EVALUATION OF THE STRATIGRAPHIC SEQUENCES IN THE “ALPHA” FIELD,
EASTERN COASTAL DEPOBELT, NIGER DELTA BASIN

BY

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CERTIFICATION

This is to certify that this work titled: “Evaluation of the Stratigraphic Sequences in the ‘Alpha’ Field, Eastern Coastal Depobelt, Niger Delta Basin” was carried out by Oleson, Jude Enyinnaya (20124764378) in partial fulfillment of the requirements for the award of the degree of Master of Science (M.Sc.) in Sedimentary/Petroleum Geology in the Department of Geology, Federal University of Technology, Owerri.

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This work is dedicated to my parents, Mr. and Mrs. Tony A. Oleson.
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ABSTRACT

A sequence stratigraphic analysis of depositional systems in the “Alpha-field” located at the eastern coastal swamp depobelt of the Niger delta was carried out using Well logs, Seismic and Biostratigraphic data from 6 wells to delineate potential hydrocarbon prospects. The genetic sequence stratigraphic model was adopted and three 3rd order depositional sequences (SQ1, SQ2 and SQ3) were revealed. Two 3rd order Maximum Flooding Surfaces (MFS1 and MFS2) characterized by marker shales (Umgerna 8 and Nonon 4), high faunal abundance/diversity and high gamma ray peak were delineated and correlated with the Niger delta chronostratigraphic chart, dated 9.5 and 10.4 Ma respectively. Lithofacies identified on well logs includes coarse-grained sandstones facies; shaly sandstone facies; mud-rock facies. These lithofacies showed three major stacking patterns (progradational, aggradational and retrogradational) and were used to predict environments of deposition interpreted as fluvial channel deposits, tide-dominated estuarine environment and offshore deposits of outer neritic/bathyal environments respectively. The result of this study showed that there are seven reservoir sands. Three major systems tract were delineated as Lowstand Systems Tract (LST), Highstand Systems Tract (HST) and Trangressive Systems Tract (TST) using their maximum flooding surfaces which represent depositional systems deposited during different phases of base level changes. The Lowstand Systems Tract (LST) consists of Basin Floor Fans (BFF), Slope Fans and amalgamated channel Sands deposited when sea level was low and accommodation space lower than rate of sediment influx. Highstand Systems Tracts (HST) consisted of shoreface sands displaying mostly aggradational to progradational stacking patterns. Transgressive Systems Tract (TST) consists of retrogradational marine shales deposited during high relative base levels and when accommodation space was higher than rate of sediment influx. The sands of LST and HST show good reservoir qualities while the shales of the TSTs form potential reservoir seals. Structural analysis revealed some dominating features such as antithetic faults, growth faults and collapse crest structures and these constitute the major hydrocarbon traps in the area. In sweetness seismic volume, isolated sand bodies and shale successions showed stronger, broader reflections than the surrounding shale. Discontinuities caused by faults and channels were detected in the variance seismic volume by their high coefficients. In the Root Mean Square (R.M.S) seismic section, a high R.M.S indicated a channel reservoir results from either a high acoustic impedance contrast of channel fill with the surrounding lithology. Relative acoustic impedances were calculated from the thin-bed reflectivity volume, and the equivalent section showed the separation of sand bodies in the reservoir.

Keywords: Sequence Stratigraphy, System tracts, Stacking Patterns, Seismic.
CHAPTER ONE
INTRODUCTION

1.1 Background of study
Demand for oil and gas has continued to increase all over the world and the huge profit derived from the venture has resulted to a corresponding increase in exploration. The Niger Delta Basin is one of such places with abundant crude oil reserves. It has become needful to develop more accurate techniques of stratigraphic analysis. Recently, emphasis has shifted from structural traps to stratigraphic prospects. Seismic sequence stratigraphy is the latest technique combined with structural methods, well logs and biostratigraphy to assist in predicting some of the world’s largest known reservoirs.

One of the most challenging targets for stratigraphic interpretation and petroleum exploration remain the late Cenozoic strata of the Niger Delta basin. The reason is that the surface upon which they were deposited is underlain by thick, unstable mobile clay; this loading has produced a complex series of gliding surfaces sills and sub-basins. Deposition is commonly controlled by large contemporaneous glide-plane extensional faults and folds related to diapirism, shale sills, and underlying structures in these sub-basins. Many of the sediments were deposited in bathyal water depths and are highly variable in their patterns of deposition, (Doust & Omatsola, 1990). Because of this complexity, the Niger Delta Basin remains highly attractive, but challenging as correlation of reservoirs of the same genetic units proves difficult.
Well information, biostratigraphy and seismic stratigraphy, offer an integrated sequence-stratigraphic interpretation for predicting reservoir, seal and source rocks of petroleum systems. This approach is effective in thick, complex strata, such as the late Cenozoic deposits in the Niger Delta Basin. It offers a predictive model in which a series of systems tracts within a depositional sequence is interpreted to be deposited in response to a cycle of fall and rise of sea level. This is related to a eustatic cycle. This work will offer well-log and seismic criteria for recognizing and characterizing depositional environments and siliclastic rock types occurring in sequences and systems tracts of the Niger Delta.

Sequence stratigraphic approach has proven to be one of such unique techniques for generating exploration prospects and predicting reservoir and seal qualities in both stratigraphic and structural traps. Sequence stratigraphy is an aspect of stratigraphy that subdivides rock record using a succession of depositional sequences composed of genetically related strata as regional and inter-regional correlative units (Haq et al., 1987). It deals with the changes in sedimentation relative to the rate of sea level changes. Genetically related facies are studied within a framework of chronostratigraphic significant surfaces (van Wagoner et al., 1990), and rock units that are genetically related are constrained by time lines (Reijers, 1997). The chronostratigraphic surfaces are either unconformities or bounding discontinuities or their correlative conformities which form sequence boundaries. Hence, a depositional sequence is made up of series of discrete packages, bounded by these surfaces. These packages are generally arranged in a predictable order in a depositional sequence known as systems tracts. These system tracts are defined as a linkage depositional systems formed at the time (Brown & Fisher, 1977).
The study shows how structural deformation influenced patterns of deposition and the evolution of stratigraphic sequences within a prograding clastic wedge. It also reveals how large-scale syn-depositional faulting can locally steepen proximal-distal gradients on Deltas, allowing deep incision by rivers and submarine mass flows that are potentially not directly related to regional changes in basin accommodation and sediment supply.

The interpretation of the lithostratigraphy of the Niger Delta sediments across time lines links laterally to the diachronous continental Benin sands, paralic Agbada succession of interbedded sands and shales, and prodelta akata marine under-compacted shale which is an overall product of tectonics and eustacy (Short & Stauble, 1965; Weber & Daukoru., 1987; White, 1982). The Niger Delta structural style is dominated by a series of growth faults which increases in complexity seawards (Merki., 1972; Doust & Omatsola, 1990).

Hence, the sequence stratigraphic interpretation of the coastal swamp depobelt of the Eastern Niger Delta using well information, biostratigraphy data and seismic data of some wells drilled in the fields are carried out to delineate sequence boundaries, systems tracts and maximum flooding surfaces in order to predict reservoir and isolate hydrocarbon traps and seals.

1.2 Statement of the problem
The Niger Delta Basin is very complex and very challenging for stratigraphic interpretation. The surface upon which it is deposited is underlain by thick, unstable mobile clay; which has produced complex series of gliding surfaces, sills and sub-basins and contemporaneous glide-plane extensional faults and folds related to diapirism, shale sills, and underlying structures. Due to this complexity, it has become necessary to employ proven and reliable techniques to carry out accurate
sequence stratigraphic and geophysical survey in today’s expensive deep-water drilling environments to achieve a cost-effective hydrocarbon exploration.

1.3 Justification of the study
The sequence stratigraphic approach has proven to be a more reliable tool in predicting oil reservoirs, cap rock and seal rocks.

1.4 Objectives of study
This study aims at providing sequence stratigraphic interpretation using well logs, seismic data and biofacies data in the eastern coastal swamp of the Niger Delta in order to improve further exploration activities within the field.

This study has the following objectives:

- To recognize sand and shale bodies through facies analysis and deduce environment of deposition.
- To recognize systems tracts and sequences from well logs and seismic data to identify the plays and prospects of the field.
- To generate and describe a generalized depositional model showing the relationship between the sequences and system tracts in a sub-basin controlled by eustacy to infer depositional processes.
- Using seismic attributes to improve delineation of hydrocarbon prospect.

1.5 LOCATION OF THE STUDY AREA
The Niger Delta basin is situated at the apex of the Gulf of Guinea on the west coast of Africa (Figure 1.1). The sedimentary basin occupies a total area of about 75,000 km² and is at least 11 km deep in its deepest parts.
The study area is located on the offshore part of the Eastern Coastal Swamp of the Niger Delta Basin. The wells in the area lies between Latitudes 4° 33’ 20” N and Longitudes 6° 54’ 7” E and covers an area of 3610.656 km² (Figure 1.2).

\[ \text{Figure 1.1: Location Map of the Study Area (Corredo et al., 2005)} \]
Figure 1.2: Base map of the field showing well location

1.6 Review of previous studies

Detailed discussion on the history, evolution, and structural features of the Niger Delta can be found in the works of Allen 1993 & 1965, Hospers 1965, Burke et al., 1972 and Whiteman 1982. Burke et al., 1972 analyzed and discussed the mega tectonic setting of the Niger Delta. The syn-sedimentary tectonics of the Tertiary Delta was extensively described by Evamy et al. (1978). Detailed studies on tectonics, stratigraphy, depositional environment, petrophysics, sedimentology and hydrocarbon potential are well documented in the literature (Weber & Daukoru, 1987; Doust & Omatsola, 1990; Reijers & Nwajide, 1997, among others) The modern
Niger Delta has distinctive basinward variations in structural style that define (1) an inner extensional zone of growth faults beneath the outer shelf; (2) a translational zone of diapirs and shale ridges beneath the upper slope; and (3) an outer compressional zone of imbricate toe-thrust structures beneath the lower slope (Hospers et al., 1956). These areas of contrasting structural style are linked on a regional scale by slow gravity collapse of this thick Deltaic prism (Damuth, 1994).

A framework of chronostratigraphy and sequence stratigraphy for the Niger Delta was produced by Stacher (1995). Ejadawe et al. (1981) examined the regional sequence stratigraphy and sand fairways as controls on hydrocarbon. Although broad regional relationships between patterns of deposition and deformation caused by structural collapse within the inner extensional zone of the Niger Delta have been proposed (Knox & Omatsola, 1989), details of high-frequency sequence development within this setting are less well documented. Most recent stratigraphic studies of the Niger Delta deposits based on modern three-dimensional (3-D) seismic records have focused on relationships between depositional patterns within the compressional toe of this clastic wedge along the base of the continental slope (Corredor et al., 2005).

Short & Stauble (1965) defined three formations within the 13,000 ft thick Niger Delta clastic wedge based on sand/shale ratios estimated from subsurface well logs: (1) basal, offshore marine, and pro-delta shale of the Akata Formation; (2) interbedded sandstone and shale of the dominantly deltaic Agbada Formation; and (3) the capping sandy fluvial Benin Formation.

Previous biostratigraphic studies (Stacher, 1995) and sequence-stratigraphic studies (Reijers et al., 1997) revealed how eustatic cycle combines with local tectonics.
Depositional sequences as defined by Vail (1987) and consisting of strata bounded by unconformities and their lateral equivalents are only recognised in specific sectors of the delta. In contrast, delta wide genetic sequences as defined by Galloway (1989) and consisting of strata bounded by maximum flooding surfaces within transgressive shales are more readily identifiable in the Niger Delta. Individual sea-level cycles are reflected in the Niger Delta in various sedimentary sequences. Interferences of cycles with different periods result in mega sequences that are confined by chronostratigraphy and characterised by sedimentology.

Sequence stratigraphic concepts are increasingly finding new and unique applications in the regressive siliciclastic deposits of the Niger Delta. Haq et al., (1987), found that the most useful criteria for the recognition of sequence boundaries in the acreage in the Niger Delta include truncation of underlying reflections, drape, dip discordance, or onlap of younger reflection over topography on sequence boundary, contrasts in seismic attributes across the sequence boundary and the sequence termination of faults at the sequence boundary.

Stacher (1994), revised the earlier SPDC Bio and Time-Stratigraphic Scheme and put the scheme in a sequence stratigraphic framework allowing correlation with Haq et al. (1987) sea level curve.

Merki (1972), described the structural geology of the Tertiary Niger Delta, which is on the overlap sequence that is deformed by synsedimentary faulting and folding. Ekweozor & Daukoru (1979 & 1980), presented a detailed report on the petroleum geology and stratigraphy of the Niger Delta showing the relationship between depositional patterns, structures and stratigraphy and their influence on the oil generation in the Niger Delta basin.
This current work focuses on understanding the, stratigraphic configuration, structural trend, and distribution within the paralic sequence of Middle to Late Miocene age across several petroleum plays in the eastern coastal swamp of the Tertiary Niger Delta.

1.7: Concepts of Sequence Stratigraphy
Van Wagoner (1995) defined Sequence stratigraphy as the study of the relationships of rocks with time and stratigraphy of a cycle of genetically related strata separated by their bounding surfaces such as surfaces of non-deposition or erosion, or their correlative conformities.

According to Galloway (1989), sequence stratigraphy studies the repetition of genetically related depositional units separated by a surface of non-deposition or erosion. A sequence is the fundamental unit of sequence stratigraphy, it is a succession of similar and genetically related strata separated by unconformities and correlative conformities (Mitchum, 1977). Each system tract is composed of a linkage of contemporaneous depositional systems (Brown & Fisher, 1977).

Four systems tracts are recognised (Vail, 1988): low stand systems tract (LST), transgressive systems tract (TST), high stand systems tract (HST), and shelf margin.

Sequence stratigraphy is an approach that is used to interpret depositional origin of sedimentary strata and assumes an implicit connection to base level change. It does this by establishing how the succession of strata accumulated in order in the sedimentary section over a framework of subdividing surfaces.

Assumptions behind the concept of sequence stratigraphy (Van Wagoner et al., 1990) are:

a. Marine sedimentation patterns are controlled by changes in relative sea level.
b. Eustacy, tectonics, subsidence and sedimentation rate are controlled by relative sea-level. Primarily, Eustacy is more important on trailing-edge continental shelf environments. The role of Eustacy may be masked by tectonics in epeiric basins. It is assumed that subsidence and sedimentation are occurring at the same time and are not as important as other factors.

c. Sea level changes yields sedimentation patterns that have distinct geometries called system tracts that are easily recognised on well logs, seismic lines, well log, cross sections, outcrops and cores.

d. On passive margin shelves, as these geometries are eustatically-controlled, they are similar worldwide. Once the geometry has been calibrated in a known area, it can be used as a correlation tool to identify and date seismic data elsewhere.

e. The building block of depositional sequence are laminae and laminae sets, beds and bed sets, parasequence and parasequence sets. Sequences are bounded above and below by unconformities (also called sequence boundaries) which records a fall in relative sea level.

f. Sequence stratigraphy may be applied at any scale. They also have the same characteristics at any such scale. First-order eustatic sequences are developed in the Phanerozoic. Haq et al. (1998) described first order sequences as mega-sequences. This is similar to the cratonic sequences described by (Sloss, 1963). Second-order eustatic sequences or the super sequences described by Haq et al. (1988) are developed in Geological Eras. However, Seismic stratigraphy is based on third-order sequences. Third, fourth and fifth-order sequences are the focus during geologic studies of well log cross sections, outcrops and cores (Van Wagoner et al., 1990).
1.7.1 Parasequences

Parasequences are a succession of asymmetrical shallowing-upward sedimentary cycles with similar and genetically related beds or bedsets separated by marine flooding surfaces and their correlative surfaces.

The vertical occurrence of repeated cycles of coarsening or fining upwards sediment called parasequences stacking patterns is the second step in the interpretation of well logs. It is used to identify the Lowstand System Track (LST), Transgressive System Track (TST), and the Highstand System Track (HST) that are developed by the Maximum Flooding Surface (MFS), Transgressive Surface (TS) and Sequence Boundary (SB). Stacking patterns are shown by well log signatures of either gamma ray, resistivity or SP log.

This parasequence cyclic stacking patterns are commonly identified on the basis of variations in grain size. The fining upward sequences are indicated by triangles whose apex is pointing upwards while a coarsening upward sequence is indicated by inverted triangles whose apex is pointing downwards (Figure 1.4).

1.7.2 Parasequence sets and stacking patterns

Usually, there will not be just one parasequence, but a series of parasequences which may display consistent trends in thickness and facies composition and these sets may be progradational, aggradational, or retrogradational. (Figure 1.3) The rate of deposition and accommodation defines this patterns. Other factors include the ratio and kind of materials deposited (sandstone or mudstone), the environment of deposition (coastal, shallow marine or deep marine) and the ratio of the thickness of different parasequences and parasequence sets. A parasequence represents a single episode of progradation which occurs when the shoreline moves seaward
producing a shallowing-upward succession. The shallowing-upward succession shows that sediments being deposited are greater than the available space.

1.7.2.1 Progradational Stacking
In a progradational set of parasequences, each parasequence builds out or advances somewhat farther seaward than the parasequence before. This results to a shallower set of facies than the parasequence before. This produces an overall shallowing-upward trend within the entire parasequence set and the set is referred to as a progradational parasequence set or is said to display progradational stacking. A progradational parasequence can be recognised in a cross section by seaward movement of a particular facies contact. Progradational stacking results when the rate of sedimentation exceeds the rate of accommodation in the long term. By this, the depth of water becomes shallower as there is insufficient space to contain sediments causing them to move away from the sea over time.

1.7.2.2 Aggradational Stacking
Aggradational parasequences produces aggradational stacking, each parasequence above and below contains essentially the same suite of parasequences. There is no change in overall facies hence no net vertical trend in water depth. An aggradational parasequence can be recognized in a cross-section by a characteristic stability in their facies contact at an equivalent position in a parasequence. Aggradational stacking results when sedimentation rate closely matches accommodation rate in the long term. By this the depth of water across all parasequences remains the same as accommodation space is filled up as quickly as it is created and there is no movement landward or seaward. There is shallowing-upward in each parasequence bounded by their flooding surface. Yet, this is counter-balanced by the deepening at
the underlying surface, hence there is no net movement of facies across each parasequences.

1.7.2.3 Retrogradational Stacking
In a retrogradational parasequences, progradation in each parasequence is less than the parasequence preceding it. It means that there is a net facies shift since the set of facies in each parasequence is deeper than the parasequence below. There is an overall deepening upward trend within the entire parasequence set produced by a net facies shift which displays retrogradational stacking or backstepping. The landward movement of a particular facies contact at an equivalent position in a parasequence symbolizes a retrogradational stacking in a cross section. Retrogradational stacking results when the accommodation rate exceeds sedimentation rate in the long term. By this, the depth of water becomes deeper due to sparsely filled abundant accommodation space and there is landward movement of facies.
Figure 1.3: Parasequence sets stacking patterns (Van Wagoner et al., 1990)
1.7.3: Depositional Sequence

A depositional sequence is a succession of similar and genetically related strata separated by their sub-aerial unconformities or their correlative conformities. A sub-aerial unconformity is an erosional surface or a sub-aerial exposure including features formed by soil or karst surfaces and down-cutting rivers.

The boundaries of depositional sequences include a combination of subaerial unconformities that are the classic "sequence boundaries" of Vail *et al*., (1977), and their marine correlative conformity. Catuneanu (2002) equates the timing of this subaerial unconformity with a stage in the base level fall at the shoreline.

Correlative conformities are surfaces that correlate updip to a sub-aerial unconformity. Every depositional sequence is the record of one cycle of relative sea level. As a result, depositional sequences have a predictable internal structure of surfaces and systems tracts (suites of coexisting depositional systems, such as coastal plains, continental shelves, and submarine fans) (Figure 1.4).

In the four system tract model, all depositional sequences contain the following systems tract in this order: lowstand systems tract, transgressive systems tract, highstand systems tract, and falling-stage systems tract. In this view, a sequence begins with the slow rise following a fall in sea level, and continues through the next fall in sea level. Some important surfaces separates these system tracts. The transgressive surface separates the lowstand and transgressive systems tracts. The maximum flooding surface separates the transgressive and highstand systems tracts. The basal surface of forced regression separates the highstand and falling-stage systems tract.
Figure 1.4: Genetic 3rd order system tracts and bounding surfaces (Galloway, 1989)

Figure 1.5: Type one sequence (Van Wagoner et al., 1990)
1.7.4: Systems Tracts
A system tract is a three-dimensional depositional unit, defined by its boundaries and internal geometry. Three systems tracts commonly occur within a single cycle of sea-level changes (Figure 1.5). The highstand (or highland) systems tract, lowstand (or lowland) systems tract, and, between them, the transgressive systems tract, and also regressive systems tract.

1.7.4.1: Highstand Systems Tract
Highstand occurs during the late stage of base level rise when the rate of sea level rise drops below the sedimentation rate or when sea level was high and stable, or falling slowly. In this period of sea level highstand is formed. It is bounded by maximum flooding surface at the base and composite surface at the top. This systems tract is commonly widespread on the shelf and may be characterized by one of more aggradation to progradational parasequence sets with prograding clinoform geometry (Figure 1.6).

1.7.4.2: Lowstand Systems Tract (LST)
A lowstand systems tract forms when the rate of sedimentation outpaces the rate of sea level rise during the early stage of the sea level curve. The maximum regressive surface separates the LST at the top and the base is bounded by subaerial unconformity or its correlative conformity. Posamentier & Allen (1999) described the sediments of the LST to include deposits such as a basin-floor fan, slope fan, and lowstand wedge which accumulated on the sequence boundary over the

1.7.4.3: Transgressive Systems Tract (TST)
A transgressive systems tract is bounded by two surfaces. The maximum flooding surface at the top and the maximum regressive surface at the base. TST forms when there is a rapid sea level rise which outpaces the rate of sedimentation. The
stacking patterns of parasequences exhibit backstepping onlapping retrogradational aggrading clinoforms that thicken landward.

1.7.4.4: Regressive System Tract
Also called forced regressive systems tract or falling stage system tract, FSST. (Plint & Nummedal., 2000) forms in the marine part of the basin during the base level or sea level fall due to subsidence. Occurrence of subaerial unconformities at the landward side of the basin also characterises the regressive system tract. Forced regressive deposits display diagnostic progradational and downstepping stacking patterns (Posamentier & Allen, 1999; Catuneanu, 2002).

1.7.5: Bounding Surfaces
These are surfaces that subdivides sequence boundaries and system tracts and their representation in a cross section (Kendall & Alnaji, 2002). They include sequence boundary, transgressive surface and maximum flooding surface.

1.7.5.1: Sequence Boundary
The sequence boundary is an unconformity updip and a correlative conformity downdip. At a surface of subaerial exposure and erosion, it is called an unconformity. A sequence boundary is identified by an abrupt shift of facies basinward at the downdip of its correlative conformity. Some authors call this abrupt shift a Forced Regression to distinguish it from seaward movement of shoreline due to sedimentation, which is termed Normal Regression. Relative fall in sea level resulting from tectonic subsidence or eustatic rise gives rise to sequence boundaries when both factors result to a net loss of accommodation space. An erosion in the form of an incised channel or an underlying strata that is structurally tilted is a major indication of an unconformity. Regionally, the relief of unconformities could be up to tens or hundreds of metres.
Figure 1.6: Stacking patterns regression and transgression relative to sediment influx
1.7.5.2: Transgressive Surface
The transgressive surface is a prominent flooding surface capping the lowstand system tract. It is the first major flooding surface to come after the sequence boundary different from other relatively minor flooding surfaces separating parasequences in the lowstands. During the lowstands system tracts, relative sea level gradually rises following the relatively low rates of accommodation. A major flooding surface forms from a parasequence boundary when a long-term rise combines with a short term rise.

1.7.5.3: Maximum Flooding Surface
The last significant flooding surface that caps the transgressive system tract is the maximum flooding surface. It marks the point where retrogradational stacking in the transgressive systems tract turns to aggradational or progradational stacking in the early highstand systems tract. It is usually noted in a cross section by extensive marine facies condensation at the widest landward extent of deep-water. In an outcrop the maximum flooding surface is identified by deposits in the deepest water within a sequence. The transgressive surface may merge with the maximum flooding surface in distal areas where the former is absent.

1.7.6: Termination Patterns
Depositional sequence boundaries are recognized on seismic data by identifying reflections caused by lateral terminations of strata termed onlap, downlap, toplap, truncation (figure 1.7).

1.7.7 Applications to sequence stratigraphy
Although sequence stratigraphy was originally developed from seismic stratigraphy, the principles can be readily applied to outcrop, core, and well logs. It also has chronostratigraphic and biostratigraphic applications.
Figure 1.7 (A-C): Termination patterns in a depositional sequence (Galloway, 1989)
1.7.7.1 Seismic Stratigraphy
Seismic Stratigraphy is basically a geologic approach to the stratigraphic interpretation of seismic data. Seismic and outcrop studies provide the lateral continuity to the sequence stratigraphic framework. Seismic stratigraphy has developed into three separate disciplines. The first, pioneered by Vail et al. (1977), is seismic sequence analysis. It is the study of recognizing and correlating regional stratal surfaces to define genetically related rock units that represent discrete chronostratigraphic intervals (Van Wangonner et al., 1988). Seismic data is used extensively in sequence stratigraphy, as primary seismic reflections are generated by time correlative bedding surfaces and surfaces that separate sets of contemporaneous depositional systems (system tracts) (Van Wangonner et al., 1988).

The second discipline is Seismic facies analysis. It is defined as the description and geological interpretation of packages of seismic reflections. Parameters within this packages include configuration, continuity, amplitude, phase, frequency, and interval velocity (Vail et al., 1977).

The third discipline is seismic attribute analysis. Subtle changes in properties of particular reflections are examined to determine rock properties, including fluid contents (Sengbush, 1962.)

1.7.7.2 Well log based sequence stratigraphy
Well logs are primarily applied in sequence stratigraphy to establish grain size and lithology of penetrated wells. In addition to cores and outcrops studies, well logs show the vertical resolution of sedimentary sections. Well logs are used to analyse sequences and systems tracts after seismic sections have been used to analyse the sequences. Well log analysis involves using cuttings and cores to interpret depositional lithofacies on logs and identifying system tracts and sequences from the
interpreted logs. Cross sections and individual logs display stacking patterns which
shows changes in accommodation space and further assist in identifying sequences
and system tracts.

1.7.7.3 Biostratigraphy in Sequence Stratigraphy
Biostratigraphy is a branch of stratigraphy that uses fossil assemblages contained in
them to correlate and assign relative ages to rock strata. The primary purpose is
correlation, used in showing that a strata in a geological section is a time equivalent
of another strata at some other section. Fossils are important in differentiating
sediments of the same age which may have different appearance across different
sedimentary environment. Paleontologic (the study of fossils to determine organisms'
evolution and interactions with each other and their environments) data, integrated
with seismic and well log data, are an integral part of sequence stratigraphic
analysis. Paleontology provides two critical types of data:

a. Age control for chronostratigraphic horizons, especially sequence boundaries
b. Paleoenvironmental control for systems tract interpretations

1.7.7.4 Chronostratigraphic Applications
Chronostratigraphy is the branch of stratigraphy that studies the time relation of rock
strata. The primary purpose of chronostratigraphy is to study the sequential
arrangement of rocks deposition within a geological region and the entire geologic
record of the earth at the time they were deposited. As a stratigraphic nomenclature
standard, the chronostratigraphic system is based on time intervals defined by
palaeontology and fossil assemblages or biostratigraphy. Chronostratigraphy
apportions actual age dates to these fossil assemblages and their interfaces. The
methodologies used are two geological principles, the law of superposition and the
principles of cross-cutting relationships. Sequence boundaries are mostly relied upon for correlating chronostratigraphic surfaces.

1.7.8 Sequence stratigraphic model
Table 1 below shows a summary of the different sequence stratigraphic models and their utilities.

1.7.8.1 Depositional sequence
The boundaries of depositional sequences include a combination of subaerial unconformities that are the classic "sequence boundaries" of Vail et al., (1977), and their marine correlative conformity. Catuneanu (2002) equates the timing of this subaerial unconformity with a stage in the base level fall at the shoreline.

1.7.8.2 The genetic stratigraphic sequence
Galloway (1989) developed the genetic sequence stratigraphic model in which he used the maximum flooding surfaces as sequence boundaries. He showed that the maximum flooding surface lies between the transgressive system tract and the highstand system tract. He further defined the lowstand system tract as a relative fall and an early rise.

1.7.8.3 The transgressive-regressive sequence (T-R sequence)
The transgressive-regressive sequence (T-R sequence) of Embry and Johannessen (1992) is enveloped by "composite surfaces" that include subaerial unconformities and/or ravinement surfaces and their correlative maximum regressive surfaces (Catuneanu, 2002).
<table>
<thead>
<tr>
<th>Sequence model</th>
<th>Depositional Sequence</th>
<th>Genetic Sequence</th>
<th>T-R Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>end of transgression</td>
<td>HST</td>
<td>early HST</td>
<td>HST</td>
</tr>
<tr>
<td>end of regression</td>
<td>TST</td>
<td>TST</td>
<td>TST</td>
</tr>
<tr>
<td>end of base level fall</td>
<td>late LST (wedge)</td>
<td>LST</td>
<td>LST</td>
</tr>
<tr>
<td>onset of base level fall</td>
<td>early LST (fan)</td>
<td>late HST (fan)</td>
<td>FSST</td>
</tr>
<tr>
<td></td>
<td>HST</td>
<td>early HST (wedge)</td>
<td>HST</td>
</tr>
</tbody>
</table>

*After Catayama (2002)*

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- **sequence boundary**
- **within systems tract surface**
CHAPTER TWO
REGIONAL GEOLOGY OF THE NIGER DELTA

2.1 Geological settings
2.1.1 Geology of Niger Delta Province

The Niger Delta Basin, is an extensional rift basin surrounded by other basins in the area formed under similar conditions. It is positioned on the passive continental margin of Gulf of Guinea near the western coast of Nigeria. It is also bounded by Cameroon, Equatorial Guinea and São Tomé and Príncipe (Figure 2.1). The basin which contains a very productive Petroleum system is known for its complexity and high economic value. It is one of the largest sub aerial basins in Africa with a sub aerial area of about 75,000 km², a total area of 300,000 km², and a sediment fill of 500,000 km³ and depth 9-12 km. The Niger Delta basin lies in the south westernmost part of a larger tectonic structure, the Benue Trough (Figure. 2.1).

The onshore portion of the Niger Delta province is delineated by the geology of southern Nigeria and south-western Cameroon (Figure. 2.1). It is bounded to the north by the Benin Flank, an east-northeast trending hinge line at the south of the West Africa basement massif. Outcrops of the Cretaceous Abakiliki high demarcates the province to the Northeast and the Calabar Flank (a hinge line bordering the adjacent Precambrian) to the east-south-east. The province is bounded offshore by the Cameroon volcanic line to the east. To the west it is bounded to the west by the easternmost West African transform-fault passive margin, the Dahomey Basin. Also in this direction is a two-kilometer sediment thickness contour to the south and southwest. Part of the province is the geologic extent of the Akata-Agbada Formation in the Tertiary Niger Delta Petroleum System.
2.1.2 Regional tectonic setting
The Niger Delta Basin is located within the Abakaliki-Benue suture zone of the much larger southern Nigerian basin. On the west, it is separated from the Dahomey (or Benin) basin by the Okitipupa basement high, and on the east it is bounded by the Cameroun volcanic line. The Anambra Basin, Abakaliki uplift, Afikpo syncline, and Calabar flank transects several older (Cretaceous) tectonic elements at the northern margin (Figure 2.2).

The Niger Delta evolved by tectonically controlled pre- and syn-sedimentation as described by Evamy et al. (1978), Ejedawe (1981) and Stacher (1995). The tectonic framework of the continental margin along the West coast of equatorial Africa is controlled by Cretaceous fracture zones expressed as trenches and ridges in the deep Atlantic. In Nigeria, the boundary faults of the Cretaceous Benue-Abakaliki Trough far into the West African shield is one of the individual basins divided by the fracture zone ridges (Figure 2.3). The trough represents a failed arm of a rift triple junction associated with the opening of the South Atlantic. Rifting in this region began in the Late Jurassic and continued into the Middle Cretaceous (Lehner & De Ruiter, 1977). In the Niger Delta region, rifting came to a stop in the Late Cretaceous. Figure 2.4 shows the gross paleogeography of the region as well as the relative position of the African and South American plates since rifting began.

2.1.3 Basin Formation
The Niger Delta Basin started developing during the separation of the South American and African, at the time the South Atlantic was also opening at the junction of a failed rift (Figure 2.4). This separation caused by the rifting began in the late Jurassic and ended in the mid Cretaceous. The rifting is associated with several faults, amongst which thrust faults are more prevalent. Regression was evident early
Fig 2.1: Index map of Nigeria and Cameroun

Figure 2.2: Tectonic map showing the Niger Delta (Modified after Kogbe, 1989)
Figure 2.3: Models for the RRR Rift origin of the Benue Trough of Nigeria. (a) Spreading Ridge Model (Avbovbo et al., 1986); (b) Aulacogen Model (Olade, 1975).

Figure 2.4: South Atlantic opens showing fracture zone ridges (Gibson, 2014)
in the basin Formation as syn-rift sands and shales where also deposited at the time in the late Cretaceous. During these processes, the basin was being extended by high angle normal faults and fault block rotation. A large transgression occurred at the beginning of the Paleocene during which the Akata Formation was deposited.

The Akata Formation is predominantly shales, Agbada is made of shales and sands while Benin is mostly sands.

Due to the tectonic nature of the basin Formation, it is divided into three different zones. An extensional zone caused by the thickened crust lay on the continental shelf. There is also a transition zone and in the deep part of the basin lies the third, a contraction zone.

2.1.4 Shale Tectonics
Deformational processes marked the end of rifting in the basin. Gravity tectonism occurred in the form of shale mobility which induced internal deformation (Kulke, 1995). This occurred in two processes, first there was poor loading of over-pressured and poorly compacted Prodelta and delta slope clays of the Akata Formation by Agbada Formation with a higher density Delta-front sands. This resulted to shale diapirs. Secondly, lack of lateral basin-ward support for the under-compacted Akata Formation resulted to slope instability (Figure 2.5). In all the depobelts, complex structures arising from gravity tectonics had finished forming before the deposition of Benin Formation. In addition to shale diapirs, other complex structures (Figure. 2.6 & 2.7) include back-to-back features, and steeply dipping, closely spaced flank faults, roll-over anticlines, collapsed growth fault crests (Evamy et al., 1978). Most parts of the Agbada Formation are counterbalanced by these faults which flattened near the top of Akata Formation at detachment planes.
Fig 2.5: Schematic seismic section showing effects of internal gravity tectonics on sediments at the distal portion depobel of the Niger Delta (Lehner & De Ruiter, 1977; Doust & Omatsola, 1990).

Fig 2.6: Examples of field structures and associated trap types in the Niger Delta (Doust & Omatsola, 1990; Stacher, 1995).

Figure 2.7: Schematic Dip Section of the Niger Delta (Weber & Daukoru, 1975).
2.1.5 Structural setting
The structural setting of the Niger Delta basin consist three linked gravity systems. There is growth fault dominated updip extension. Secondly, there are compressional systems dominated by a downthrust related fold. Between those is a translational shale diapir control system.

A subdivision of five major structural provinces/zones has been made out of these three tier systems based on seismic revealed structural styles and high resolution bathymetry data. They include: extensional province; mud diapir zone; inner fold and thrust belts; transitional detachment fold zone; outer fold and thrust belt zone. These structural zones, most of which are still active till present day have resulted to expression of bathymetric structures still exposed despite recent deposition (Figure 2.8). Predominantly, the structural features within the Niger Delta are the Normal faults, growth faults and roll over anticlines.

2.1.6 Regional stratigraphic setting
A 12 km thick upward-coarsening regressive association of Tertiary clastics make up the Niger Delta stratigraphic sequence. Doust 1990, classified it informally into three gross lithofacies: (i) basal marine claystones and shales of unknown thickness; (ii) alternation of sandstones, siltstones and claystones, with upward increment of sand percentage; (iii) top alluvial sands.

Three lithostratigraphic units have been recognized in the subsurface of the Niger Delta (Short & Stauble, 1967; Avbovbo, 1978). These are from the oldest to the youngest, the Akata, Agbada and Benin Formations all of which are strongly diachronous (Figure 2.9). These are prograding depositional facies identified based on their sand-shale ratios. Many authors have published the type sections of these
Formations, they are Short and Stäuble (1967), (Avbobvo, 1978; Doust and Omatola., 1990; Kulke, 1995).

At the base of the delta, the Akata Formation is of marine origin. It comprises thick shale sequences that make up the potential source rock, turbidite sand reservoirs, and small amount of silt and clay. Akata Formation formed at the beginning of the Paleocene lowstands when clays and terrestrial organic matter were transported to low energy and hydrogen deficient deep water areas (Stacher, 1995). Doust and Omatsola, 1990 estimated the overpressured Akata Formation to be about 7,000 metres thick. Deep sea sand fans were likely deposited at the upper Akata by turbidity currents when the Delta was developing (Burke, 1972).

Agbada Formation, the major petroleum-bearing unit overlies Akata Formation. Its deposition began in the Eocene and continued into the recent (Figure 2.8, 2.9, 2.10). The 3700 m thick deposit consists of paralic siliciclastics representing the actual deltaic portion of the sequence. The clastics were deposited in different deltaic environment including delta-front, delta-topset, and fluvio-deltaic environment. Shale and sandstone beds were deposited in equal proportions in the lower Agbada Formation with the upper portion mostly sand with minor shale interbeds.

The third Formation, Benin Formation overlies the Agbada Formation. It is made up of 200 m thick continental deposit of alluvial and upper coastal sands aged Eocene to recent (Avbovbo, 1978).
Figure 2.8: Map of the Niger Delta showing the distribution of the main structural styles.

**Fig 2.9:** Stratigraphic section and time equivalent Formations in the Niger Delta from the Late Cretaceous through the Eocene (Reijers et al., 1997).
Fig 2.10: Three Formations of the Niger Delta shown in a stratigraphic column (Shannon & Naylor, 1989; Doust & Omatsola, 1990).
2.1.6.1 Akata Formation (Marine Shales)
The Akata Formation is the oldest lithostratigraphic unit in the Niger Delta. The Akata Formation (Eocene – Recent) is a marine sedimentary succession that is laid in front of the advancing Delta and ranges from 1,968 to 19,680 ft in thickness. It consists of mainly uniform under-compacted shales, clays, and silts at the base of the known Delta sequence with lenses of sandstone of abnormally high pressure at the top (Avbovbo, 1978). These streaks of sand are possibly of turbidite origin, and were deposited in holo marine (Delta-front to deeper marine) environments. The shales are rich in both planktonic and benthonic foraminifera and were deposited in shallow to deep marine environments (Short & Stauble, 1967). The base of the sequence in each depobelt aged Paleocene to Holocene are made up of Marine shales. An outcrop of Marine shales called Imo shale is visible offshore along the continental slope, and onshore in the northeastern part of the Delta where they occur in diapirs.

2.1.6.2 Agbada Formation (Paralic Clastics)
The 3,000 m thick Agbada Formation, aged Eocene to Recent is composed of sandstone and shale (Reijers, 1996). They make up the Deltaic portion of the sequence having been deposited in Deltaic environments including Delta-front, Delta-topset, and fluvio Deltaic environments. Shale with marine fauna first occurred at the top of Agbada Formation and coincided with the continental-transitional lithofacies at the base (Adesida & Ehirim., 1988). The sandstone body at the base coincides with Akata Formation at the top (Short & Stauble, 1967). It was thought that the source rock was the shales of Agbada Formation until Ejedawe et al. (1984) deduced it to be the shales of the Akata Formation. The Agbada Formation forms the hydrocarbon reservoir sequence in the Niger Delta as it contains most exploration
The paralic sequence aged Eocene to Pleistocene is present in all depobelts as with the marine shales.

### 2.1.6.3 Benin Formation (Continental Sands)

The youngest lithostratigraphic unit in the Niger Delta is the Benin Formation. It is Miocene –Recent in age with a minimum thickness of more than 6,000ft and made up of continental sands and sandstones (>90%) with few shale intercalations. The shallowest part of the sequence is composed almost entirely of non-marine sand. The sands and sandstones are coarse-grained, sub-angular to well-rounded and are very poorly sorted. The Benin Formation was deposited in upper coastal plain or alluvial environments as the Deltaic deposition shifted southwards into a new depobelt. Oligocene is thought to be the oldest continental sands, although they are impossible to date since they lacked fauna. The sands thins out close to the edge of the shelf.

### 2.2 Niger Delta Petroleum System

There’s accumulation of Petroleum in Agbada Formation of the Niger Delta clastic wedge. The ratio of gas to oil is likely to increase southward within individual depobelts even though hydrocarbon distribution is generally complex (Doust & Omatsola, 1989). A hydrocarbon habitat model which provides a short summary of reservoir, source rock, basin, trap and hydrocarbon character was developed by Stacher (1995) using the sequence stratigraphy of some oil-rich belts within the Niger Delta area (Table 2 & 3).

Below is the summary of Formations of the Niger Delta Basin.
Table 2: Stratigraphy of the basin (Modified from Short & Stauble, 1967).

<table>
<thead>
<tr>
<th>Subsurface</th>
<th>Surface outcrops</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Youngest known age</strong></td>
<td><strong>Oldest known age</strong></td>
</tr>
<tr>
<td>Recent</td>
<td>Benin (Afam (clay member))</td>
</tr>
<tr>
<td>Recent</td>
<td>Agbada</td>
</tr>
<tr>
<td>Recent</td>
<td>Akata</td>
</tr>
<tr>
<td>Unknown</td>
<td>Paleocene Maastrichtian Campanian Campanian/ Maastrichtian Coniacian/ Santonian Turonian Albian</td>
</tr>
</tbody>
</table>
Table 3: Hydrocarbon habitat table. Modified from Stacher (1995).

<table>
<thead>
<tr>
<th>Geology</th>
<th>Passive continental margin of south Atlantic produces tropical delta; Aged Early Tertiary to recent; Depositional model mostly shallow ramp; Locally mappable Shelf break.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traps</td>
<td>Dip closures characterized by rollover anticline in growth fault; Traps bounded by faults; Stratigraphic traps including truncation traps, channels, tidal Deltas, etc.</td>
</tr>
<tr>
<td>Reservoir</td>
<td>Deltaic sandstones e.g shoreface, channel, beach, etc; Alternations of stacked sand/shale; Multi-reservoir fields at depth 5000-14000 ft.</td>
</tr>
<tr>
<td>Source rocks</td>
<td>High Potential Marine Akata shales) with land plant material; Type III/II, III vitrinite Liptinite, S.O.M; within well penetrations measured VR less than 0.7; Top oil window variable 9000- 14000 ft.</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>Oil/condensate/gas; Gravity 15-25 API biodegraded; Gravity 25- 45 API non-biodegraded: Low sulphur/nickel; Pristane/Phythane ratio 0.6-1.6; Rich in waxes/resins, other land plant material S.O.M.</td>
</tr>
</tbody>
</table>
CHAPTER THREE
MATERIALS AND METHOD

The study focused on integrating well logs, biofacies and seismic in evaluating the stratigraphic sequence of ‘Alpha’ field within the eastern coastal depo-belt of the Niger Delta (Figure 3.1). This quantitative and qualitative research design approach is effective in thick, complex strata, such as the late Cenozoic deposits of the Niger Delta Basin.

3.1 Data sets
The data used for this study were obtained from Shell Petroleum Development Company of Nigeria (SPDC) with permission from the Department of Petroleum Resources, (DPR). The field in this study was renamed “Alpha” field for proprietary reasons. The data include well logs (Gamma ray, Density and Resistivity logs) from 6 wells, biostratigraphic data (foraminiferal diversity/population, benthic diversity/population, planktic diversity/population), seismic data and check shot data. The biostratigraphic data, extracted from core samples, side-wall samples and ditch-cuttings were calibrated and depth matched with corresponding wire line logs.

3.2 Software resources
Petrel, a software platform developed and built by Schlumberger, used in the exploration and production sector of the petroleum industry is the main computer software used for this research. It was run on high definition Linux workstations and 64bits windows vista workstation respectively. Well log data for 6 wells and the seismic volume were loaded into Petrel. It was used to interpret seismic data, perform well correlation, interpret results and produce maps.
Figure 3.1: Workflow methodology

Well log analysis → DATA → Seismic analysis

Well to Seismic tie

Checkshot data

Structural mapping → Horizon mapping → Seismic Sequence Strat.

Correlation with Seismic profiles

Surfaces (Well log/Biostrat correlation) and system tracts identification/mapping

Determination of Parasequence Stacking Patterns

Lithofacies / FOD interpretation

Biostratigraphic analysis

Petroleum play interpretation and mapping
3.3 Methods

3.3.1 Sequence model

The genetic stratigraphic sequence (Galloway, 1989) is the method of sequence delineation adopted in this research. It uses maximum flooding surfaces as sequence boundaries, and it is subdivided into highstand, lowstand (fall and early rise), and transgressive systems tracts. This model overcomes the recognition problems related to the correlative conformity. Its advantage is that maximum flooding surfaces are relatively easy to map across a basin. The sequence stratigraphic analysis utilized genetic sequences constrained within chronostratigraphic packages. The maximum flooding surface (MFS) within the condensed section were used to define the genetic packages.

3.3.2 Well log analysis

Well log shapes were interpreted to infer lithology, lithofacies of the penetrated sediment depositional environment and the depositional sequence (Figure 3.2 and 3.3).

Well logs were used to establish the grain size and the lithology. Well logs provided access to a detailed vertical resolution of sedimentary sections. After seismic sections have been analysed for sequences, well logs were analysed for sequences and systems tracts. This involved interpreting depositional lithofacies on logs and then identifying sequences and systems tracts from the interpreted logs. Stacking patterns displayed in cross sections and individual logs show accommodation space changes which help us identify sequence and systems tracts.

The procedure for well log sequence analysis carried out is listed below:

a. Lithofacies was interpreted on logs and calibrated and environment of deposition predicted.
b. Sequences and systems tracts were delineated from the interpreted lithofacies using regional cross sections with well and outcrop data.

c. Accommodation space changes were determined from parasequence stacking patterns seen in well log cross sections.

d. Sequences and systems tracts was checked by:
   - Correlating between wells that have biostratigraphic-time correlations, well log marker-bed correlations, and the global sea cycle chart.
   - Correlating with seismic profiles.

3.3.2.1 Delineation of lithofacies and environments of deposition

Architectural patterns on Gamma ray log exhibiting either funnel, bell, hour glass or cylindrical shapes with the biofacies data was used to interpret lithofacies and infer their environments of deposition (Figure 3.2 and 3.3). Well logs (Density, Resistivity and SP) were used to mark out lithofacies area with clean sandstone close to each other or with little separation and shale filled areas with wide separations.

3.3.2.2 Stacking patterns and parasequences

The well log suites made available for this research displayed at consistent scales to reveal log trends and enhanced the identification of facies stacking patterns and parasequences. Parasequence stacks (vertical occurrences of coarsening or fining upward sequences of repeated cycles) identified resulted to progradational, retrogradational, or aggradational parasequence sets (Onyekuru et al., 2010).
Figure 3.2: Gamma ray response to grain size variation model (Emery & Myers, 1996)

Figure 3.3: Gamma Ray Log Response and Depositional on Deltaic and Fluvial, Clastic Marine, and Deep Sea Setting. (Kendall (2003), modified from Rider, 1999).
3.3.2.3 Stratigraphic surfaces, systems tracts and depositional sequences

The maximum flooding surface (MFS) was mapped using wireline logs and biostratigraphic data. It was marked as the surface that caps the transgressive systems tract and marks the turnaround from retrogradational stacking in the transgressive systems tract to aggradational or progradational stacking in the early highstand systems tract. It was further delineated as units with maximum positive Neutron-Density separation, high gamma response, minimum shale resistivity and high faunal diversity and abundance and maximum water depth.

The transgressive surface of erosion (TSE), a prominent flooding surface that caps the lowstand systems tract, is the first significant flooding surface to follow the sequence boundary and forms the lower boundary of the retrogradational parasequence stacking patterns of the transgressive systems tract. This was delineated and inferred from a characteristic signature on the resistivity logs caused by presence of carbonate cements probably derived from the carbonate fauna eroded during ravinement of already deposited sediments. Sequence boundaries were identified in areas where faunal abundance and diversity were low and/or bioevents were lacking, this corresponded to high resistivity value and low gamma ray responses within the shallowing section.

Sequence boundaries were identified at the base of thickest and coarsest sand units between two adjacent maximum flooding surfaces, which naturally coincided with the shallowest environments marked by low or total absence of foraminiferal abundance and diversity.

Three systems tracts comprising lowstand systems tract, transgressive systems tract, and highstand systems tract were identified and mapped with the aid of depositional sequence models (Figure 3.4a, 3.4b, 3.4c).
**Figure 3.4a:** Lowstand clastic stacking on Clastic Marine Settings (Kendall (2004), based on Rider, 1999 and Baum x-section).

**Figure 3.4b:** Transgressive clastic stacking on Clastic Marine Settings (Kendall (2004), based on Rider, 1999 and Baum x-section).
Figure 3.4c: Highstand clastic stacking on Clastic Marine Settings (Kendall (2004), based on Rider, 1999 and Baum x-section).
3.3.3 Biostratigraphic analysis
Biostratigraphy data was used to correlate and assign relative ages of rock strata by using the fossil assemblages contained within them. It was used to show how a particular horizon in one geological section represents the same period of time at another horizon at some other section. Biostratigraphic data enabled delineation of the maximum flooding surface, an age and paleoenvironmental control for system tract interpretations. The population and diversity of the benthic and planktonic foraminifera with corresponding lithofacies were used for interpretation of environment of deposition and paleobathymetry (Figure 3.5). The relative ages of surfaces mapped were determined using the Niger Delta chronostratigraphic chart (Figure 3.6).

3.3.4 Well correlation
Well correlation was done in Petrel window with maximum flooding surfaces of same geologic age defined in the study area. Marine flooding surfaces were the best markers on which the correlation cross sections were hung. Correlation was done to determine lateral continuity of facies, thereby aiding reservoir studies in the fields. The delineated MFSs were dated with marker shales (P and F zones) and by correlation with the Niger Delta chronostratigraphic chart (Figures 3.6).

3.3.5 Structural analysis and mapping
Seismic reflection data was used to create maps depicting the geometry of a subsurface structure. Structural faults in 3D seismic image space was detected, mapped and transferred to the associated 3D seismic wiggle-trace data volume. This analysis aided the construction of detailed models of the internal architecture of targeted reservoirs.
**Figure 3.5:** Paleobathymmetry and Depositional Environment Chart (Modified After Allen, 1965).
Figure 3.6: Niger Delta chronostratigraphic chart (adapted from SPDC, 2010)
3.3.6 Seismic sequence stratigraphy
Seismic stratigraphy was incorporated to provide a geologic approach to the stratigraphic interpretation of seismic data. Seismic studies provided the lateral continuity to the sequence stratigraphic framework. It was employed to recognise and correlate regional stratal surfaces to define genetically related rock units that represent discrete chronostratigraphic intervals (Vail et al., 1977). Primary seismic reflections were generated by time correlative bedding surfaces and surfaces that separate sets of contemporaneous system tracts (Van Wangoner et al., 1988).

3.3.6.1 Seismic facies analysis
Seismic facies analysis was carried out by describing and interpreting seismic reflections of lithofacies with parameters such as continuity, amplitude, frequency, and interval velocity.

3.3.6.2 Seismic attribute analysis
Seismic attribute analysis to examine subtle changes in properties of particular reflections to determine rock properties, including fluid contents (Sengbush, 1962).

Seismic interpretation was carried out using below procedure:

a. Depositional sequence and system tracts was delineated
b. Seismic facies within each system tracts were delineated and mapped.
   c. Attributes within specific seismic facies were evaluated.

Well log and biostratigraphic data were integrated at all phases of this interpretation effort.
CHAPTER FOUR
DATA ANALYSIS, RESULTS AND INTERPRETATIONS

4.1 Delineation of lithofacies and inferred environments of deposition

Three groups of lithofacies were identified and marked on the well logs (Figure 4.1). They consists of coarse-grained sandstones facies; shaly sandstone facies; mud-rock facies.

4.1.1 Coarse-grained sandstones facies
Cylindrical blocky log motif was delineated as thick uniformly graded coarse grained sandstone unit, probably deposits of braided channels and tidal channel deposits. The coarse-grained sandstone facies consists of amalgamated and isolated sharp-based fining upward sand bodies characterized by blocky to bell-shaped gamma ray log motif (Figure 4.1). The sand units are locally separated by thin bands of shale and lack marine fauna. The facies is interpreted as fluvial channel deposits based on these characteristics. These channel deposits represent deposition in a coastal plain setting landward of the tidal zone (McCabe et al., 1992). The blocky log pattern is common in incised valley fills (Allen et al., 1965).

4.1.2 Shaly sandstone facies
The Shaly sandstone facies (Figure 4.1) mainly consists of fine to medium-grained sandstones and mudstone/shale interbeds; serrated funnel shaped Gamma Ray Log pattern representing upward coarsening succession from mud to shallow/marginal marine sandstones; and sometimes serrated bell to blocky shaped patterns at certain intervals. These intervals are also characterised by high Neutron and Density Porosity Log values. As a result of the cyclic alternation of sandstones and mudstones it contains, it is interpreted as tide dominated estuarine deposits. Also, alternation of high Gamma Ray Log responses, serrated funnel, bell shaped and
blocky Gamma Ray Log motif indicate frequent fluctuations in current strength which is common in tidal processes. The successions are indicative of a prograding, estuarine environment.

4.1.3 Mudrock Facies
This facies is inferred to originate from off-shore deposits since it is predominantly composed of shale units with thin siltstone intercalations displaying a retrogradational parasequence pattern (Figure 4.1). Mudrock facies exhibited high frequency and diversity of foraminifera particularly indicating Outer Neritic (ON) and Bathyal (BA) depositional environments.
Figure 4.1: Three representative wells showing lithofacies delineation in the field

Legend

- Coarse grained sandstone facies
- Shaly sandstone facies
- Mudrock facies
4.2: Parasequence stacking patterns

The well log suites made available for this research displayed at consistent scales to reveal log trends and enhanced the identification of facies stacking patterns and parasequences. Parasequence stacks (vertical occurrences of coarsening or fining upward sequences of repeated cycles) identified resulted to progradational, retrogradational, or aggradational parasequence sets (Figure 4.2). This shows the detail sequence stratigraphic representation regarding the shoreline migration relative to accommodation space created and sediments supplied with evidence of the textural gradients of deposits. The stacking patterns are represented using black arrows and they show overall coarsening upward parasequence sets.

4.3 Well log correlation

Correlation across the various fields of study (Figure 4.3) was done using the recognized and identified constrained chronostratigraphic surfaces typified by Maximum Flooding Surfaces (MFSs). The delineated MFSs were dated with marker shales (Umgerna 8 and Nonon 4) and by correlation with available biostratigraphic data.

By this, the stratigraphic section is delineated and it shows how the surfaces correlated along dip and strike at certain depths within the depositional basin, thus depicting basin geometry and depositional sequences across the fields of study.

Results of well correlation showed that delineated constrained surfaces were not laterally continuous due to truncations caused by the sydepositional faults in the field. These faults are known to form the major hydrocarbon traps in the region. Also, the shale of TST and shale units within the HST could form top and bottom seals for hydrocarbons in the reservoir sand.
Figure 4.2: Stacking patterns across wells

Legend

↑ Fining upward
↓ Coarsening upward
↓ Aggradational
Figure 4.3: Correlation chart of well logs showing surfaces in the “Alpha – field”
The reservoir rocks of the LST and HST and the seals from shales of the TST can combined to constitute stratigraphic traps for hydrocarbon accumulation in the well field.

4.4 Results of Genetic Sequence Stratigraphic analysis

Two Maximum Flooding surfaces (MFS) were extracted from biostratigraphic interpretation with associated sub aerial unconformities (SU). However, most of the interpreted logs did not penetrate down to the depth of the deepest MFS. The encountered MFS’s are 9.5 Ma and 10.4 Ma. One complete and two incomplete depositional sequences and the accompanying systems tracts were interpreted and mapped within the ‘Alpha’ field based on log–motifs of the various reference wells (AA-001, AA-002, AA-003, AA-005, AA-006) within the spatial distribution of the recognized constrained surfaces (Figure 4.4a).

The First (SEQ1) and third (SEQ3) formed the deepest (oldest) and topmost (youngest) depositional sequences respectively (Figure 4.4a). First sequence is an incomplete sequence with thickness approximately 1000 ft.

Second sequence (SEQ2) is a complete depositional sequence, approximately 3000 ft thick. The Systems Tract of this sequence formed thick as well as thin sand and shale deposits interpreted as regressive to transgressive shore face Delta deposits and channel fills. This sequence is dominated by sand units typical of basin floor fans and slope fans.

The third and last sequence (SEQ3), also an incomplete sequence overlies the 9.5 Ma MFS. The sequence has a thickness of about 8000 ft. The sequence is mostly composed of highstand system tract and displayed both progradational and retrogradational stacking pattern which contains reworked channel sand deposits.
which were more pronounced in the down dip wells and some predominantly mud fill channels, also typical of river mouth bar and Delta.

4.4.1 Maximum Flooding Surfaces

Two Maximum Flooding Surfaces were recognised on well logs and biostratigraphic data. The Maximum flooding surfaces were dated MFS1 9.5 Ma and MFS2 10.4 Ma using the Niger Delta Chronostratigraphic Chart, a regional marker and biozone (Figure 4.4b). The regional marker for the first Maximum Flooding Surface (MFS1) is Umgerna 8 and the occurrence of the event within P820 and F9600 biozones. Likewise, the regional marker for the second maximum flooding surface (MFS2) occurred within P780 and F9600 biozones characterised by Nonon 4 marker shale.

4.4.2: Lowstand Systems Tract (LST) and Reservoir mapping

The Lowstand System Tracts interpreted in this study is as shown in (Figure 4.4c) and these formed due to earliest sea level rise and normal regression relative to the accommodation space created and sediments deposited. This system Tracts is underlain by a sequence boundary and is capped by the transgressive surface of erosion. These reservoirs are generally progradational emanated from shoreline migration from the continental environment to the marine setting. Within the interpreted LST reservoirs are intermittent shale and shale-out units depicting prograding complex, slope wedge and basin floor deposits typical of low energy environments and tidally influenced deposits. The absence of hydrocarbon in these reservoirs observed in this study may be attributed to poor petrophysical quality of these reservoirs likely resulted from high possibility of any of the phyllosilicate mineral member.
Figure 4.4a: Cross section of the studied wells showing sequences and correlated surfaces

Legend

SQ=Sequence

………….=MFS

______=Correlation line
Figure 4.4b: Well AA-001 showing constrained maximum flooding surfaces using Niger Delta Chronostratigraphic chart

Figure 4.4c: Lowstand Systems Tract Reservoir

HST  LST  HST
4.4.3: Transgressive Systems Tract (TST) and Reservoir mapping

Typical of Transgressive Systems Tract is fining upwards textural gradient. This channel reservoir is better developed in well AA-001 and diminishes towards wells A-002 and A-003. This could be attributed to possible barriers encountered by this channel which may have retarded the channel cause translating to channel tortuosity and sinuosity. This reservoir as represented in (Figure 4.4d) is underlain by Transgressive Surface of Erosion above the late phase of the Lowstand reservoirs and capped with the thick shale sequence of the 9.5 Ma MFS. Hydrocarbon occurrence in this reservoir is concentrated in channel sand penetrated by well AA001 while the channel diminishing towards wells A-002 and A-003 are wet which could be attributed to reservoir compartmentalization, stratigraphic pinch-out and mix-clastic regime with emergence of authigenic mineral imprints. The reservoir architecture as depicted by channel motif as shown in the figure.

4.4.4: Highstand Systems Tract (HST) and Reservoir mapping

The Highstand Systems Tract (HST) include reservoirs which may vary from the base to top being aggradational to progradational and are possibly charged by the underlying organo facies rich shales which may be the Maximum Flooding Surfaces. The HST reservoirs encountered in this study are coarser towards the top and as such will have better porosities and permeabilities as interpreted from the porosity logs such as neutron, density and sonic. These reservoirs were influenced by shoreline migration from terrestrial/littoral settings towards the marine environments forming a coarsening upwards textural gradient sequence as depicted by the well logs in (Figure 4.4e).
Figure 4.4d: Transgressive Systems Tracts Reservoirs

HST  LST  HST
Figure 4.4e: Highstand Systems Tracts Reservoir

HST  LST  HST
4.5 Seismic analysis

4.5.1 Check shot data
Check-shot data were used in the conversion of two-way time to depth. Using the well logs, the tops and bases of reservoir sands were marked. The depth of these sand tops were converted to time using the check-shot data (Figure 4.5a), and the nearest, brightest and most continuous reflection were mapped on the seismic in-lines. This allows us to calibrate the relationship between the seismic time and well depth.

4.5.2 Well to seismic tie
Regional stratigraphic markers (MFS) identified from well logs were calibrated as well-tops along well-track and displayed against seismic. This made it possible to tie these markers or surfaces to seismic events (Figure 4.5b). Well-seismic tie was used to compare a unit depth measurement of well data to a unit time measurement of seismic data. This allowed correlation of horizon tops identified in a well with particular reflections on the seismic section.

Sonic and Density well logs were used to generate a synthetic seismic trace. The synthetic trace compares to the real seismic data collected near the well location. A good character (shape) tie was obtained between the real and synthetic traces, this made it possible to extract various seismic attributes (measures of the seismic wavelets) to predict rock and fluid properties. The real and synthetic traces were compared and the match was good enough for regional mapping and exploration, one data set could then be related to the other (well to seismic or seismic to well).
Figure 4.5a: Check shot plot

Figure 4.5b: Well to seismic tie using synthetic seismogram generated from well AA-02
4.6: Structural analysis and mapping

The Alpha Field within the coastal swamp depobelt is affected by a series of faulting resulting to episodic subsidence and sedimentation. The faulting and the lateral coverage of these faults is shown in (Figure 4.6a and 4.6b) at time slice 2000ms. The lateral distribution of the faults were extracted using seismic Variance (Edge Method) interpretative of the Semblance Volume. The structural connotations to stratigraphic infills were generated using volume filtering within the inlines and crosslines. Also, vertical and dip corrections with plane confidence threshold and dip guided seismic volume were integrated.

The sediments supplied were accommodated in the space created by subsidence which was initiated by faults. The sediments are generally thicker within the downthrown fault blocks relative to their up-thrown sides. Typical of the structural controls to the accommodation created and sediments supplied is shown below (Figure 4.6b).

The occurrence of the identified chronostratigraphic surfaces at different depths along dip and strike lines in the studied wells shows evidence of faulting within the fields.

Locations of major faults were interpreted from the seismic data to define structural discontinuities (Figure 4.6c). Vertical patterns in seismic reflections were used to relate strata across faults. Faults were also picked on the seismic sections along the dip (Inline). The faults are represented on the seismic lines as discontinuous lines along a preferred orientation of reflectors. The figure shows evidence of structural influence on sediment package which varies in thickness due to various faults dips.
**Figure 4.6a:** Time Slice at 2000ms from Seismic Semblance Volume

**Figure 4.6b:** 3D Seismic volume with the crossline, inline, and time slice showing interpreted faults
Figure 4.6c: Fault distributions in the field
4.7 Sequence stratigraphic integration on seismic
The seismic volume used for this study extends to 3.0 seconds two way travel time (TWT) below which reflection continuity is fair. Time slice at 2.0 seconds shows the best structural display (Figure 4.7a). The seismic volume is characterized by series of parallel/divergent reflection offset and formed by major growth faults. The seismic data where analysed, processed and a three dimensional seismic section of the area was made and interpreted. Depositional sequences, bounding surfaces (Sequence Boundaries and Maximum Flooding Surface) and Systems tracts were marked and delineated on the seismic profiles (4.7a). First, a representative well A-001 was chosen and the depths of the surfaces and system tracts penetrated by the well were determined from well log and there their corresponding time in seconds were determined from the check shot plot. This time was converted to milliseconds as calibrated on the seismic profile. The time equivalents of those depths were then marked on the seismic and mapped accordingly. Summary of the depth-time analysis is given in the Table 4.

The systems tracts identified on both well logs and seismic data were subsequently tied to the 2-way time check shot data. Flattening at various MFS(s) reveals a shift of depositional centre from Northern section towards the southern which is a typical scenario of the progradational pattern in the Niger Delta.
### Table 4: Conversion of system tract depth to seismic time

<table>
<thead>
<tr>
<th>System Tracts</th>
<th>Depth (meters) (From well log)</th>
<th>Time (secs) (From Check shot)</th>
<th>Time on Seismic (msec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST2</td>
<td>6850</td>
<td>2.0</td>
<td>2000</td>
</tr>
<tr>
<td>TST1</td>
<td>7900</td>
<td>2.2</td>
<td>2200</td>
</tr>
<tr>
<td>LST1</td>
<td>8350</td>
<td>2.4</td>
<td>2400</td>
</tr>
<tr>
<td>HST1</td>
<td>9650</td>
<td>2.75</td>
<td>2750</td>
</tr>
</tbody>
</table>

**Figure 4.7a**: Delineated depositional sequences and system tracts on seismic
4.7.1: Seismic stratigraphic interpretation

A number of parallel and nearly parallel reflections were observed in the seismic section (Figure 4.7b). The reflections are quite chaotic at the upper left and bottom left section and continuous to the top right where there are parallel reflections. The reflections are discontinuous close to and behind faults and continuous at zones away from faults at the middle right but discontinuous at the bottom right towards the downthrown side of growth faults. The reflections exhibit moderate to high amplitude across the seismic volume with and low amplitude in the chaotic areas. Data quality is generally good but deteriorates at zones of discontinuities and chaotic low amplitude reflection. Strata discontinuities and regionally parallel reflections in the seismic cube related to vertical patterns in well logs of the field correlated.

4.7.2: Interpretation of seismic facies/well-log characteristics

Random discontinuous seismic reflections are typical of chaotic facies which are commonly sand-rich when formed by channel-levee complexes. Well-developed reflection or discontinuity surface against the downthrown side of a growth faults are typical of Basin-floor Fans facies and system tracts. The well logs exhibit thick, well-sorted sands. The concave-upward reflections are typical of channels facies. Levees exhibit discontinuous to semi-discontinuous reflections that downlap away from them. Both are Lowstand slope Fan system tract. In well-logs, channels are identified as aggradational or fining-upward sequences of blocky sands some of which may be shale filled, however Levees exhibit variable lithologies. Discontinuous seismic reflections that are parallel to the sequence boundary are typical of overbank facies (Sangree & Widmier, 1979). These facies are generally mud-rich and are separated by spiky aggradational sands.
Figure 4.7b: Using cross line 1147ms to show seismic facies units/analysis
Parallel semi-continuous to continuous reflections are exhibited by Updip parallel facies. They have variable lithology. The facies exhibits aggradational, coarsening-upward, or fining upward sequences of sand, silt and mud.

Semi-continuous to discontinuous facies were observed on the seismic by semi-continuous to discontinuous reflections that are concordant. These facies are usually composed of thick muds and silts or poorly developed, mud-rich coarsening-upward sequences. Poorly developed fining-upward sequences are sometimes present.

4.8 Petroleum play interpretation
4.8.1 Reservoir potential, continuity and geometry of the “Alpha-Field”

Seven (7) potential reservoirs (R1, R2…..R7) were delineated in the ‘Alpha Field’. They are mainly the channel sands and shoreface sands of LSTs and HSTs respectively. They displayed low gamma ray and high resistivity values (Figure 4.8a). The lateral continuity of sand bodies determines reservoir area. Majority of the reservoirs R2, R3, R4 and R7 were identified within the shoreface sands of the HST and traceable to wells AA-002, AA-004 AND AA-006. Reservoir R6 was identified in well AA-005 within the channel sands of the LST in the main depositional sequence (SQ2), while reservoir R5 was identified in the sandy facies interbedded in the predominantly shale facies of the TST.

Most scholars have noted that known reservoir rocks in the Niger Delta are Eocene to Pliocene in age. They are often stacked and range in thickness from 15 m to 45 m thick (Evamy et al., 2008). The thicker reservoirs likely represent composite bodies of stacked channels (Doust and Omotsola, 1990). The various reservoirs in the wells (Figure 4.3e), which are shoreface sands, range between 80 (21 m) to 160 feet (42 m) thick.
Figure 4.8a: Well logs in the “Alpha-field” showing developed Reservoirs

HST  LST  HST
4.8.2: Seismic attributes

The main aim for using seismic reflection data to characterize the reservoirs comes from its ability to provide useful relationship between the seismic reflection data and physical properties. Volume attributes analysis such as sweetness, variance edge, RMS amplitude and relative acoustic impedance was done using the 3D seismic data from the study area alongside with the mapped horizons and faults are presented in below figures.

Sweetness is a seismic attribute that is very useful for channel detection. It is derived by dividing reflection strength by the square root of instantaneous frequency. Isolated sand bodies and shale successions showed stronger, broader reflections than the surrounding shale (Figure 4.8b).
Figure 4.8b: Sweetness volume attributes with Picked horizons and faults (a) Sweetness attribute

Figure 4.8c: Varaince edge volume attributes with Picked horizons and faults
The variance attribute was calculated in three dimensions and represented the trace-to-trace variability over the area of study and therefore produced interpretable lateral changes in acoustic impedance. Similar traces produce low variance coefficients, while discontinuities have high coefficients. Discontinuities caused by faults and channels where detected in the 3D seismic volumes by their high coefficients (Figure 4.8c). Variance is therefore seen as the lateral counterpart of RMS as the later indicates vertical variations.

The Root Mean Square (RMS) was used to measure the vertical variations in acoustic impedance over the study area. Generally the higher the acoustic impedance variation of stacked lithology (with bed thicknesses above the seismic resolution) the higher the RMS values will be. In the seismic section, a high RMS indicating a channel reservoir was as a result of a high acoustic impedance contrast of channel fill with the surrounding lithology (Figure 4.8d).

Relative acoustic impedance is an important attribute used for extracting thin-bed information from seismic data by calculating a series of thin-bed reflectivity (Chopra, 2009). The relative acoustic impedances for this seismic section were calculated from the thin-bed reflectivity volume, and the resultant section in (Figure 4.7d) shows the separation of sand bodies in the reservoir.
Figure 4.8d: RMS amplitude attributes with Picked horizons and faults

Figure 4.8e: Relative acoustic impedance volume attributes with Picked horizons and faults
4.8.3 Source rock potential
Potential source rocks for the hydrocarbons found in the reservoirs in the “Alpha” field were identified from several thick shale units of the TST identified in the studied wells of the field.

4.8.4 Trapping mechanisms
Trapping mechanism in Niger Delta is mostly structural, although stratigraphic traps can also be found. Some structural trapping elements including structures with multiple growth faults, structures with antithetic faults, and collapsed crest structures were found in ‘Alpha’ field. Interbedded shale within the Agbada Formation forms the primary seal rock for petroleum accumulation in the Delta. The shale provides three types of seals-clay smears along faults, interbedded sealing units against which reservoir sands are juxtaposed due to faulting, and vertical seals (Doust and Omatsola, 1990).
5.1: Sequence stratigraphic framework
A sequence stratigraphy of 6 wells was carried out integrating its well logs, seismic stratigraphy and biostratigraphy. Two major stratigraphic bounding surfaces, the maximum flooding surfaces (MFS) with ages 9.5 Ma and 10.4 Ma characterized by marker shales (Umgerna 8 and Nonon 4) were identified and correlated across several wells using the standard Niger Delta chronostratigraphic chart. High abundance and diversity of microfossils, thick and extensive shale units defined by thick high gamma-ray intervals were characteristic of Maximum Flooding Surfaces. In seismic section, the MFS’s were recognised by extensive and continuous conformable events that can be correlated from fault blocks.

5.2 Framework of depositional sequence
The Lowstand Systems Tracts (LSTs), Transgressive Systems Tracts (TSTs) and Highstand Systems Tracts (HSTs) all make up the depositional systems in the “Alpha-field”.

The LST’s represents fluvial-deltaic and shoreface sands deposited during maximum regression by deep-water gravity flows and/or traction processes within the shelf-edge or canyon head Delta. In the “Alpha-field”, sediments recognised are the Fluvial Channel Sands and Slope Fans (SF). Fluvial channel sands originate from erosion of incised canyons into slopes and fluvial valleys into the shelf. The basic feature of the Slope Fan systems are crescent log motif in levee channel units, thickening and thinning of overbank sands and fining upwards of channel sands from a sharp base.
Slope fans are formed when sea level rise associated with subsidence becomes greater than sea level fall.

The Transgressive Systems Tract (TST) developed in response to sea level rise and when sedimentation rate was not able to keep pace with the rate of sea level rise, thus marine facies retrograde landward to flood the shelf; Deltaic progradation ceases and much of the sand is trapped updip in estuaries. The MFS caps the upper boundary of the TST and characterized by faunal abundance and diversity peaks are developed near this surface. In the studied wells across ‘Alpha field’, TSTs deposited on the LST Facies were observed to be very thick and contained mainly marine shales with minor transgressive sands. Hence the shale of the TST forms the potential source rocks of the “Alpha-field”.

Sea level was falling during the development of HSTs causing fluviac and deltaic sands to prograde laterally into Neritic shales. In the studied wells, the intervals are quite thick, this may be attributed to very high rates of subsidence, high sediment input and instability similar to sediment pattern in the Gulf Coast (Winker, 1982). The HST contains upward coarsening sands with shale intercalations, this makes it the potential reservoir in “Alpha-field”.

The alternation of the HST and TST sands and shale therefore provide a combination of reservoir and seal rocks that are essential for hydrocarbon accumulation and stratigraphic trapping in the field. Moreso, the shale of TST and shale units within the HST formed the top and bottom seals for hydrocarbons in the reservoir sand. The reservoir rocks of the LST and HST and the seals from prodelta shales of the TST can combined to form stratigraphic traps for hydrocarbon accumulation in the field.
5.3 Structural framework and trapping mechanism
Structural interpretation of the Alpha field revealed the presence of growth fault, antithetic faults, collapsed crest structures, rollover anticlines and crestal faults which served as path ways for upward migration of hydrocarbon and constituted the major traps for hydrocarbon accumulation.

5.4: Seismic attributes analysis
Sweetness attribute analysis was carried out to identify and map ‘sweet spots’ on the seismic section. High regions of sweetness within the seismic data indicated high amplitude and low frequency of hydrocarbon bearing sand units. Sweetness attribute (Figure 4.8b) is effective for detecting channel characterization of gas charged bearing sand units. The variance edge seismic attribute correlated wells with faults and fractures within the study area. Faults signatures were enhanced through calculating the variance within the seismic data volume with an edge enhancement option, thereby enabling the mapping across discontinuities within the data (Figure 4.8c).

The attributes were able to demonstrate the prediction of lithology within the reservoir layers by extracting seismic attributes from the 3D seismic data. Bright spots appeared across the seismic data indicating the porosity of the delineated reservoir sand units (Figure 4.8d). Similarly the acoustic impedance attributes (Figure 4.8e), which depends significantly on the velocity, density and seismic reflection across the interface of two acoustically different media.
5.5: Reservoir potential of the alpha field
The Niger Delta basin where the “Alpha-field” is located is known for its hydrocarbon potentials. Several oil and gas fields have been discovered in the study area with appreciable production history. Potential reservoirs were delineated in the field, they were mainly the channel sands and shoreface sands of LSTs and HSTs, respectively. They displayed low Gamma Ray and high Resistivity values. (Figure 4.4b). A number of faults cutting through the reservoir sand units were identified and mapped on the variance edge seismic attributes (Figure 4.7b). These faults structured in various ways formed trapping mechanism resulting to probable hydrocarbon prospects in the field.

5.6: Conclusion
Sequence stratigraphic studies of nine (6) wells in the Alpha field of the eastern coastal swamp of the Niger Delta were carried out using well logs, biostratigraphy and seismic data all integrated with sequence stratigraphic tool which provided a rare opportunity to the mapping and interpretation of depositional sequences and systems tracts, reservoirs and mapping of faults.

The vertical succession of depositional facies revealed a three third order depositional sequences of mid-Miocene age bounded chronologically by 9.5 and 10.4 Ma MFS using the genetic sequence stratigraphic model. The depositional sequences experienced major flooding episodes characterized by high faunal population and diversity. The lowermost sections of each sequence characterised low sea level deposits forming channels and slopes. The second and middle sequence is a complete cycle of HST and TST deposits. The third and topmost sequence was deposited when the Highstands began to drop gradually.
The sand units of the LST and HST formed the basin floor fans, channel and shoreface sands of the Delta and their high resistivity log values revealed that they are potential hydrocarbon reservoirs. The shales of the TST from which the MFS was delineated are potential seal rocks of the reservoir units. A stratigraphic trap that should be targeted for hydrocarbon exploration arises from the combination of the reservoir sands of the LST and HST and the shale units of the TST.

Total depositional environments in the study area spans through incised Canyons and channels, Inner Mid Shelf, Shelf Margin and Slope Margin.

Trap structures were identified with the aid of mapped faults. Such structures include simple/faulted rollovers, collapse crest structures, hanging walls and sub-detachment structures. The structural framework of the study area reveals that structural deformation to a large extent determined the stratigraphy of the area.

Seismic attributes within provided good information about the mapped reservoirs and identified structural traps towards a better delineation of hydrocarbon prospects and improved reservoir characterization. It has been further demonstrated that seismic attributes are complementary to the information derived through traditional methods of seismic interpretation. Extraction of seismic attributes from seismic data brought new information and insights into stratigraphic and structural interpretations. The outcome from seismic attributes extraction and analysis will help greatly in reducing exploration and development risk.

The “Alpha-field” has a high prospect for hydrocarbon exploration.
5.7: Contribution to knowledge

In addition to the regular and traditional method of seismic interpretation, I applied some advanced seismic attributes which are rarely used. None had I observed among the literatures in my study area. Seismic attributes such as sweetness attribute, variance edge attribute, RMS amplitude attribute and relative acoustic impedance amplitude gave further insights to structural and stratigraphic interpretations. They assisted in a finer and detailed delineation of hydrocarbon leads and prospects thus greatly reducing exploration / development risk and cost.
RECOMMENDATION

A more intensive analysis and interpretation should be carried out in surfaces and structures at deeper horizons to improve seismic data quality. Sweetness attribute is less effective when the acoustic impedance contrast between shale and sand units are low; and when both lithologic units are highly inter bedded, hence a more effective seismic analysis is required.
REFERENCES


