30)

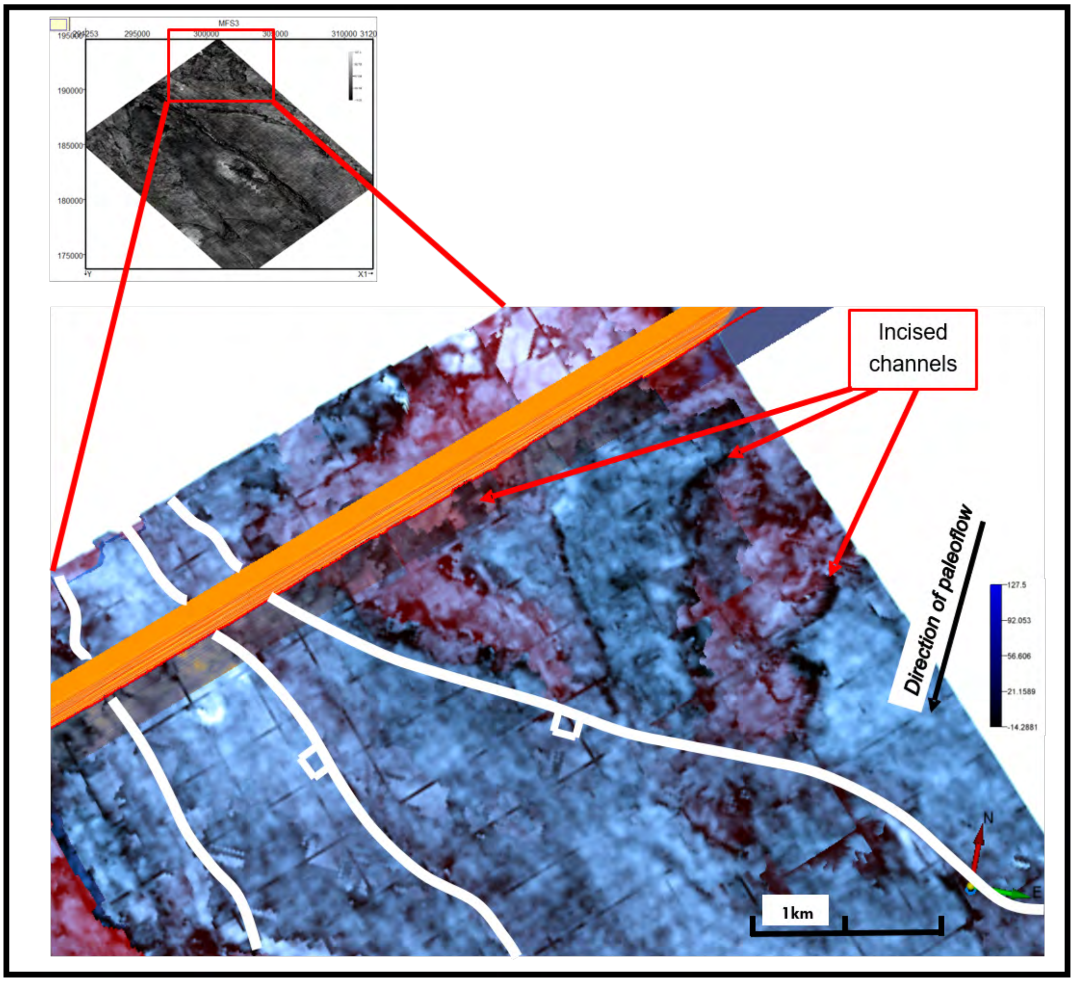


Figure 3.27: Spectral decomposition at (10Hz and 40Hz) on $MFS-3$ stratal slice showing the channel NE SW direction (+30ms and -30ms). A relatively pronounced sinuous channel was observed in the northeastern part of the field. Scale bar is amplitude values

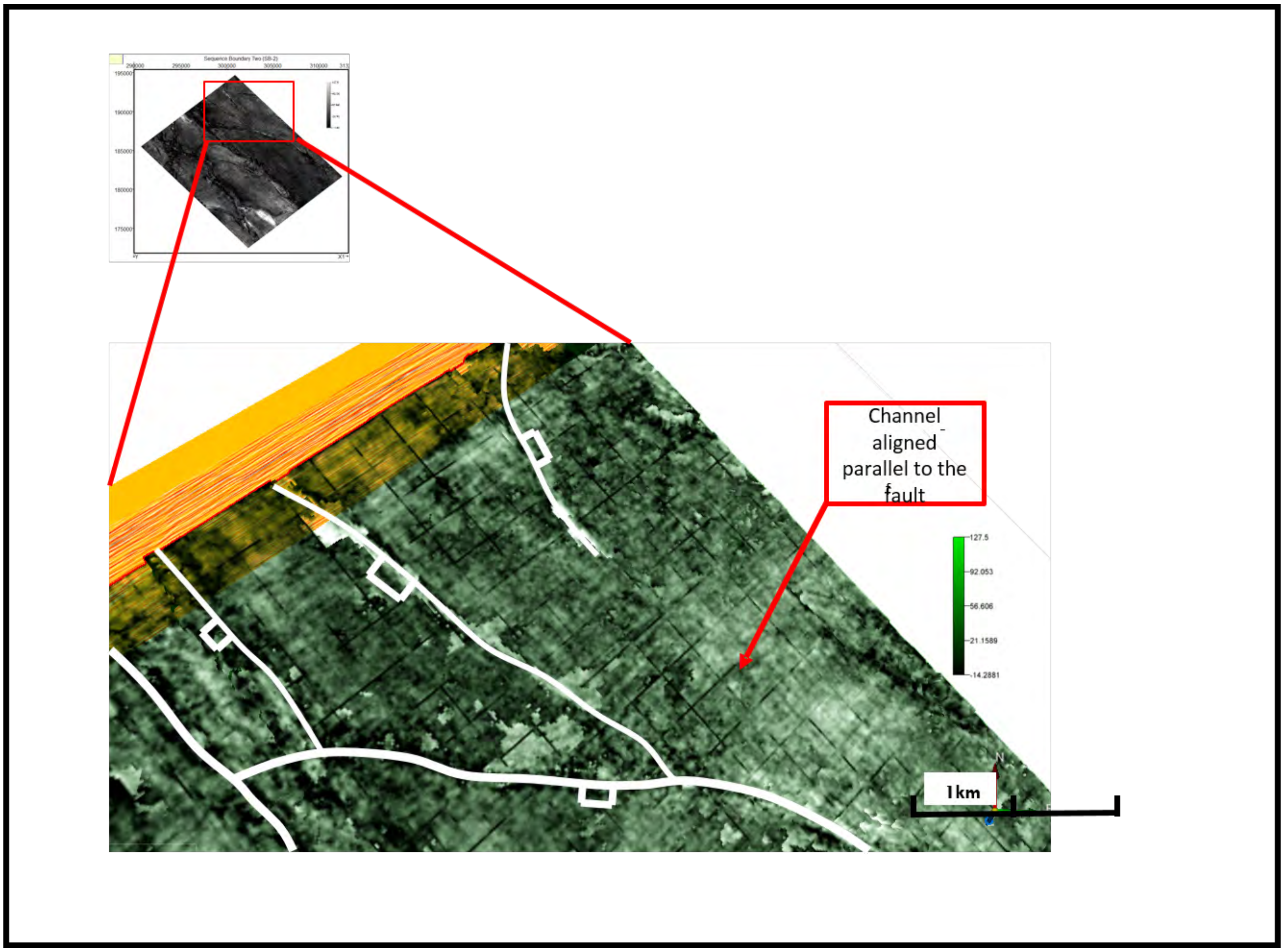


Figure 3.28: Spectral decomposition at (10Hz and 20Hz) on $SB-3$ stratal slice showing the channel NE-SW direction (+30ms and -30ms). The individual channel observed on SB-3 is subtle and directed along the hanging wall of the fault. Scale bar is amplitude values

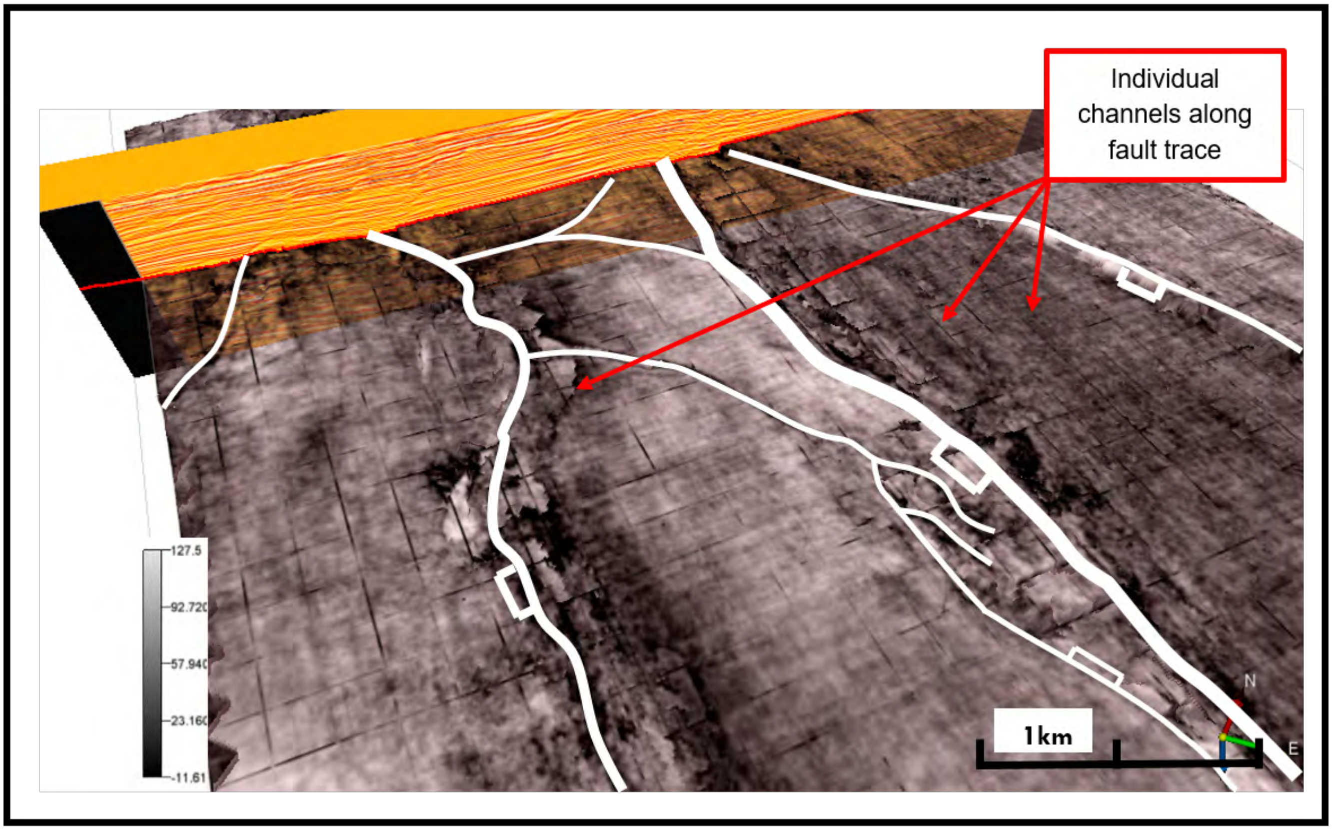


Figure 3.29: Similarity (Coherency) on $SB-2$ stratal slice (+30ms and -30ms). The individual channel observed on SB-2 is subtle and directed along the hanging wall of the fault, running parallel along the fault trace

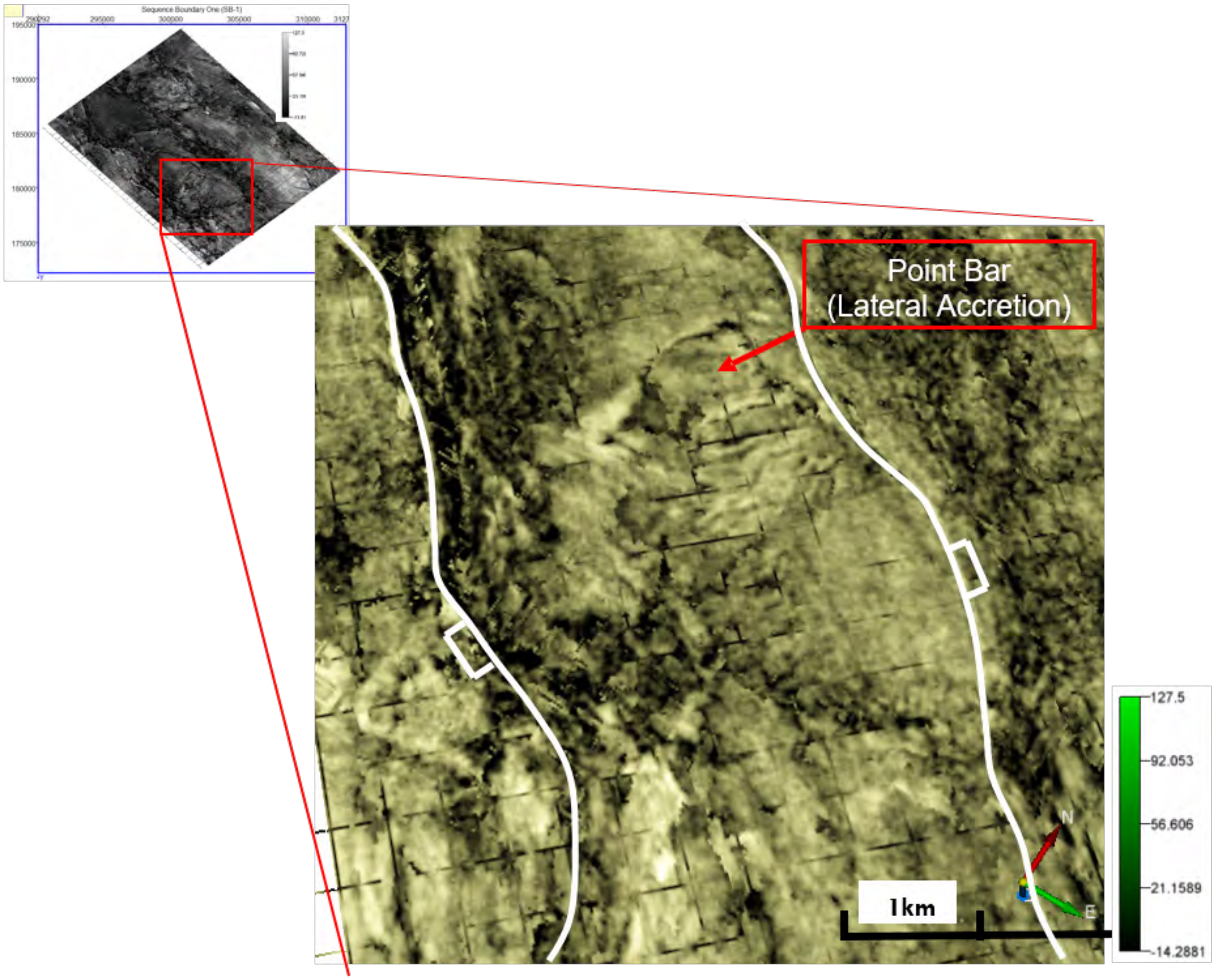


Figure 3.30: Spectral decomposition at (10Hz and 40Hz) on $SB-1$ stratal slice showing a meandering channel belt with its characteristics point bar flowing at an obtuse angle in the NE-SW direction (+30ms and -30ms)

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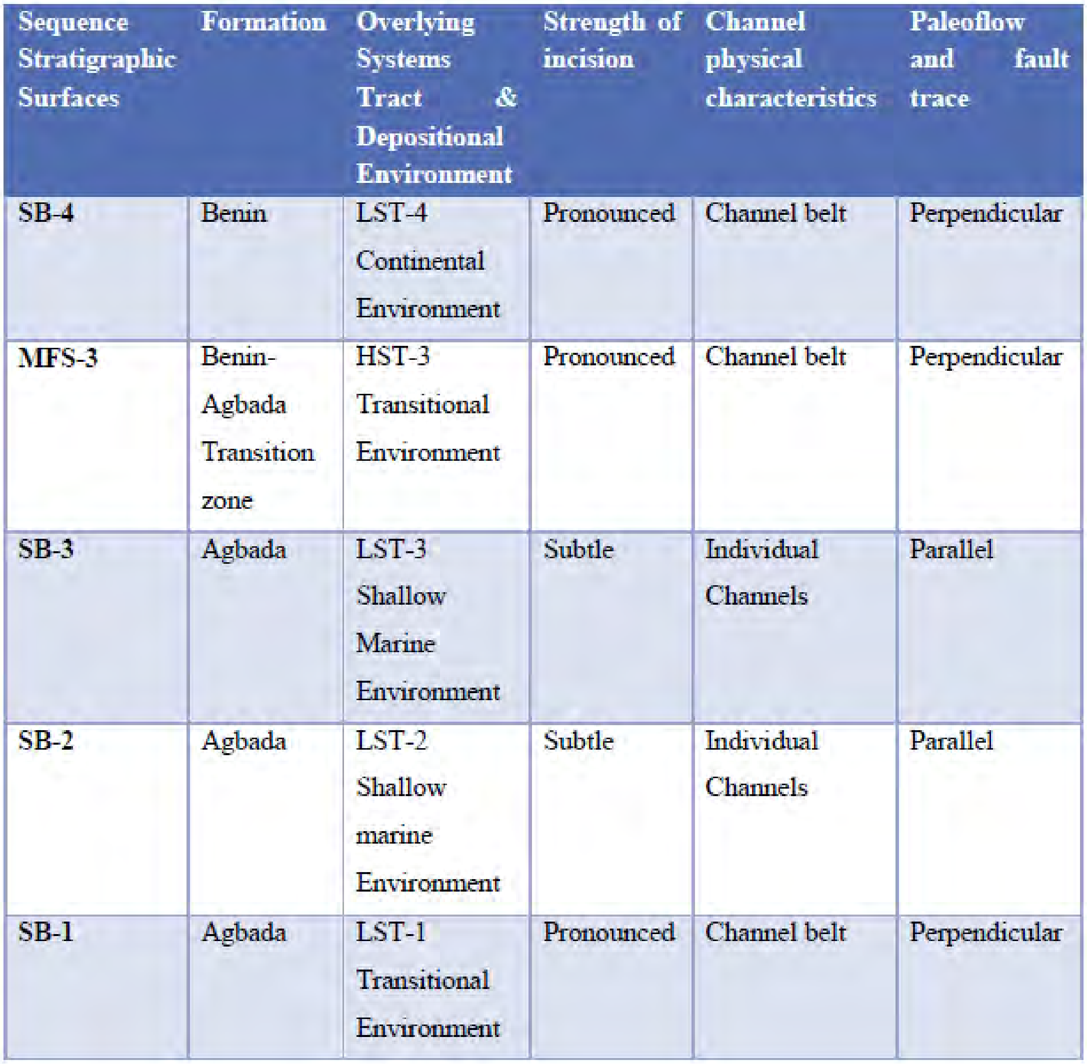
Table 3.2 shows the relationship between the type of channel observed in the sequences, channel orientation relative to fault, sequence stratigraphic surface, and the depositional environments.

3.8 Discussion

Our interpretations suggest that most sequence boundaries are eroded by fluvial mass flows forward of the delta front. Patterns of sequence erosion, deeper in footwalls of faults and along edges of rollover anticlines, and the thickening of deposits across down-dropped blocks, suggest that multiple faults moved during Agbada formation deposition. This reflects the larger-scale collapse of the Niger Delta clastic wedge as sediments loaded the underlying Akata formation shales. Sequence boundary erosion thus probably reflects increased slopes over this collapsing wedge (Figure 3.31), rather than fluvial lowstand incision. The depositional environments of sediments filling sequence surface topography are more difficult to constrain without core sample. Well logs through some sequences clearly show an up-section progression from upward-coarsening successions (prograding lobes) to blocky and upward fining successions (channel deposits). It may be that this reflects a progression from pro-delta and deltaic shorelines to fluvial depositional settings. Alternatively, however, these trends may reflect progression from lobe to channel deposits within a prograding submarine system.

Table 3.2: Relationship between the type of channel, channel orientation relative to fault, sequence stratigraphic surface and the depositional environments



Sequence Stratigraphic Surfaces	Formation	Overlying Systems Tract & Depositional Environment	Strength of incision	Channel physical characteristics	Paleoflow and fault trace
SB-4	Benin	LST-4 Continental Environment	Pronounced	Channel belt	Perpendicular
MFS-3	Benin-Agbada Transition zone	HST-3 Transitional Environment	Pronounced	Channel belt	Perpendicular
SB-3	Agbada	LST-3 Shallow Marine Environment	Subtle	Individual Channels	Parallel
SB-2	Agbada	LST-2 Shallow marine Environment	Subtle	Individual Channels	Parallel
SB-1	Agbada	LST-1 Transitional Environment	Pronounced	Channel belt	Perpendicular

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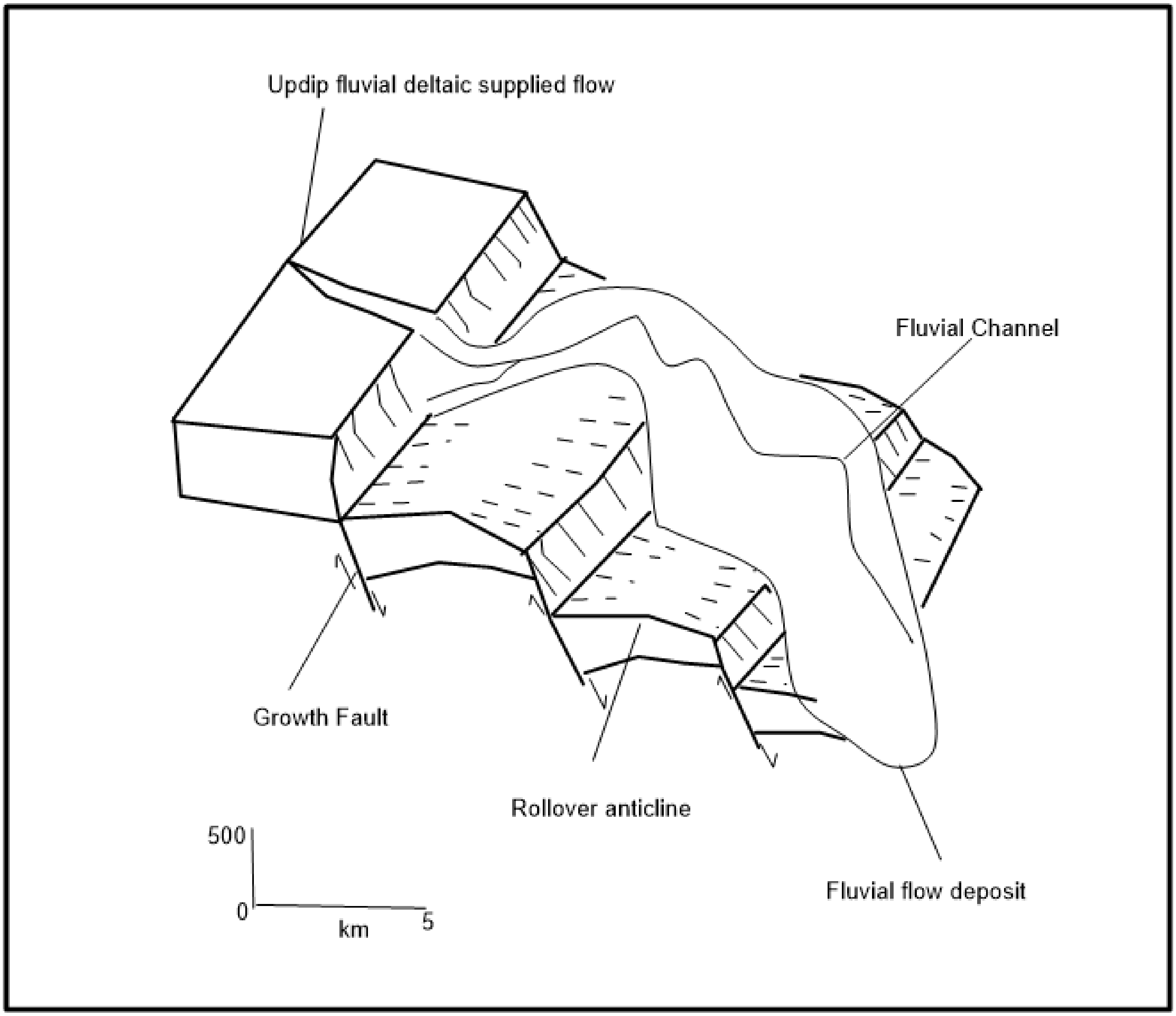

Figure 3.31: Sequence boundary development on down faulted blocks. Sequence boundary erosion shows increased slopes over the collapsing wedge rather than fluvial lowstand incision

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Although syndepositional deformation significantly complicated local basin slopes, locations of sequence boundary incision, sediment transport patterns, and local sediment accumulation rates and the general association between eustatic sea level fall and the age of sequence boundaries suggests a causal relationship. It may be that falls in sea level forced deltas to prograde more rapidly, increasing loading on Akata formation shales, and accelerating rates of clastic wedge collapse into the basin. Falling sea level may have also been associated with less storage of muds in the fluvial system, and an increase in hyperpycnal flow from the Niger River system onto the shelf.

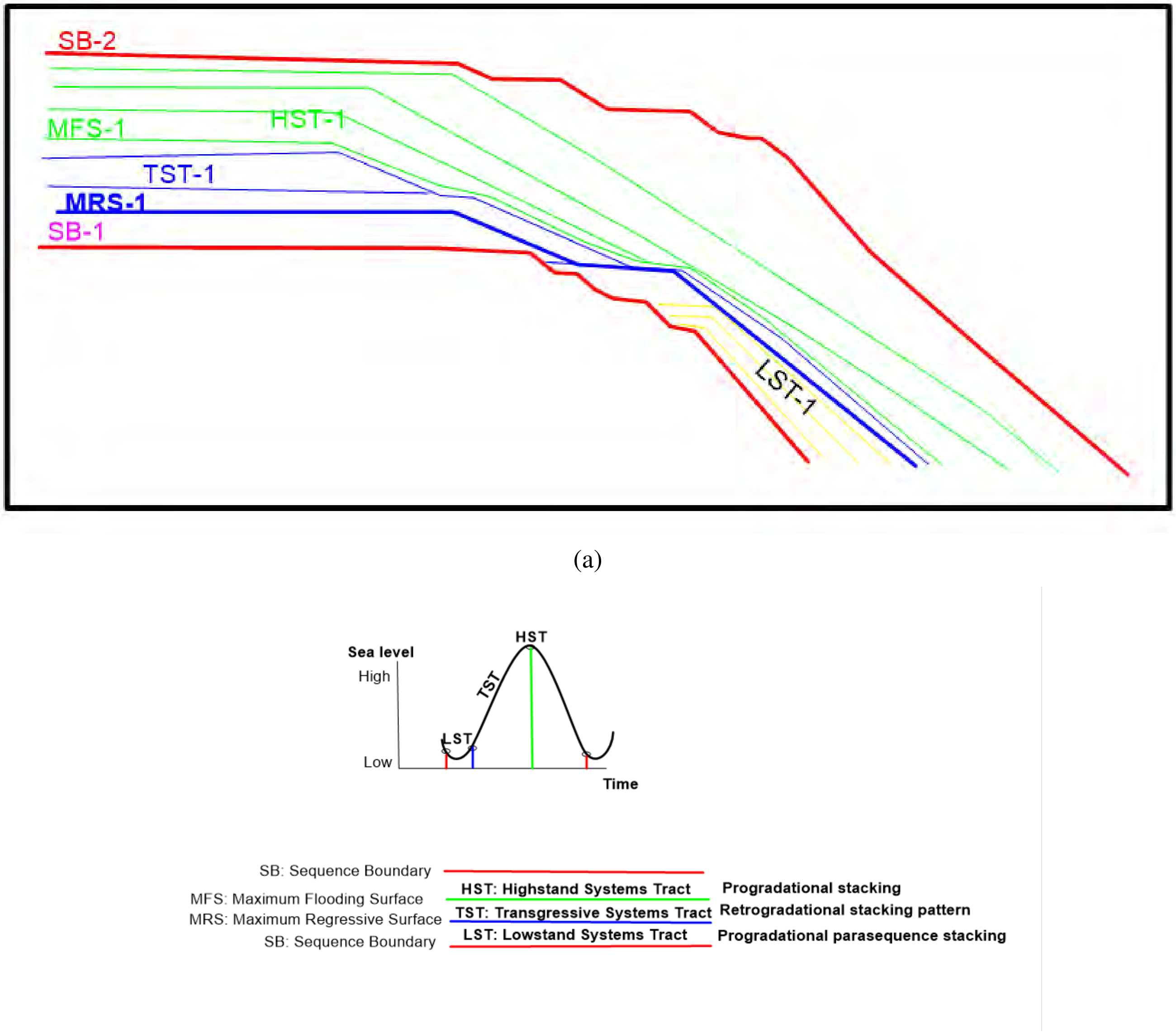
In this scenario, sequence boundary erosion would reflect increased basin gradients across the faulted shelf-slope edge. Gradients and associated erosion would have increased during rapid delta progradation due to associated structural collapse of the shelf, rather than times of lowstand shelf exposure when incised fluvial valleys carried sediments directly to the slope edge. Deepening of facies directly above sequence boundaries reflect the down dropped faulted blocks as shorelines continued to regress.

Progressive decrease in the thickness of successive sequences, and increase in local incision at the base of successive sequences, reflects the filling of accommodation in the area of Otu field, greater rates of sediment bypass, and thus decreased local rates of sediment loading. As accommodation filled, the locus of sediment deposition, and location a fastest sediment loading would also have shifted seaward.

The evolution of channel meanders appear to be similar to fluvial meandering channels in terms of direction and geometry of channel migration but channel fills are fine-grained. Changes in gravity flows have been associated with the formation of sinuous crosscutting channel preserved on the floor of a larger canyon at Benin-major in the Niger Delta (Deptuck et al., 2003).

3.9 Depositional Sequences and Model

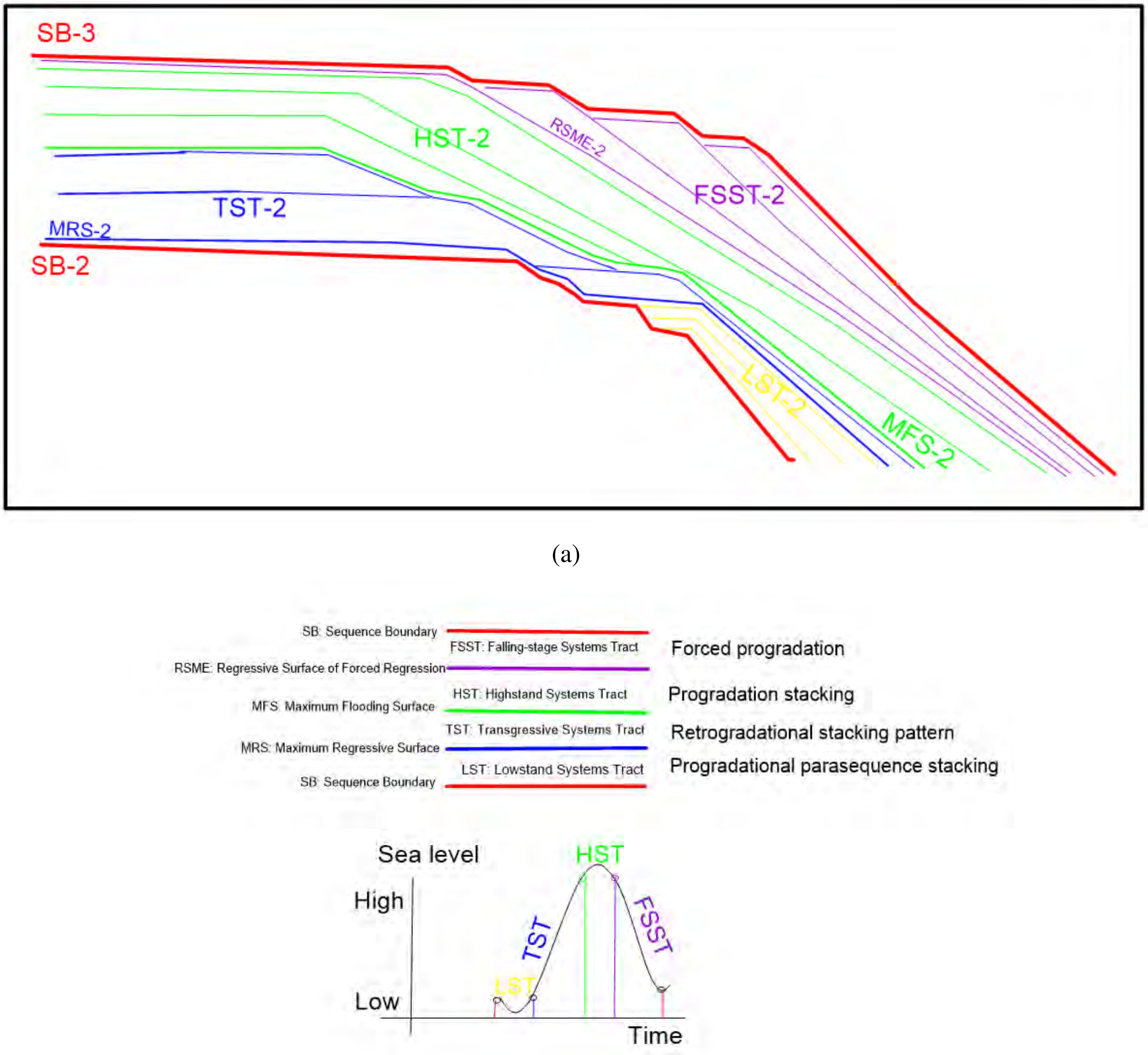
The depositional sequences within the Otu field are shown in Figures 3.32, 3.33 and 3.34 . The Figures illustrate the three sequences mapped in Otu Field with their systems tracts as a result of an interplay of variation in sea level and accommodation rates. However, the depositional models for all the three sequences were constructed as shown in Figure 3.35.



(a)

(b)

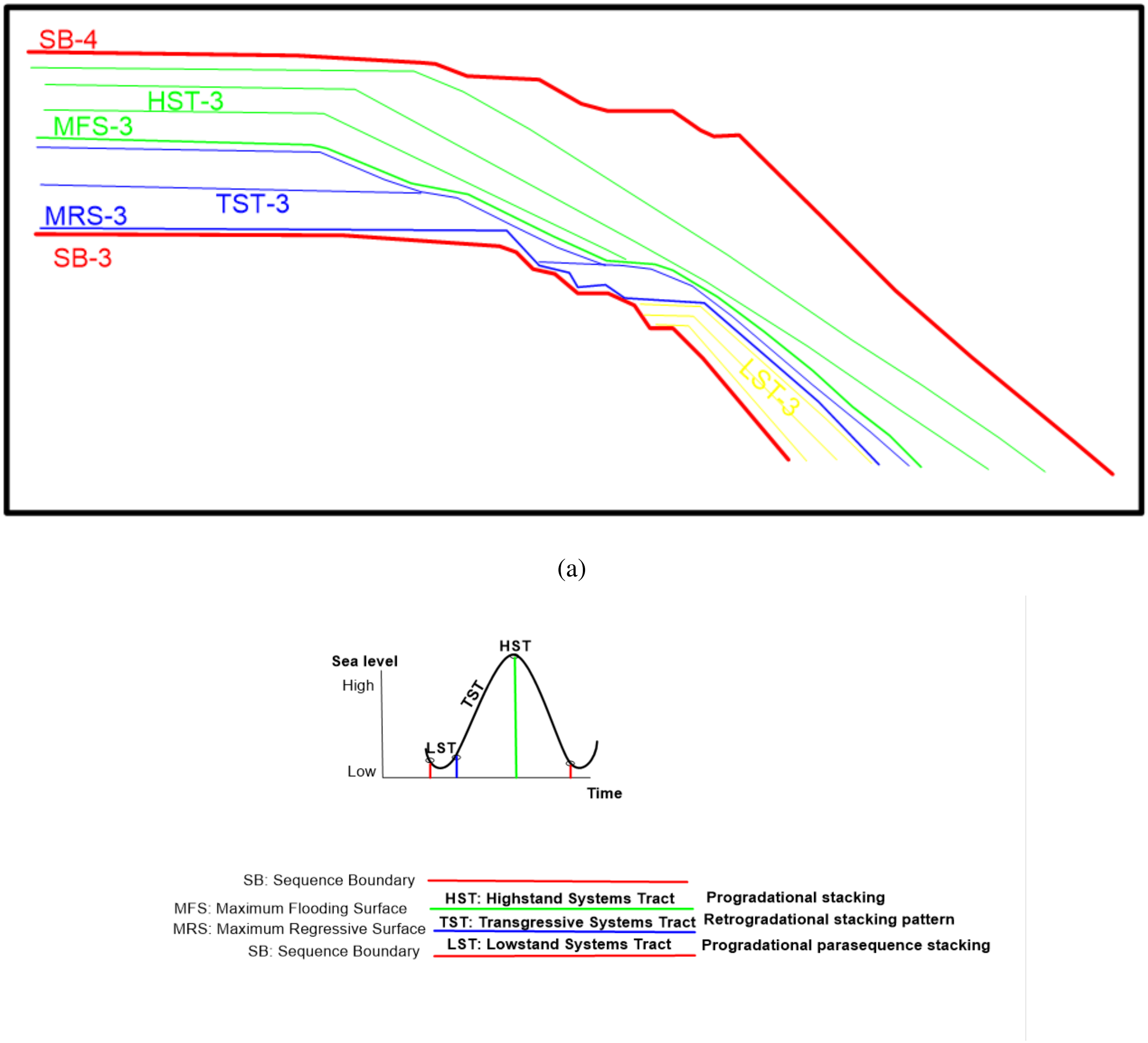
Figure 3.32: (a) Depositional sequence one in Otu field. It shows key stratigraphic surfaces and various systems tracts. (b) Variation with sea level. The model is based on the integration of seismic and well logs and was not drawn to scale



(a)

(b)

Figure 3.33: (a) Depositional sequence two in Otu field showing key stratigraphic surfaces and various systems tracts (b) Variation with sea level. Note that the model is based on the integration of seismic and well logs and was not drawn to scale



(a)

(b)

Figure 3.34: (a) Depositional sequence three in Otu field showing key stratigraphic surfaces and various systems tracts (b) Variation with sea level. The model is based on the integration of seismic and well logs and was not drawn to scale

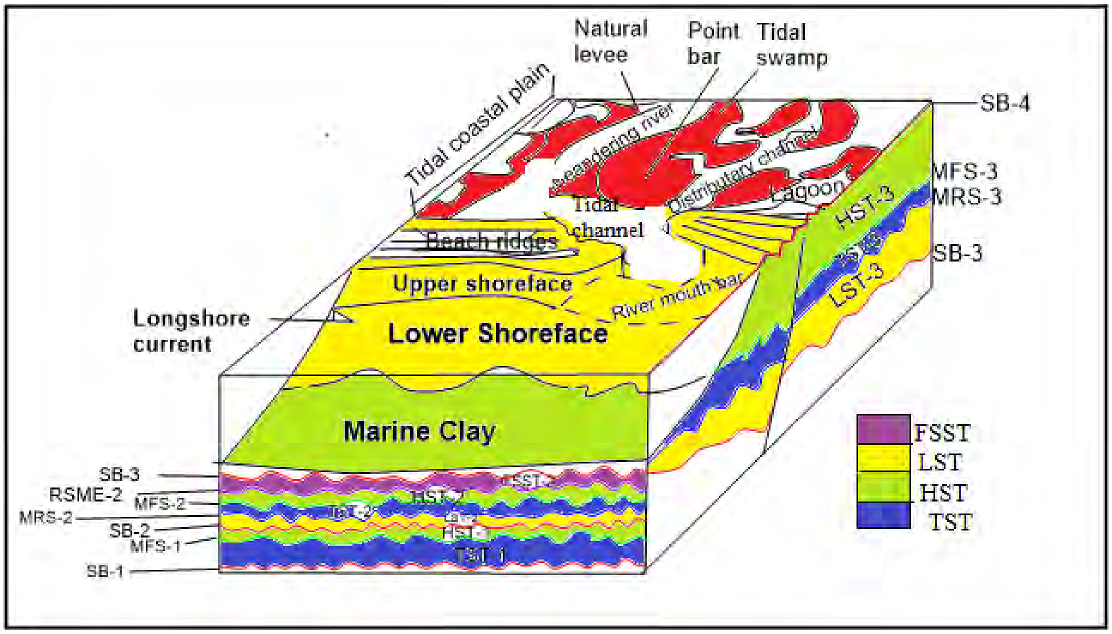


Figure 3.35: Geomorphology, cyclic sedimentation and an active fault in the Tertiary Niger Delta coastal zone (modified after Reijers (2011)

3.9.1 Depositional Sequence Architecture

The depositional systems in Otu field are made up of lowstand systems tracts (LST), transgressive systems tracts (TST), falling stage systems tracts (FSST) and highstand systems tracts (HST). Sediments identified within the LST are the fluvial channel sands. These sands are related to the incision of fluvial valley into the shelf. There is presence of prograding forced regressive deposits (FSST). These fluvial channel sands have excellent qualities as reservoir. The TSTs in the field capped the LST facies and consist of mainly marine shales. HSTs are made up of coarsening and shallowing upwards intervals, having fluvial and deltaic sands near the top of the unit. HSTs are very thick in most of the wells studied in Otu field. This may be as a result of high subsidence rates, high input of sediments and instability caused by underlying shale which is similar to the pattern of sediments observed in the Gulf Coast (Winker, 1982).

3.10 Reservoir Potential of Otu Field

Five (5) potential reservoirs (A, B, I, J and K) were delineated in the field. These reservoirs are mainly channel sands of LST and HST.

3.10.1 Porosity Evaluation

Porosity was evaluated from seven (7) wells. The evaluation of porosity was not possible for five (5) wells (Otu 6, Otu 8, Otu 19, Otu 46 and Otu 56) because there were no neutron, density or resistivity logs in those wells. The results of porosity evaluation is given in Table 3.3.

Table 3.3: Average Effective Porosity for the Reservoirs

Reservoirs	**Average Effective Porosity**		
	Minimum	Mean	Maximum
A	0.243	0.299	0.342
B	0.220	0.278	0.315
I	0.298	0.313	0.329
J	0.232	0.272	0.288
K	0.233	0.276	0.305

Table 3.4: Porosity values for Reservoirs Qualitative Description (Adapted from Rider (1986))

Percentage Porosity	**Qualitative Description**
0 - 5	Negligible
5 - 10	Poor
15 - 20	Good
20 - 30	Very Good
>30	Excellent

Table 3.3 shows a good reservoir quality and probably reflects well sorted coarse grained sandstone reservoirs with little cementation. According to Rider (1986), the porosity in all the reservoirs fall within very good porosity except reservoir I which have an excellent porosity. The results are consistent with recent studies in nearby fields (Ajisafe and Ako (2013); Richardson (2013); Adeoti et al. (2014)).

3.10.2 Reservoir Continuity

Reservoirs A and B were identified within the LST of sequence three. Reservoir A are traceable within seven wells and absent in Otu 4, Otu 6 and Otu 38. Reservoir B on the other hand are traceable within five wells (Otu 29, Otu 11, Otu 21, Otu 8 and Otu 4). Reservoirs I and J are found within the LST of sequence two. Reservoir I has lateral continuity from wells Otu 4, Otu 8, Otu 21, Otu 29 and Otu 32. Reservoir J however has lateral continuity from wells Otu 4, Otu 5, Otu 6 Otu 8, Otu 11, Otu 19, Otu 21, Otu 29, Otu 36 and Otu 38. However, reservoir K represents the thick facies of the HST in sequence one and are traceable within wells Otu 4, Otu 8, Otu 11, Otu 21 and Otu 29.

3.10.3 Reservoir Geometry

The Niger Delta is known to have stacked reservoirs that have thickness in the range of less than 15 m to greater than 45 m (Evamy et al., 1978). However, thicker reservoirs are likely to be composite bodies of stacked channels (Doust and Omatsola, 1990). Therefore, the reservoirs in the field are stacked channel sands and have thickness as in the range of 11 m to about 62 m. On the basis of reservoir quality and geometry in Otu field, point bars of fluvial channels that are cut by sand-filled channels are the most important. Also based on their porosity evaluation, the reservoir shows a good reservoir quality.

3.10.4 Source Rock Potential

The marine shale units of the transgressive systems tracts (TST) that were identified in the field would probably serve as the potential source rocks for the hydrocarbon found in the reservoirs of the field.

3.10.5 Trapping Mechanisms

The results of lithostratigraphic analysis show some sand units occurring at greater depth than their adjacent units. These were interpreted to be a result of syndepositional faulting in Otu field. These faults probably constitute the major traps for the accumulation of hydrocarbons. However, the shale units of the TST and those in HST could provide both top and bottom seals for hydrocarbon in the reservoir sands within Otu field. Therefore, the reservoir rocks of the LST and HST and seals from marine shale of the TST can together to form stratigraphic traps for hydrocarbon accumulation.

CHAPTER 4

CONCLUSION AND RECOMMENDATION

4.1 Conclusion

The Agbada formation of the Niger Delta is characterized by both structural and stratigraphic features which controls the trapping of hydrocarbon within its deposits. This study seeks to understand the relationship between these two features within the Otu field.

The structural analysis of the study area reveals a complex faulting system. The structural styles observed include horst and graben structures, structures with collapsed crest, structures with rollover anticlines. These faults play a major role in the hydrocarbon trapping in the study area. A prominent hanging wall closure in the central part of the field is the primary target of all the wells that penetrated the field. Lithostratigraphic analysis assisted in identifying and delineating fourteen reservoir sands in the field.

The subsurface facies of Otu field is subdivided into three sequences from the sequence stratigraphic interpretation carried out using well logs and 3-D seismic data. Sequence one is the deepest sequence subdivided into $LST-1$, $TST-2$ and $HST-3$ and interpreted to consist predominantly deposits of the transitional environment. Overlying sequence one is sequence two which consists of $LST-2$ (LPW), $TST-2$, $HST-2$ and $FSST-2$ and its depositional environment is interpreted to be predominantly shallow marine. Sequence three is the shallowest sequence stretching from the Agbada formation into the Benin formation, and consists of $LST-3$ (LPW), $TST-3$, $HST-3$ and were interpreted to be deposits representing transitional to shallow marine environments.

The seismic geomorphological study carried out on all the sequence boundaries ($SB1$ to $SB4$ and $MFS-3$) reveals a link between the depositional environment, type of channel and direction of paleo-flow relative to the faults. Channel belts are associated with continental to transitional depositional environment deposits while individual (relatively thin and less sinuous) channels were associated with shallow marine deposits. Channel belts are oriented perpendicular to the fault while individual channels (incised valley) were parallel and rarely affected by the faults.

This integrated study therefore reveals insights into the effects of tectonic events as it significantly affect the relationship between structural features such as faults and stratigraphic features such as channels within the field: therefore, providing a profitable means to guide hydrocarbon exploration and production strategies.

On the basis of reservoir quality in Otu field, point bars of fluvial channels that are cut by sand-filled channels are the most important reservoir rocks of the LST and HST and seals from marine shale of the TST could also combine to form stratigraphic traps for hydrocarbon accumulation in Otu field. Five hydrocarbon bearing sands were also identified and the evaluation of their porosities shows very good to excellent porosities.

4.2 Recommendation

Additional biostratigraphic, core and permeability data needed to integrate the results in order to establish more reliable interpretation in the field.

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- Usage of Resistivity meter (Campus Ohmega, ABEM 1000 and Geopulse Tiger) for geophysical investigations and thermal resistivity KD 2 probe
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- A self-motivation
- Open-minded (can take suggestions and criticism as positive)
- A functional team player
- Task oriented and can work under pressure

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- King Fahd Postgraduate Scholarship, Saudi Arabia, 2013
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- Siyan Malomo Prize in Geology, University of Ibadan, 2007
- Dean's Roll of Honour, University of Ibadan, 2004 - 2006
- Best Graduating Geology student, The Polytechnic, Ibadan, 2002
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PROFESSIONAL COURSES ATTENDED

- DOWAC- *Sequence Stratigraphy Applied to Exploration*, 2010
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- SEG – Non Mathematical Overview of Modeling, Migration, Velocity Analysis and Full waveform Inversion, 2014

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