SEDIMENTOLOGICAL AND BIOSTRATIGRAPHICAL STUDY OF WELL X-1 AND ITS IMPLICATIONS FOR HYDROCARBON POTENTIAL IN THE GREATER UGHELLI DEPOBELT, NIGER DELTA BASIN, SOUTHERN NIGERIA

BY

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A PROJECT WORK SUBMITTED TO THE

DEPARTMENT OF GEOLOGY,

FACULTY OF PHYSICAL SCIENCES

UNIVERSITY OF BENIN,

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DEDICATION

This work is devoted to **God Almighty**, the eternal source of my strength, wisdom, and inspiration.

It is also dedicated, with deepest love and gratitude, to my beloved parents, whose immense sacrifices and constant, unwavering encouragement were the foundation of this academic pursuit.

Finally, I dedicate this project to all those who believed in me and provided support throughout my educational journey.

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ABSTRACT

This study examines the sedimentological and biostratigraphical characteristics of Well X-1 in the Greater Ughelli Depobelt of the Niger Delta Basin, Southern Nigeria, in order to determine the age, depositional environment, and hydrocarbon potential of the penetrated strata. Seventy two ditch cutting samples collected between 4500 ft and 11460 ft were analyzed using reflected light microscopy to document lithology, grain size, sorting, and other sedimentological attributes. Four main lithofacies were identified. These are sandstone, shale, sandy shale, and shaly sand. Forty nine lithozones were delineated and used to interpret the vertical depositional succession. The sandstone and sandy shale units form a continuous reservoir interval between 5340 ft and 7260 ft, while the thick shale units below 7860 ft represent the probable source rock. A shale dominated interval above 4740 ft was interpreted as the seal or cap rock. Biostratigraphical interpretation using foraminiferal biofacies, F zone data, P zone data, and the Niger Delta chronostratigraphic chart revealed five maximum flooding surfaces at 6265 ft, 6688 ft, 7247 ft, 7771 ft, and 10280 ft, together with eight sequence boundaries occurring between 5899 ft and 10602 ft. These surfaces correspond to ages ranging from the Aquitanian to the Chattian. Foraminiferal abundance patterns show a dominance of calcareous benthonic species, which indicates deposition in a shelf environment. The alignment of the Bolivina 27 shale marker at 28.1 Ma with the basal shale supports its interpretation as the source rock interval. The combination of sedimentological and biostratigraphical evidence confirms the presence of the essential elements of a petroleum system, with favourable timing for hydrocarbon generation, migration, and entrapment.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Petroleum exploration remains an important global activity due to the increasing demand for energy, industrial development, and population growth. Although renewable energy technologies are expanding, fossil fuels continue to dominate global energy consumption because they are more reliable, accessible, and able to support large scale industrial processes. Crude oil and natural gas remain especially important for transportation, petrochemical production, and electricity generation. This continuous reliance on hydrocarbons makes the evaluation of sedimentary basins critical for identifying and developing new reserves.

The Niger Delta Basin of Southern Nigeria is one of the most prolific hydrocarbon provinces in Africa. It contains significant reserves of oil and gas that have been commercially exploited for several decades. The basin developed as a result of the interplay between sediment supply from major rivers, subsidence, and structural deformation during the Cenozoic period (Short and Stauble, 1967). Its complex stratigraphy, structural features, and depositional environments make it an important region for geological and petroleum studies.

Understanding subsurface geology is essential for successful hydrocarbon exploration. Sedimentology provides insight into lithofacies distribution, reservoir properties, and depositional processes. Biostratigraphy, which involves the study of foraminifera, palynomorphs, and other microfossils, provides age control, correlation of subsurface units, identification of maximum flooding surfaces, and reconstruction of paleoenvironments (Petters, 1982; Ozumba, 1995; Okosun and Liebau, 1999).

The petroleum system concept forms the basis for understanding how hydrocarbons are generated, migrated, accumulated, and preserved. A functioning petroleum system requires a mature source rock, a porous and permeable reservoir rock, an effective seal, and a trapping mechanism, all occurring within a favourable thermal history (Magoon and Dow, 1994). The Niger Delta contains these elements, particularly within the Agbada and Akata Formations, which are known to host important source, reservoir, and seal rocks (Doust and Omatsola, 1990; Evamy et al., 1978).

This study focuses on Well X-1 in the Greater Ughelli Depobelt of the Niger Delta Basin. By analysing the sedimentological and biostratigraphical characteristics of ditch cutting samples, the study reconstructs the depositional environment, establishes the age of the penetrated sediments, identifies stratigraphic surfaces, and evaluates the hydrocarbon potential of the well. This provides insight into the geological framework of the area and contributes to ongoing regional exploration efforts.

1.2 Aim and Objectives

Aim

The aim of this study is to determine the age, depositional environment, and hydrocarbon potential of sediments penetrated by Well X-1 using sedimentological and biostratigraphical analysis.

Objectives

The objectives of this study are to:

1. Describe the lithology and sedimentological features of ditch cutting samples from Well X-1.
2. Identify lithofacies and interpret their depositional significance.

3. Establish lithozones and recognise vertical facies successions.
4. Identify probable reservoir, source, and seal rock intervals.
5. Use foraminiferal and palynological evidence to determine the age of the sediments.
6. Interpret stratigraphic surfaces such as maximum flooding surfaces and sequence boundaries.
7. Reconstruct the depositional environment of the penetrated interval.
8. Evaluate the petroleum system implications of the well.

1.3 Location of the Study Area

Well X-1 is located in the Greater Ughelli Depobelt of the Niger Delta Basin in Southern Nigeria. The Niger Delta extends across approximately 300,000 square kilometres and lies between latitudes 4° and 6° N and longitudes 5° and 8° E. The basin consists of several depobelts formed by the progressive seaward progradation of the delta during the Cenozoic (Short and Stauble, 1967). The Greater Ughelli Depobelt is structurally complex and is characterised by growth faults, rollover anticlines, and fault-assisted closures that influence reservoir distribution and hydrocarbon accumulation (Doust and Omatsola, 1990).

The exact location of Well X-1 within the depobelt is shown in **Figure 1**, which illustrates the regional map of the Niger Delta and highlights the study area.

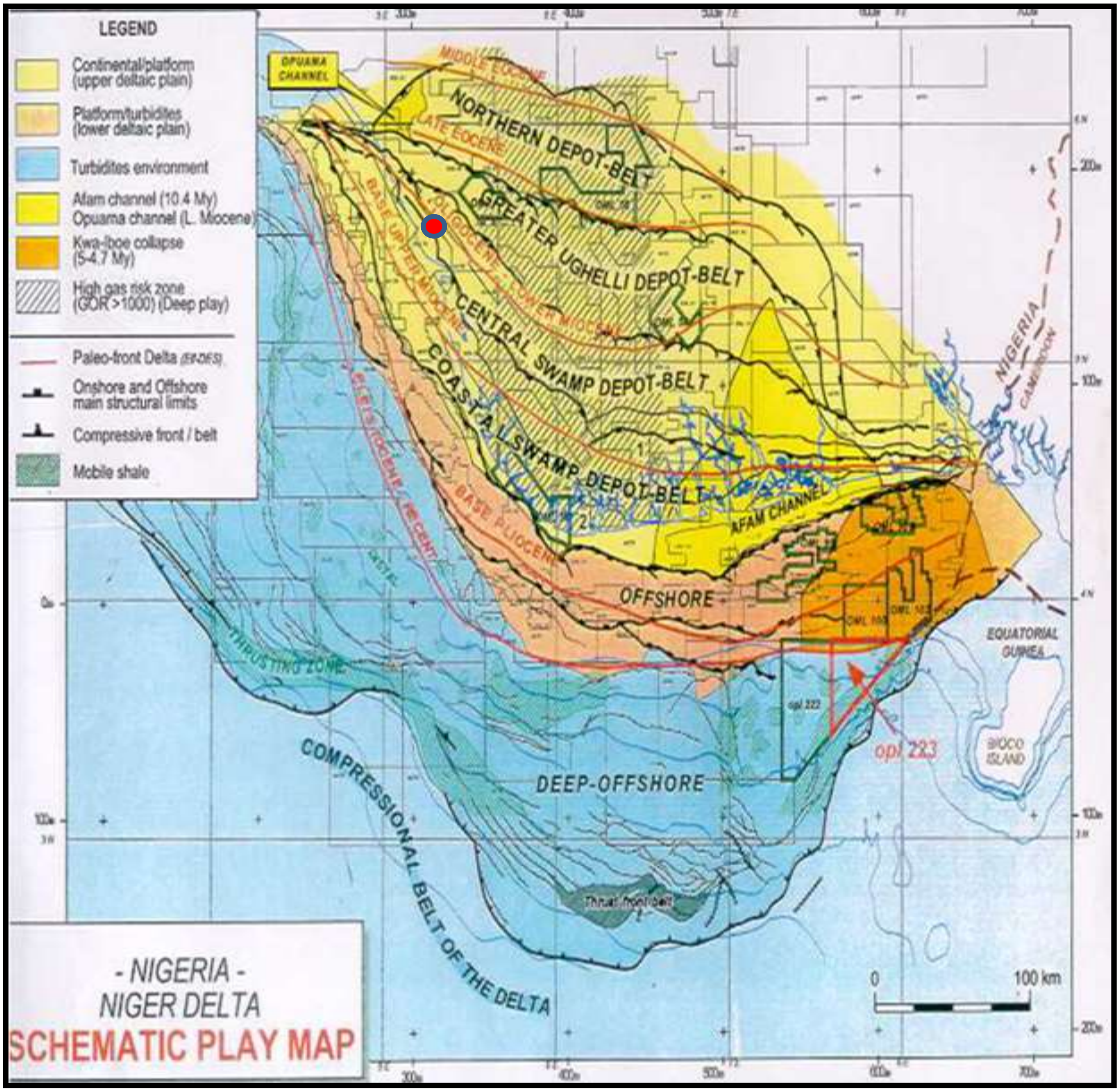


Figure 1: Map of the Niger Delta Showing the Location of the Study Area (Nwozor et al., 2019)

1.4 Geological Setting of the Niger Delta Basin

The Niger Delta Basin is a large clastic wedge developed along the passive margin of West Africa. The basin formed during the breakup of the South American and African plates in the Late Jurassic to Cretaceous. Subsequent subsidence and high sediment supply during the Paleogene and Neogene led to the accumulation of a thick sedimentary sequence exceeding 12 km in some areas (Doust and Omatsola, 1990).

Sedimentation was controlled by fluvial discharge, coastal processes, and marine transgressions. The basin is divided into structural belts known as depobelts, each reflecting a phase of delta progradation. These include the Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp, and Offshore depobelts (Knox and Omatsola, 1989). Growth faults dominate the structural framework, and these faults have created numerous traps associated with rollover anticlines, fault closures, and stratigraphic pinch outs.

Marine transgressions produced widespread maximum flooding surfaces that are important for biostratigraphical correlation and sequence stratigraphic interpretation. These surfaces also serve as markers for dividing the sedimentary record into systems tracts.

1.5 Stratigraphy of the Niger Delta

The stratigraphy of the Niger Delta is divided into three major formations (Short and Stauble, 1967):

1.5.1 Akata Formation

- Paleogene in age
- Composed mainly of dark grey to black shales
- Recognised as the primary source rock
- Deposited in marine environments

1.5.2 Agbada Formation

Eocene to Pliocene

Alternating sandstones and shales

Represents the primary reservoir and seal units

Deposited in delta front, distributary channel, and marine settings

1.5.3 Benin Formation

Oligocene to Recent

Predominantly continental sands

Deposited in alluvial and coastal plain environments

This stratigraphic framework provides the foundation for understanding the subsurface geology of Well X-1 and interpreting its hydrocarbon potential.

1.6 Scope of the Study

The study involves sedimentological and biostratigraphical analysis of ditch cutting samples from Well X-1. It includes:

i. Lithological description
ii. Lithofacies interpretation
iii. Lithozonation
iv. Biostratigraphy (foraminifera and palynology)
v. Age determination
vi. Paleoenvironmental interpretation
vii. Identification of stratigraphic surfaces
viii. Petroleum system evaluation

1.7 Justification of the Study

Understanding the geological characteristics of wells in the Niger Delta is important for petroleum exploration. Sedimentological analysis helps in predicting reservoir quality, thickness, and continuity. Biostratigraphy provides reliable age models and paleoenvironmental information required for correlation and basin analysis. The results from this study will improve geological knowledge of the Greater Ughelli Depobelt and support future exploration and development activities in the region.

CHAPTER TWO

GEOLOGICAL SETTING AND LITERATURE REVIEW

2.1 Literature Review

2.1.1 Introduction to the Literature Review

A literature review provides a synthesis of existing knowledge relevant to the topic of a study. It examines published work, identifies established concepts, highlights methodological approaches, and discusses research findings that inform the current investigation. In subsurface geological studies, the literature review helps to clarify how previous researchers have interpreted lithofacies, depositional environments, stratigraphic surfaces, and microfossil assemblages.

The Niger Delta Basin has been extensively studied by several authors, including Short and Stauble (1967), Weber and Daukoru (1975), Evamy et al. (1978), Petters (1982), and Reijers (2011). Their work provides the scientific foundation needed for analysing wells within the region. These studies also highlight the importance of integrating sedimentological and biostratigraphical methods when reconstructing depositional settings and determining the hydrocarbon potential of subsurface units.

This literature review is therefore organised into subsections that address key themes relevant to the present study, including sedimentology, lithofacies and facies models, biostratigraphy, zonation schemes, sequence stratigraphy, and petroleum system studies. The reviewed literature provides a background understanding that supports the interpretation of the sediments encountered in Well X-1.

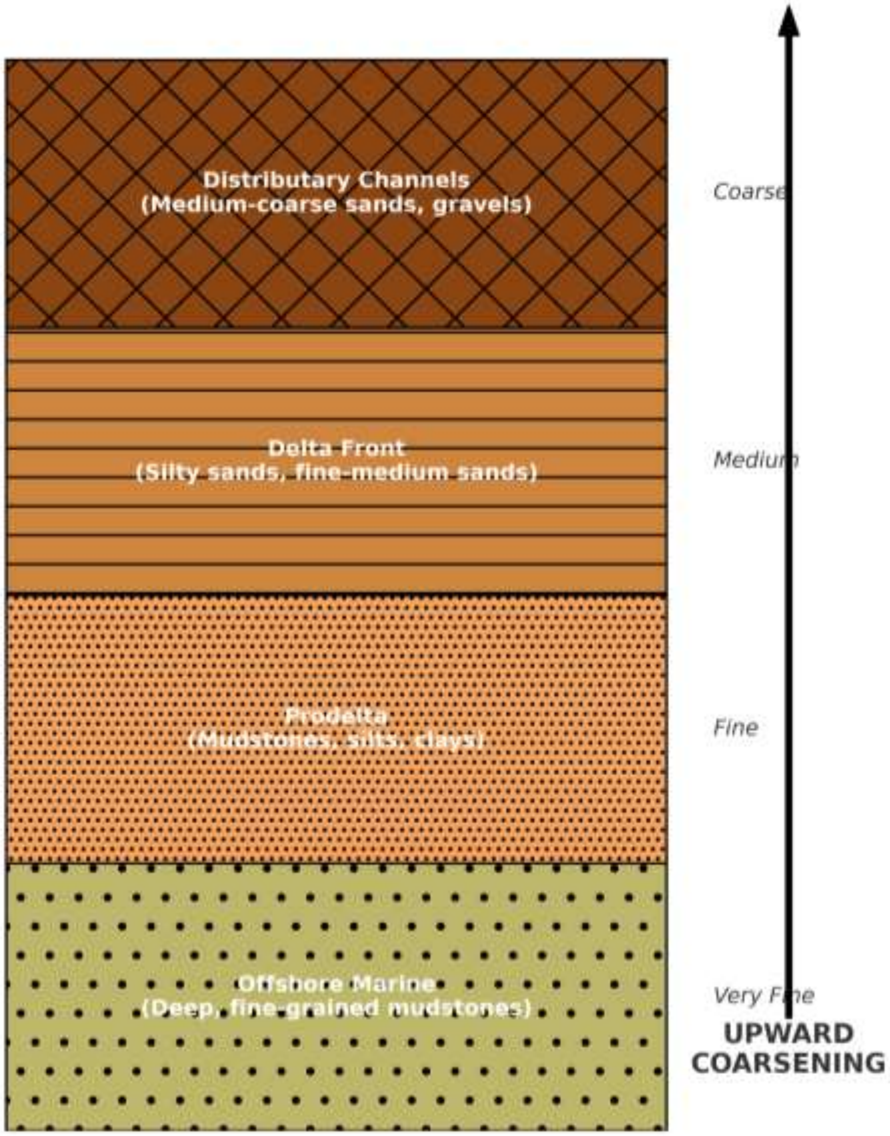
2.1.2 Overview of Sedimentology

Sedimentology is the study of sediments and sedimentary rocks, focusing on their origin, transport, deposition, and post-depositional modification. It is a fundamental tool in reconstructing past depositional environments and understanding reservoir behaviour in sedimentary basins. Tucker (2001) noted that sediments record physical attributes such as grain size, sorting, roundness, colour, and sedimentary structures, which reflect the environmental conditions in which they were deposited.

Sedimentary structures such as ripple marks, laminations, graded bedding, and cross-bedding provide important clues about flow direction, depositional energy, and sedimentation mechanisms (Selley, 1985). Dott (1964) emphasised that grain size and sorting reflect the transporting medium and energy conditions, while Reijers (2011) highlighted the importance of vertical facies successions for interpreting cyclic sedimentation patterns in paralic settings.

In the Niger Delta, sedimentology guides the interpretation of stacked sand and shale sequences that reflect shifts between prodelta, delta-front, and distributary channel environments. Weber and Daukoru (1975) demonstrated that many reservoir sands in the Niger Delta occur within upward-coarsening sequences that represent shoreline progradation. These cycles are common in wells drilled within the Greater Ughelli Depobelt and are directly relevant to the sediments encountered in Well X-1.

Deltaic depositional systems typically display a vertical facies pattern that fines downward, transitioning from distributary channel sands to delta-front silty sands and prodelta mudstones. This characteristic upward-coarsening sequence is illustrated in **Figure 2.**



Modified after Tucker (2001).

Figure 2: Conceptual deltaic depositional model showing upward-coarsening succession typical of deltaic environments (Modified after Tucker, 2001).

This vertical trend has significant petroleum implications because coarser upper intervals generally form better reservoir targets, while finer lower intervals may act as seals or baffles to fluid flow.

The key sedimentological indicators used for interpreting depositional environments in this study are summarised in Table 1.

Table 1: Key sedimentological characteristics and their environmental significance

Sedimentary Feature	Interpretation	Reference
Grain size variation	Reflects depositional energy gradients	Tucker (2001)
Sorting and roundness	Indicates transport mechanism and duration	Dott (1964)
Ripple marks and laminations	Evidence of shallow-water or tidal deposition	Selley (1985)
Cross-bedding and foresets	Suggest channelised or directional flow	Reijers (2011)
Alternation of sand and shale	Indicates cyclic sea-level changes or progradation	Weber and Daukoru (1975)

These sedimentological principles form the basis for analysing the ditch cutting samples from Well X-1 and help establish the depositional framework of the study area.

2.1.3 Lithofacies and Facies Models

Lithofacies represent bodies of rock distinguished by their physical, mineralogical, and sometimes biological characteristics. They reflect the conditions under which sediments were deposited and therefore serve as fundamental tools for reconstructing depositional environments. According to Reading and Collinson (1996), a lithofacies can be identified based on observable properties such as grain size, sedimentary structures, colour, mineral composition, bedding style, and fossil content. These characteristics allow geologists to classify sedimentary units into groups that share common depositional processes.

In petroleum geology, lithofacies analysis helps determine reservoir quality because facies influence porosity, permeability, and fluid flow pathways. Selley (1985) noted that sand-dominated facies with good sorting typically form high-quality reservoirs, while shale-rich facies function as seals or barriers to fluid migration. Within deltaic settings such as the Niger Delta, lithofacies commonly occur in stacked successions that reflect fluctuations in fluvial input, tidal influence, and marine processes.

A facies model is a conceptual representation of how different lithofacies are arranged within a depositional system. It explains spatial relationships between sediments deposited in proximal and distal positions within ancient environments. Facies models help predict the lateral and vertical extent of reservoirs and their sealing units. Walker (1990) described facies models as essential interpretative tools that support sequence stratigraphy and reservoir characterisation.

In the Niger Delta, facies models are typically based on deltaic progradation. Weber and Daukoru (1975) recognised three broad facies belts: the continental delta-top facies, the paralic delta-front facies, and the prodelta marine facies. These belts reflect a general upward-coarsening trend where deeper marine mudstones grade into silts and sands of the delta front, and then into coarser distributary channel sands. This arrangement is consistent with the conceptual model shown in Figure 2.

Lithofacies in deltaic environments commonly include mouth bars, distributary channels, levees, shoreface sands, tidal flats, and lagoonal muds. Each facies type exhibits distinctive features. Distributary channel sands contain cross-bedding, medium to coarse grain sizes, and sharp basal contacts, while delta-front sediments show finer grain sizes, laminations, and occasional wave-influenced structures (Reijers, 2011). Prodelta facies are dominated by clay-rich sediments with low fossil diversity, reflecting deposition in deeper, low-energy settings. A summary of these common deltaic lithofacies and their attributes is presented in Table 2.

These facies relationships are important for interpreting Well X-1. Alternations of shale and sandstone within the well can represent repeated shifts between prodelta, delta-front, and channel environments. Such cyclicity reflects changes in relative sea level and sediment supply, which are common in the Greater Ughelli Depobelt. Lithofacies analysis therefore provides a framework for identifying reservoir zones, potential sealing intervals, and depositional trends observed in ditch cutting samples.

Table 2: Summary of Common Deltaic Lithofacies and Their Characteristics

Lithofacies	**Key Characteristics**	**Typical Depositional Setting**	**Reference**
Distributary Channel Sands	Medium to coarse grains, cross-bedding, erosive bases	Channelised fluvial or tidal flow	Weber and Daukoru (1975)
Mouth Bar Sands	Fine to medium sands, upward-coarsening, bi-directional structures	Zone of flow deceleration at river mouth	Reading and Collinson (1996)
Delta Front Silts and Sands	Fine sand to silt, laminations, wave-influenced structures	Moderately energetic shallow marine	Reijers (2011)
Prodelta Clays	Very fine-grained mudstone, low fossil diversity, massive bedding	Low-energy offshore or deeper water	Selley (1985)
Tidal Flat Mudstones	Mud drapes, flaser and wavy bedding	Tidal influence, brackish zones	Walker (1990)

2.1.4 Biostratigraphy

Biostratigraphy is the branch of stratigraphy that uses fossil content to establish the relative ages of rock units and interpret past depositional environments. It is based on the principle that fossil organisms have evolved through time and are preserved in sedimentary strata in a predictable order. According to Petters (1982), the distribution of microfossils such as foraminifera and palynomorphs provides an effective means of subdividing sedimentary sequences into biostratigraphic zones that help in age determination and correlation.

In petroleum geology, biostratigraphy plays a crucial role in well correlation, sequence stratigraphy, paleoenvironmental reconstruction, and identifying key stratigraphic surfaces. Microfossil groups commonly used in biostratigraphy include foraminifera, pollen and spores, nannofossils, and ostracods. These fossils respond sensitively to changes in salinity, temperature, water depth, and sedimentation rate, which makes them valuable indicators of paleoenvironmental conditions (Reijers, 2011).

The Niger Delta Basin contains abundant and diverse microfossils because it developed within a tropical delta system with a wide range of marine, marginal marine, and delta plain environments. Evamy et al. (1978) established a widely used biozonation scheme for the Niger Delta based on planktic and benthic foraminifera. This zonation provides important age markers from the Paleocene to the Recent and is routinely applied in hydrocarbon exploration and well evaluation.

Biostratigraphic studies in the Niger Delta involve identifying the first appearance, last appearance, abundance peaks, and turnover events of key species. These markers are used to delineate biozones, correlate stratigraphic intervals across wells, and interpret paleoenvironmental changes. For example, the presence of *Bolivina*, *Uvigerina*, and *Cibicides* species often indicates marine to marginal marine settings, while terrestrial palynomorphs such as *Monoporites annulatus* and *Zonocostites ramonae* suggest proximity to continental sources (Petters, 1982).

Biostratigraphy also supports sequence stratigraphy by helping identify maximum flooding surfaces (MFS), transgressive surfaces, and condensed sections. Maximum flooding intervals typically contain abundant planktic foraminifera, high-diversity assemblages, and well-preserved palynomorphs (Reijers, 2011). These intervals are essential for correlating stratigraphic sequences across different depobelts of the Niger Delta.

In this study, biostratigraphy is important for determining the age of the intervals encountered in Well X-1 and for establishing the relationship between lithological changes and depositional environments. The integration of foraminiferal and palynological data, combined with sedimentological observations, improves the accuracy of stratigraphic interpretation and enhances understanding of the depositional history of the Greater Ughelli Depobelt.

2.1.5 Foraminiferal Zonation in the Niger Delta

Foraminifera are among the most important microfossils used in biostratigraphic studies of the Niger Delta. They occur abundantly in marine and marginal marine sediments and respond sensitively to changes in salinity, temperature, water depth, and oxygen conditions. Their stratigraphic distribution makes them ideal for establishing biostratigraphic zones, correlating wells, and interpreting depositional environments.

The most widely used foraminiferal zonation scheme for the Niger Delta was developed by Evamy et al. (1978). This scheme covers the Paleocene to Recent succession and is based on the first appearance, last appearance, and abundance peaks of key planktic and benthic foraminiferal species. The zonation includes major planktic taxa such as *Globorotalia*, *Globigerina*, and *Globigerinoides*, as well as benthic forms such as *Bolivina*, *Bulimina*, *Uvigerina*, *Alabamina*, and *Cibicides*. These species help identify important stratigraphic intervals, including maximum flooding surfaces, condensed sections, and transgressive phases.

Planktic foraminifera are generally used for regional and inter-well correlation because they have a wider geographic distribution and faster evolutionary rates. Benthic foraminifera, on the other hand, are more sensitive to local environmental conditions and help reconstruct paleo-water depths and depositional settings (Petters, 1982). For example, species such as *Bolivina imperialis* and *Uvigerina peregrina* often indicate deeper marine, oxygen-poor environments, while *Ammonia beccarii* and *Elphidium* species suggest shallow, marginal marine conditions (Reijers, 2011).

The Niger Delta foraminiferal zones are closely linked to sequence stratigraphy. Maximum flooding surfaces (MFS) in particular are marked by high-diversity planktic assemblages and increased abundance of deep-marine benthic forms. Evamy et al. (1978) identified several key MFS that serve as regional markers across the delta. These include MFS 24, MFS 23, and MFS 22 (Miocene), which are used extensively in correlating wells in the Greater Ughelli Depobelt.

In subsurface studies, the identification of foraminiferal zones assists in determining the geological age of well intervals, correlating units across different depobelts, and distinguishing between marine and marginal marine facies. The application of this zonation scheme is particularly useful for Well X-1 because the presence or absence of diagnostic foraminiferal species provides important constraints on the depositional environment and age of the sediments encountered.

The integration of foraminiferal zonation with lithological and sedimentological observations enhances the reliability of stratigraphic interpretation. This combined approach supports accurate correlation, improved identification of key stratigraphic surfaces, and better reconstruction of the depositional history of the Niger Delta Basin.

2.1.6 Palynological Zonation in the Niger Delta

Palynology involves the study of pollen, spores, dinoflagellate cysts, and other acid-resistant organic microfossils preserved in sedimentary rocks. These microfossils are highly valuable in biostratigraphy because they occur abundantly in coastal and deltaic environments, have wide geographic distribution, and often show rapid evolutionary changes through time. Palynological analysis is therefore widely applied in the Niger Delta for age dating, correlation, and paleoenvironmental reconstruction (Petters, 1982).

The most widely used palynological zonation framework in the Niger Delta is the one developed by Evamy et al. (1978). This scheme divides the Tertiary succession into palynological zones based on the first and last appearances, abundance peaks, and evolutionary changes of key pollen, spores, and dinocysts. Important marker species include *Zonocostites ramonae*, *Monoporites annulatus*, *Retitricolporites irregularis*, *Psilatricolporites crassus*, *Proxapertites cursus*, *Echitriporites trianguliformis*, and several others that reflect terrestrial-to-marginal marine environments.

Palynological assemblages are sensitive indicators of climatic conditions and vegetation patterns. High proportions of mangrove pollen such as *Zonocostites ramonae* generally reflect deposition in brackish-water or marginal marine settings, whereas terrestrial rainforest taxa such as *Monoporites annulatus* and *Retitricolporites* species are associated with fluvial or delta plain environments (Reijers, 2011). Dinoflagellate cysts such as *Achomosphaera*, *Spiniferites*, and *Operculodinium* indicate marine influence and are often abundant in maximum flooding intervals.

Evamy et al. (1978) recognised several key palynological zones spanning the Paleocene to Recent, each defined by diagnostic species. These zones are widely used in petroleum exploration to identify maximum flooding surfaces (MFS), which serve as regional stratigraphic markers across the Niger Delta. Maximum flooding intervals often contain high-diversity assemblages, increased dinocyst abundance, and well-preserved spores and pollen, which make them easily recognisable during well analysis.

Palynological zonation is particularly useful in wells where foraminifera are scarce or poorly preserved. It complements foraminiferal zonation by providing age control in marginal marine or delta plain intervals where calcareous microfossils may be absent. The technique is therefore essential for interpreting the sediments of Well X-1, especially in intervals characterised by shale or clay-rich facies where palynomorph preservation is typically good.

Palynology also supports paleoenvironmental interpretation. The relative abundance of marine dinocysts versus terrestrial pollen provides clues about water depth, salinity, sediment supply, and proximity to shoreline systems. Thus, when integrated with lithofacies analysis and foraminiferal data, palynological zonation enhances the accuracy of depositional environment reconstruction and improves stratigraphic correlation within the Greater Ughelli Depobelt.

2.1.7 Sequence Stratigraphy Concepts

Sequence stratigraphy is the study of sedimentary strata and their arrangement in time and space based on changes in relative sea level, sediment supply, and accommodation space. It provides a framework for correlating stratigraphic units, interpreting depositional environments, and identifying key surfaces that record major shifts in basin conditions. The approach integrates sedimentology, biostratigraphy, and seismic stratigraphy, making it a powerful tool in petroleum geology (Catuneanu, 2006).

A sequence is defined as a succession of genetically related strata bounded above and below by unconformities or their correlative conformities. These bounding surfaces are formed in response to relative sea-level changes, which influence the distribution of sediments across a basin. Vail et al. (1977) introduced the concept of systems tracts within sequences, each representing a particular phase of sea-level fluctuations. The main systems tracts include the Lowstand Systems

Tract (LST), Transgressive Systems Tract (TST), and Highstand Systems Tract (HST). Each system tract has characteristic facies, stacking patterns, and depositional features.

The **Lowstand Systems Tract (LST)** is deposited when sea level is relatively low. Sediments tend to be coarse-grained and deposited in more basinward positions. Channelised sands, basin-floor fans, and early delta progradation typically belong to this systems tract. Such deposits often have good reservoir potential due to their high porosity and permeability (Catuneanu, 2006).

The **Transgressive Systems Tract (TST)** forms when sea level rises and landward shoreline migration occurs. Finer-grained sediments are deposited as marine conditions deepen. Maximum flooding surfaces (MFS) occur at the peak of transgression and represent the deepest water conditions. These surfaces are highly useful for correlation because they contain condensed sections and diverse fossil assemblages, especially planktic foraminifera and marine dinocysts (Reijers, 2011).

The **Highstand Systems Tract (HST)** develops when sea level stabilises or rises slowly. Sediment supply typically outpaces the creation of accommodation space, leading to progradation. HST deposits often show upward-coarsening patterns and form major reservoir units in deltaic settings. In the Niger Delta, many stacked channel sands and delta-front facies belong to the highstand phase (Weber and Daukoru, 1975).

Sequence stratigraphy is important in the Niger Delta because the basin is strongly influenced by repeated cycles of relative sea-level change and sediment supply. These cycles produce characteristic vertical facies successions that can be observed in wells and outcrops. Maximum flooding surfaces such as MFS 24, MFS 23, and MFS 22 serve as key regional markers for correlating stratigraphic intervals across the various depobelts (Evamy et al., 1978).

In well studies, sequence stratigraphy assists in identifying depositional trends, predicting reservoir distribution, and recognising stratigraphic traps. The alternations of sand and shale observed in Well X-1 likely correspond to successive highstand and transgressive phases, with shale intervals representing flooding events and sand intervals representing regressive or progradational phases. Integrating sequence stratigraphy with sedimentology and biostratigraphy therefore enhances the interpretation of depositional environments and stratigraphic architecture within the Greater Ughelli Depobelt.

2.1.8 Petroleum System Studies in the Niger Delta

Petroleum system studies focus on understanding the geological factors responsible for the generation, migration, accumulation, and preservation of hydrocarbons within a basin. These factors include source rocks, reservoir rocks, seals, traps, timing of hydrocarbon generation, and the geodynamic processes that control basin evolution. Magoon and Dow (1994) defined a petroleum system as a natural, geologically based system that encompasses all essential elements and processes required to form and preserve hydrocarbon accumulations.

In the Niger Delta, extensive petroleum system research has established that the basin contains a single major petroleum system known as the Tertiary Niger Delta (Akata–Agbada) Petroleum System (Doust and Omatsola, 1990). This system consists of three primary lithostratigraphic units:

1. **Akata Formation**, which serves as the main source rock
2. **Agbada Formation**, the primary reservoir–seal complex
3. **Benin Formation**, which forms the overlying continental sands

Akata Formation comprises thick marine shales deposited in deep, low-energy environments. These shales are rich in organic matter and are thermally mature at depth, making them effective source rocks for generating oil and gas (Evamy et al., 1978). Under increasing burial and temperature, organic-rich shales expel hydrocarbons that migrate upward into the overlying Agbada Formation.

Agbada Formation contains alternating sandstone and shale units deposited in delta-front and delta-top environments. The sandstones serve as reservoirs due to their good porosity and permeability, while the shales function as seals that trap hydrocarbons within structural or stratigraphic traps. Growth faults, rollover anticlines, and fault-assisted closures are common trapping mechanisms in the Niger Delta (Weber and Daukoru, 1975).

Benin Formation consists mainly of unconsolidated continental sands deposited in fluvial environments. While it rarely serves as a reservoir for major hydrocarbon accumulations, it contributes to the overburden necessary for thermally maturing the underlying source rocks (Reijers, 2011).

Hydrocarbon migration in the Niger Delta is strongly influenced by synsedimentary faulting associated with delta progradation and shale mobility. Fault-assisted pathways allow hydrocarbons to move vertically and laterally into reservoir units within the Agbada Formation. Doust and Omatsola (1990) emphasised that migration pathways often align with major growth faults that formed during the accumulation of the delta’s thick sedimentary pile.

Timing is a critical factor in petroleum system studies. Hydrocarbon generation in the Niger Delta began in the Miocene and continued into the recent geological past, coinciding with the development of traps and sealing units (Stacher, 1995). This favourable overlap of elements and processes has contributed to the formation of numerous prolific oil and gas fields across the basin.

Petroleum system studies also aid in predicting reservoir distribution, estimating hydrocarbon potential, and reducing exploration risk. For Well X-1, understanding the Akata–Agbada Petroleum System provides context for interpreting reservoir quality, source potential, and the likelihood of hydrocarbon presence within the studied interval. Integrating this knowledge with sedimentological and biostratigraphical evidence improves the reliability of the overall geological interpretation.

2.1.9 Previous Studies on the Greater Ughelli Depobelt

The Greater Ughelli Depobelt is one of the most productive petroleum depobelts in the Niger Delta, known for its thick sediment accumulations, well-developed growth faults, and high-quality reservoir sands. Numerous geological studies have been carried out in this region to understand its stratigraphy, depositional patterns, hydrocarbon prospectivity, and structural framework.

Reijers (2011) described the Greater Ughelli Depobelt as a zone characterised by rapid sedimentation and vigorous syndepositional faulting, which resulted in the formation of rollover anticlines and fault-assisted traps. These structural features have played a significant role in hydrocarbon entrapment across the depobelt. Doust and Omatsola (1990) also noted that the depobelt contains a combination of structural and stratigraphic traps that formed during the progressive seaward progradation of the Niger Delta.

Weber and Daukoru (1975) conducted one of the earliest detailed studies on reservoir properties within the depobelt. Their work demonstrated that the alternation of sand and shale reflects cyclic depositional processes linked to delta-front and distributary channel environments. They reported that the reservoir sands often exhibit good porosity and permeability, making them highly favourable for hydrocarbon accumulation.

Biostratigraphic studies in the depobelt, including those by Evamy et al. (1978), Petters (1982), and Stacher (1995), provided detailed frameworks for age dating and correlation across wells. These studies showed that maximum flooding surfaces such as MFS 24, MFS 23, and MFS 22 serve as reliable markers for correlating stratigraphic intervals within the depobelt. Such surfaces are particularly useful for reconstructing depositional sequences and identifying transgressive–regressive cycles.

Several palynological studies have also been conducted in the region. These include analysis of pollen and spores to infer paleoenvironmental conditions and identify delta plain, marginal marine, and nearshore environments. Researchers such as Oboh-Ikuenobe and Yepes (1997) demonstrated the usefulness of palynology in distinguishing between marine and non-marine intervals, particularly in areas where foraminiferal preservation is poor.

Recent studies have focused on integrating sedimentology, biostratigraphy, and sequence stratigraphy for reservoir characterisation. Otobo et al. (2015) and Omosanya et al. (2017) applied combined analytical approaches to identify reservoir quality trends, depositional cycles, and potential hydrocarbon-bearing intervals. Their work emphasises the importance of multidisciplinary analysis in understanding reservoir heterogeneity in the Greater Ughelli Depobelt.

These previous studies form the scientific foundation for interpreting the sedimentological and biostratigraphical characteristics of Well X-1. By comparing ditch cutting descriptions with the established stratigraphic and depositional patterns in the depobelt, the present study aligns its interpretations with the broader geological framework of the Niger Delta.

2.1.10 Summary of Literature and Research Gap

The reviewed literature provides a comprehensive understanding of the sedimentological, biostratigraphical, and stratigraphic framework of the Niger Delta Basin. Previous studies have established that the basin is characterised by a tripartite lithostratigraphic sequence consisting of the Akata, Agbada, and Benin Formations, deposited during progressive delta progradation from the Paleocene to the Recent (Short and Stauble, 1967; Doust and Omatsola, 1990). Research has shown that the alternation of sand and shale within the Agbada Formation reflects changes in relative sea level, sediment supply, and delta-front dynamics (Weber and Daukoru, 1975).

Biostratigraphic studies, particularly those by Evamy et al. (1978), Petters (1982), and Reijers (2011), provide essential frameworks for age dating and paleoenvironmental interpretation using foraminifera, spores, and pollen. Palynological and foraminiferal zonation schemes have helped identify maximum flooding surfaces and correlate stratigraphic intervals across different depobelts. Sequence stratigraphic concepts further strengthen the interpretation of depositional cycles, sedimentary trends, and key stratigraphic boundaries.

Studies in the Greater Ughelli Depobelt have highlighted the importance of integrating sedimentology, biostratigraphy, and structural analysis for reservoir characterisation (Stacher, 1995; Otobo et al., 2015). These works demonstrate that the depobelt contains complex depositional architectures driven by active faulting and high sedimentation rates, resulting in heterogeneous reservoir distributions.

Despite the wealth of research available, certain areas remain less explored at the scale of individual wells, particularly where core data are absent and ditch cutting samples form the primary dataset. Many previous studies provide basin-wide or regional interpretations but offer limited detail on how lithological descriptions, microfossil assemblages, and sedimentary signatures interact within specific well intervals. For Well X-1, there is a need to integrate sedimentological observations with foraminiferal and palynological evidence to accurately interpret depositional environments and establish a reliable stratigraphic framework.

This study addresses this gap by applying a combined sedimentological and biostratigraphical approach to the analysis of Well X-1. By synthesising lithofacies characteristics, microfossil data, and established zonation schemes, the study provides a well-specific interpretation that aligns with broader regional knowledge while contributing additional detail to the understanding of depositional patterns in the Greater Ughelli Depobelt.

2.2 Regional Geology of the Niger Delta

The Niger Delta Basin is one of the most extensively studied sedimentary basins in Africa due to its significant petroleum resources and complex geologic history. It lies on the passive continental margin of West Africa and covers an area of approximately 300,000 square kilometres, extending from the Calabar Flank in the east to the Benin Flank in the west and southward into the Gulf of Guinea (Doust and Omatsola, 1990). The basin developed during the Late Cretaceous to Recent as a result of the opening of the South Atlantic Ocean and the subsequent separation of the African and South American plates.

The delta evolved through continuous sediment supply from the River Niger and its tributaries, leading to the accumulation of thick sequences of clastic sediments. These sediments overlie the Cretaceous basement complex and have built outwards into the Atlantic Ocean over millions of years. The Niger Delta is characterised by a tripartite lithostratigraphic succession consisting of the Akata, Agbada, and Benin Formations, which represent marine, transitional, and continental depositional settings respectively (Short and Stauble, 1967).

The structural style of the basin is influenced by synsedimentary growth faulting, shale diapirism, and gravity tectonics, which have created numerous structural traps favourable for hydrocarbon accumulation. Deposition within the basin is organised into depobelts, which represent the most active portions of the delta at different stages of its development. Each depobelt records a distinct phase of delta progradation, subsidence, and sedimentary infill (Stacher, 1995). A clear understanding of the regional geology of the Niger Delta provides the foundation for analysing the stratigraphic successions encountered in Well X-1 and supports the interpretation of its depositional environments. The main components of the regional geology are discussed in the following subsections.

2.2.1 Morphology of the Niger Delta

The morphology of the Niger Delta reflects the combined influence of sediment supply, subsidence, structural deformation, and relative sea-level changes. The delta exhibits a broad arcuate shape and has evolved through several stages of progradation into the Gulf of Guinea. According to Doust and Omatsola (1990), the delta consists of a series of depositional belts that expand seaward, each representing a former active depocentre. These belts record the progressive outward growth of the delta from the Paleocene to the Recent.

Short and Stauble (1967) identified two major phases in the morphological development of the Niger Delta. The early phase, spanning the Paleocene to early Eocene, was characterised by concave coastlines controlled by basement topography. Sediment dispersal during this phase was strongly influenced by the pre-existing structural framework. The later phase, beginning in the Miocene, involved rapid seaward progradation that led to more uniformly convex coastlines and the formation of extensive delta-front and delta-top environments.

Delta progradation occurred along two major axes. The first followed the main flow path of the River Niger, where sediment supply exceeded subsidence. The second, smaller axis developed basinward of the Cross River and was active during the Eocene to early Oligocene. The two axes eventually merged during the Miocene as sediment supply continued to increase, filling intervening embayments and smoothing earlier irregularities in the coastline (Short and Stauble, 1967).

The morphology of the delta is also shaped by subsurface shale mobility. Underlying overpressured shales of the Akata Formation moved in response to sediment loading, forming diapiric ridges, growth faults, and structural saddles (Evamy et al., 1978). These features influenced surface topography, created local uplift, and generated erosion surfaces that cut into the advancing deltaic deposits. Deep canyons, now infilled with clay-rich sediments, were formed during periods of relative sea-level lowstands when rivers incised the shelf.

Modern delta morphology reflects the interplay of fluvial, tidal, and marine processes. The delta plain is dominated by distributary channels, meander loops, floodplains, and mangrove swamps. The coastal zone features barrier islands, tidal flats, lagoons, and estuaries, while the delta front consists of gently sloping seabed covered by fine sands, silts, and muds. These environments grade into deeper marine prodelta settings where fine-grained clay deposition dominates.

The morphological evolution of the Niger Delta provides important context for understanding sediment distribution patterns and structural controls on deposition. These factors directly influence the lithofacies encountered in wells such as Well X-1 and support interpretations of depositional environments within the Greater Ughelli Depobelt.

2.2.2 Tectonics of the Niger Delta

The tectonic evolution of the Niger Delta is closely related to the separation of the African and South American plates during the Late Jurassic and Cretaceous periods. This separation led to the opening of the South Atlantic and the creation of a passive continental margin where the modern Niger Delta later developed (Doust and Omatsola, 1990). One arm of the original rift system did not progress into oceanic spreading. This failed arm is now represented by the Benue and Anambra Rift System, which served as a major sediment transport pathway into the developing delta (Reijers, 2011).

As sedimentation increased from the Paleocene to the Recent, rapid loading on the ductile Akata Formation shales produced significant subsidence and deformation. The shales became mobile under increasing pressure and generated large-scale gravity driven structures. These include extensional growth faults, rollover anticlines, shale diapirs, and compressional toe thrust belts (Evamy et al., 1978; Corredor et al., 2005). These structural features are the main controls on hydrocarbon migration, accumulation, and trap formation across all depobelts in the Niger Delta (Weber and Daukoru, 1975).

The northern sector of the delta is dominated by listric extensional growth faults that flatten into the Akata shale detachment surface. These faults create classic rollover anticlines and fault dependent closures that frequently host petroleum accumulations (Short and Stauble, 1967). Further basinward, these extensional structures pass into a zone of intense shale mobility where diapirs rise and deform the overlying sediments. Beyond this zone lies the compressional toe thrust belt where gravity spreading creates imbricate thrusts and folds (Corredor et al., 2005).

The main tectonic provinces of the Niger Delta are illustrated in Figure 3. The figure shows the transition from extensional features on the continental shelf, through diapiric deformation on the slope, to compressional thrust belts in the deep offshore.

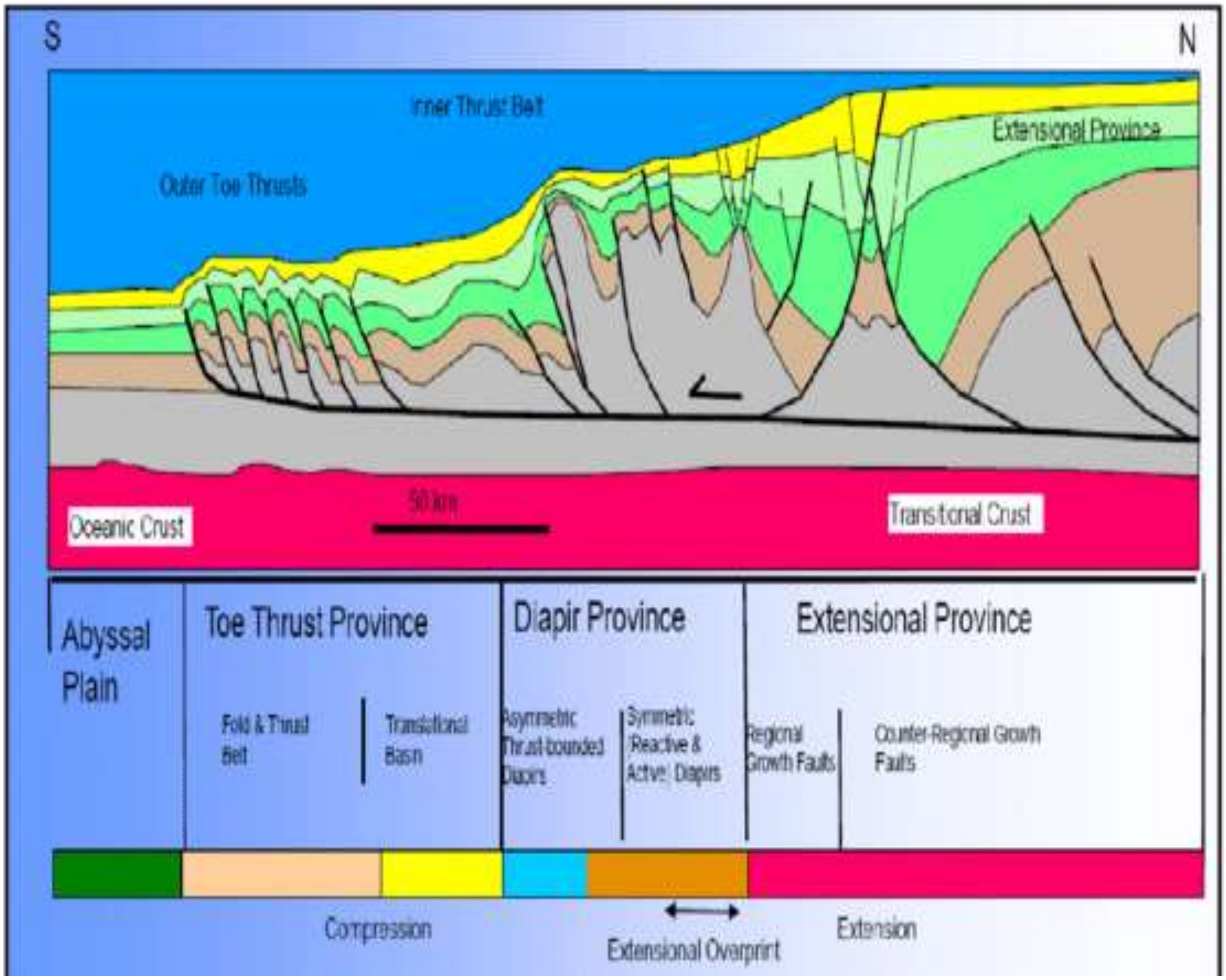


Figure 3: Schematic seismic section of the Niger Delta continental slope and rise showing extensional growth faults, diapiric structures, and toe thrust belts created by internal gravity tectonics (Modified after Olabode et al., 2010).

The progression from extension in the upper delta to compression in the deep offshore is a defining characteristic of the Niger Delta. This structural framework is particularly important in the Greater Ughelli Depobelt where Well X-1 is located, because it influences sediment distribution, reservoir geometry, and the types of hydrocarbon traps found within the area.

2.2.3 Depobelts of the Niger Delta

The Niger Delta is subdivided into a series of basinward younging depositional provinces known as **depobelts.** These depobelts represent distinct structural and sedimentary domains that formed as the delta prograded progressively into the Gulf of Guinea. Each depobelt records a period during which sedimentation, fault activity, and subsidence were concentrated in a particular zone. Once a depobelt became filled, deformation shifted seaward and a new depobelt formed, resulting in the characteristic arcuate geometry of the delta (Doust and Omatsola, 1990).

The depobelts developed as a response to rapid sediment loading on the mobile Akata Formation shales. This loading generated differential subsidence and produced extensive growth faults and rollover structures that separate one depobelt from another. These structural features strongly influence reservoir distribution, trap formation, and hydrocarbon accumulations across the Niger Delta (Evamy et al., 1978; Weber and Daukoru, 1975).

Five major Tertiary depobelts are commonly recognised (Reijers, 2011):

1. Northern Delta Depobelt

The oldest depobelt, formed during the Paleocene and early Eocene. It is characterised by relatively simple extensional growth faults and shallow basement relief (Short and Stauble, 1967).

2. Greater Ughelli Depobelt

This Eocene to Oligocene depobelt, which contains **Well X-1**, is structurally complex due to high sedimentation rates and significant shale mobility. Rollover anticlines, deep growth faults, and fault-controlled closures are common features (Weber and Daukoru, 1975). The depobelt contains thick channel sands and delta front facies that make it highly prospective for hydrocarbons.

3. Central Swamp Depobelt

Developed during the Oligocene and Miocene. It contains thicker paralic sediments, extensive tidal flat and lagoonal deposits, and complex fault systems (Reijers, 2011).

4. Coastal Swamp Depobelt

Formed during the late Miocene and Pliocene. Sediments include young, unconsolidated sands, floodplain deposits, and widespread channel systems (Doust and Omatsola, 1990).

5. Offshore Depobelt

This is the youngest depobelt and corresponds to the present delta front and continental slope. It is dominated by turbidites, deepwater fans, slump deposits, and compressional toe thrust structures related to gravity-driven deformation (Corredor et al., 2005).

The overall arrangement of these depobelts, along with associated structural features, is shown in **Figure 4**. The map illustrates the spatial distribution of the depobelts, their boundaries, paleo-delta fronts, compressive belts, and the relationship between continental and offshore provinces.

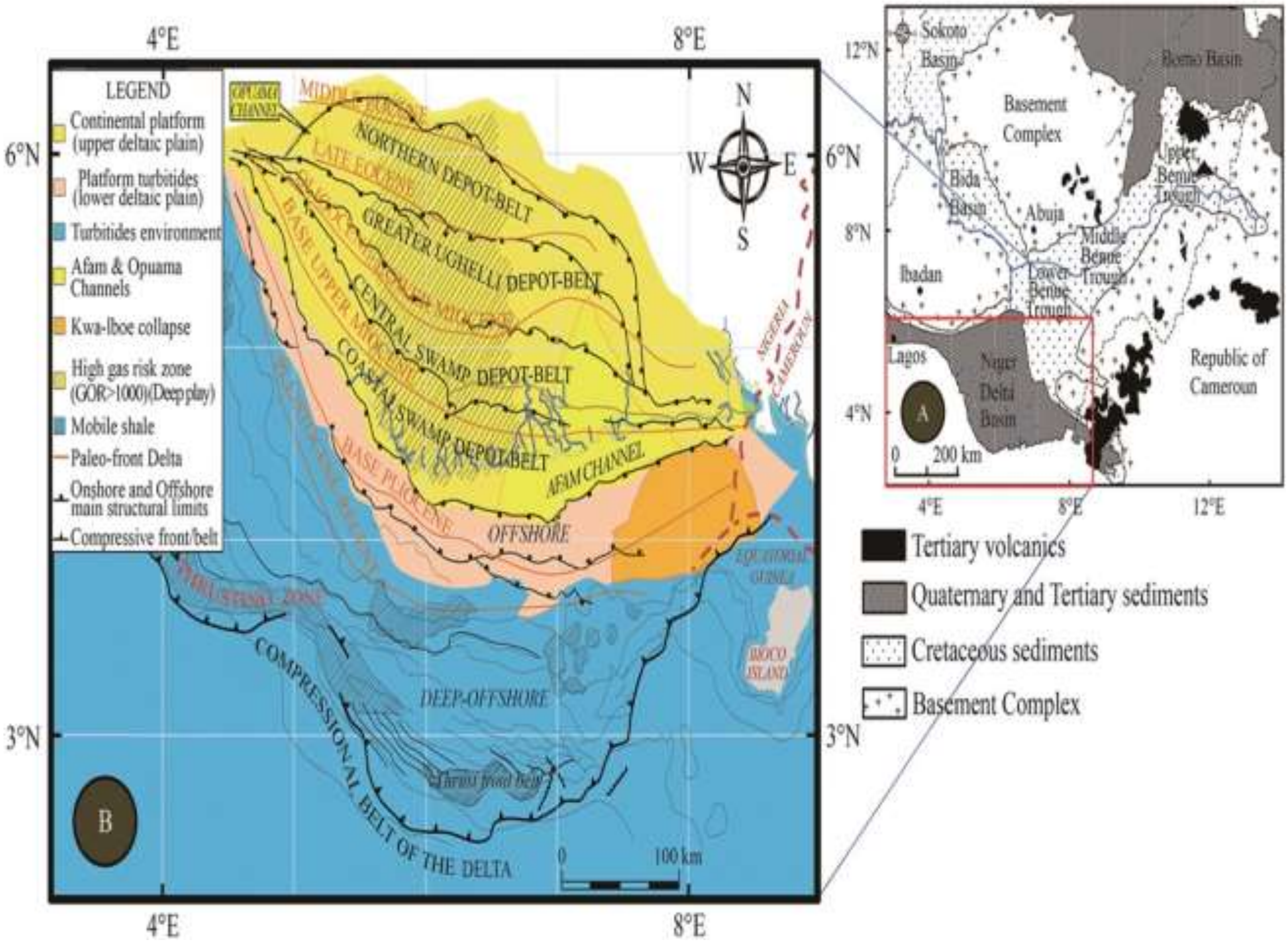


Figure 4: Map of the Niger Delta showing the major depobelts, structural limits, compressive and extensional belts, and regional geological framework. Modified after Agbasi et al. (2021) and Doust and Omatsola (1990).

This figure clearly demonstrates the sequential progradation of the delta from the Northern Delta Depobelt to the Offshore Depobelt. It also highlights the Greater Ughelli Depobelt, which is the study area for Well X-1, and shows its position relative to other structural provinces. Understanding this depobelt framework is essential for interpreting reservoir distribution, depositional systems, and hydrocarbon potential in the study area.

2.2.4 Stratigraphy of the Niger Delta

The stratigraphy of the Niger Delta is classically described using a threefold subdivision that includes the Akata Formation, the Agbada Formation, and the Benin Formation. These units represent a major coarsening upward sequence that developed during the long period of delta progradation from the Paleocene to the Recent (Short and Stauble, 1967; Doust and Omatsola, 1990). Each formation corresponds to a specific depositional domain and contains characteristic lithologies that reflect distinct sedimentary environments and tectonic controls.

The Niger Delta contains a sedimentary wedge that is more than 10 kilometers thick in some depocentres (Kaplan et al., 1994). This thickness is a result of continuous sediment supply from the Niger and Benue river systems, combined with subsidence and shale mobility at depth. The progressive transition from deep marine to delta front and continental environments produced the stratigraphic succession shown in Figure 5.

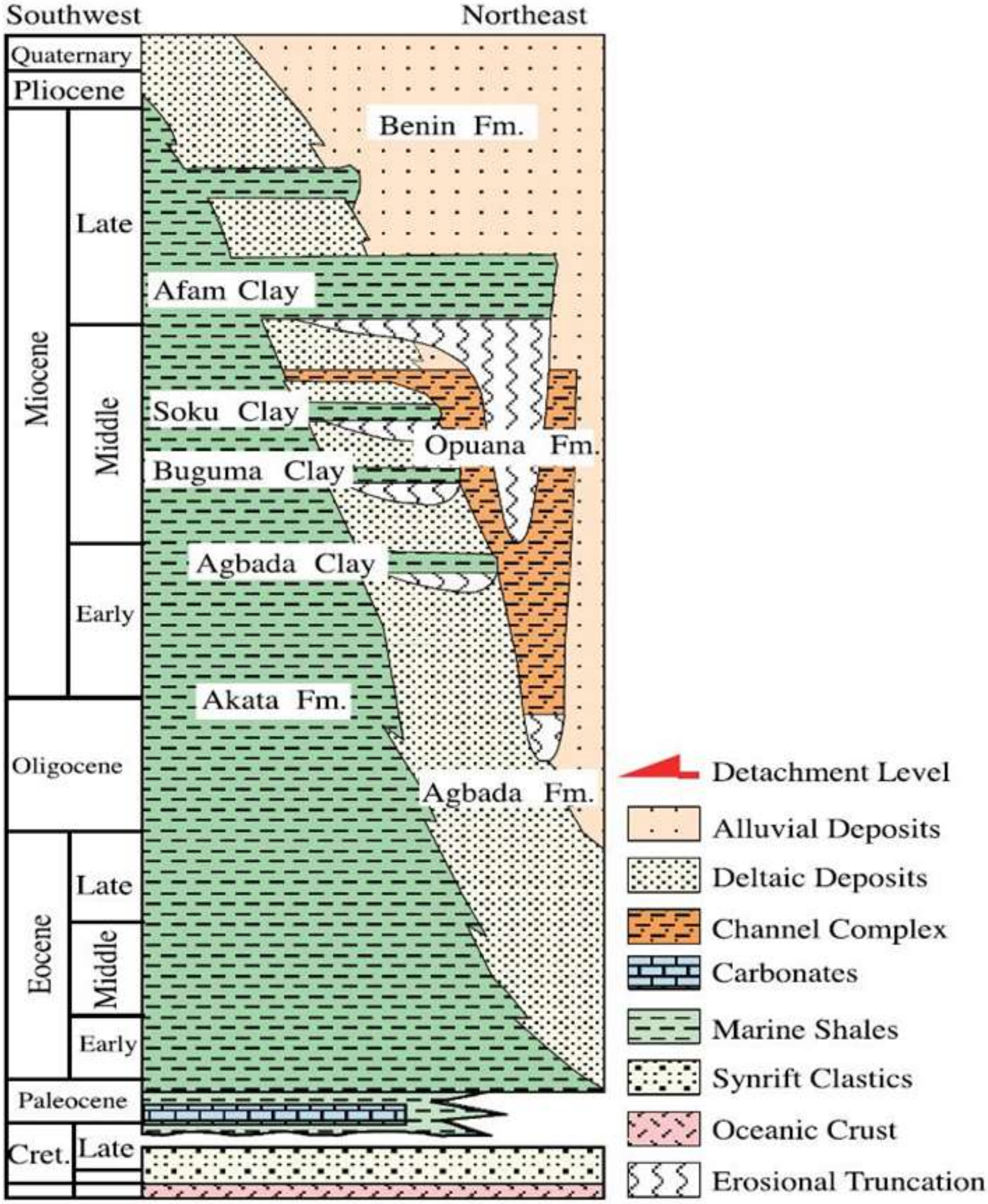


Figure 5: Regional stratigraphic framework of the Niger Delta showing major lithofacies belts, the Benin, Agbada, and Akata Formations, and their vertical relationships. Modified after Corredor et al. (2005) and Reijers (2011).

The stratigraphic relationships illustrated in Figure 5 provide the framework for understanding the sediment distribution, reservoir architecture, and petroleum system elements encountered in wells across the delta. The three formations are described below.

2.2.4.1 Akata Formation

The Akata Formation forms the basal unit of the Niger Delta stratigraphy. It consists mainly of thick, dark grey marine shales with minor siltstone and occasional turbidite sands (Short and Stauble, 1967). These sediments were deposited in a quiet, low energy, deep marine environment at the toe of the prograding delta complex. The formation is Paleocene to Recent in age and contains organic rich shales that are widely regarded as the main hydrocarbon source rocks of the delta (Ekweozor and Daukoru, 1994; Tuttle et al., 1999).

Due to rapid loading by the overlying deltaic sediments, the Akata shales are commonly overpressured and highly mobile. This mobility plays a major role in the development of growth faults, shale diapirs, and toe thrust belts that characterise the tectonic structure of the Niger Delta (Evamy et al., 1978). The thickness of the Akata Formation can exceed 7,000 meters in the basin depocentre (Kaplan et al., 1994).

2.2.4.2 Agbada Formation

The Agbada Formation represents the main paralic sequence of the Niger Delta. It consists of alternating sandstones, siltstones, and shales that were deposited in delta front, distributary channel, and marginal marine environments (Weber and Daukoru, 1975). These alternating sand and shale units form the majority of the petroleum reservoirs and seals in the Niger Delta.

The formation contains numerous offlap cycles that record repeated episodes of marine transgression and regression. The lower part is dominated by marine influenced shales and thin sands, while the upper part contains thicker continental and coastal sands (Reijers, 2011). The age of the Agbada Formation ranges from the Eocene to the Pliocene.

The sand rich intervals within the Agbada Formation form high quality reservoirs with porosity values that can exceed 30 percent in shallow sections. Many accumulations in the Greater Ughelli Depobelt occur within these sands, which are controlled by growth fault rollovers and stratigraphic variations (Doust and Omatsola, 1990).

2.2.4.3 Benin Formation

The Benin Formation forms the uppermost stratigraphic unit of the Niger Delta. It consists mainly of coarse to medium grained sands with minor clay and gravel beds. These sediments were deposited in continental environments that include braided river channels, point bars, levees, and floodplain systems (Allen, 1965).

The Benin Formation is generally unconsolidated and can reach thicknesses of more than 2,000 meters. It forms an important freshwater aquifer system across southern Nigeria but is not a significant reservoir unit for hydrocarbons due to its position high in the stratigraphic column (Reijers, 2011).

Subsurface and Surface Correlation of Niger Delta Formations

The stratigraphic units encountered in the subsurface have corresponding outcrop equivalents in southeastern Nigeria. These correlations provide insight into the delta’s evolution and help integrate well data with regional geological history (Short and Stauble, 1967). The relationships between the subsurface formations and their surface equivalents are presented in Table 3.

Table 3: Sedimentary formations in the Niger Delta Basin and their surface outcrop equivalents. Modified after Short and Stauble, 1967

Subsurface			Surface Outcrops		
Youngest Known Age		Oldest Known age	Youngest Known Age		Oldest Known Age
Recent	Benin Formation (Afam Clay Member)	Oligocene	Plio/Pleistocene	Benin Formation	
Recent	Agbada Formation	Eocene	Miocene Eocene	Ogwashi Asaba Formation Ameki Formation	Miocene Eocene
Recent	Akata Formation	Eocene	Lower Eocene	Imo Shale Formation	Paleocene
Unknown			Paleocene	Nsukka Formation	Maestrichtian
			Maestrichtian	Ajali Formation	Maestrichtian
			Campanian	Mamu Formation	Campanian
			Campanian/Maestrichtian	Nkporo Shale	Santonian
			Coniacian/Santonian	Awgu Shale	Turonian
			Turonian	Eze Aku Shale	Turonian
			Albian	Asu River Group	Albian

2.2.5 Depositional Environments of the Niger Delta

The Niger Delta is characterised by a range of depositional environments that reflect the interaction between fluvial processes, tidal influence, wave action, and marine conditions. These environments have shifted progressively seaward due to long term progradation since the Paleocene. The result is a thick regressive sequence that grades from deep marine shales at the base to continental sands near the top (Short and Stauble, 1967; Doust and Omatsola, 1990).

The three major depositional belts that define the delta are the **continental environment**, the **transitional environment**, and the **marine environment**. These belts represent the main facies associations that form the Benin, Agbada, and Akata Formations respectively.

2.2.5.1 Continental (Delta Top) Environment

The continental environment corresponds to the upper delta plain. It is dominated by fluvial processes and includes braided rivers, meandering channels, natural levees, crevasse splays, and extensive floodplain deposits (Allen, 1965).

Key characteristics include:

i. Predominantly coarse to medium grained sands deposited in channel bars and point bars
ii. Mud rich floodplain deposits with plant fragments and occasional root casts
iii. High sediment supply and rapid lateral shifting of channels
iv. Limited marine influence

The sediments deposited in this environment constitute the **Benin Formation**, which forms a thick, unconsolidated sand body that exceeds 2,000 meters in places (Reijers, 2011). This unit is important for groundwater storage but contains few hydrocarbons due to its shallow position.

2.2.5.2 Transitional (Delta Front and Lower Delta Plain) Environment

The transitional environment includes the lower delta plain, tidal flats, mangrove swamps, estuaries, barrier bars, and lagoons. This environment reflects a mixture of riverine and marine influences (Weber and Daukoru, 1975).

Key features include:

- Fine to medium grained sands with tidal cross bedding
- Brackish water faunal assemblages and palynomorphs
- Interbedded sands, silts, and shales
- Barrier bar complexes with shoreface sands

Sediments in this zone form the upper portion of the **Agbada Formation** where high quality reservoirs occur. Many hydrocarbon bearing units in the Greater Ughelli Depobelt were deposited in this setting and are commonly associated with growth fault rollovers and channel complexes (Doust and Omatsola, 1990).

2.2.5.3 Marine (Prodelta and Delta Slope) Environment

The marine environment includes the prodelta, continental shelf, and deeper marine slope. This is the lowest energy portion of the delta, dominated by suspension settling of fine grained sediments and occasional gravity flow deposits (Corredor et al., 2005).

Key characteristics include:

- Thick, dark grey marine shales
- Occasional turbidite sands and siltstones
- Abundant planktonic foraminifera and marine palynomorphs
- Progressive thickening basinward

Sediments deposited in this environment belong to the **Akata Formation**, which forms the major source rock of the Niger Delta petroleum system. Overpressure within these shales drives shale diapirism and contributes to the development of growth faults and toe thrust belts (Evamy et al., 1978).

Integrated Depositional Model

The three depositional environments occur as a vertical succession that reflects the long term progradation of the delta. The combined effect is a regional coarsening upward sequence that transitions from prodelta shales at depth to shallow marine and coastal sands, and finally to fluvial sands at the top. This relationship is consistent across all depobelts and forms the basis for reservoir distribution and stratigraphic trapping styles.

2.2.6 Occurrence of Petroleum in the Niger Delta

The Niger Delta is one of the most prolific hydrocarbon provinces in Africa. Its petroleum accumulations are closely linked to the interaction between source rock maturation, reservoir distribution, structural deformation, sediment loading, and the evolution of the depobelts. The occurrence of petroleum within the delta is controlled by the Akata–Agbada petroleum system, which is the only recognised petroleum system in the region (Tuttle et al., 1999).

Hydrocarbons originate mainly from the organic rich marine shales of the **Akata Formation,** which contain the appropriate kerogen types and thermal maturity levels for the generation of oil and gas (Ekweozor and Daukoru, 1994). As burial depth increased under the weight of the prograding delta, these source rocks entered the oil and gas windows and expelled hydrocarbons upward into the overlying Agbada Formation (Evamy et al., 1978).

The **Agbada Formation** contains the principal reservoir intervals of the delta. These reservoirs consist of thick, laterally variable channel sands, mouth bar deposits, and marginal marine sand bodies that have porosities that commonly range from 25 percent to more than 30 percent (Weber and Daukoru, 1975). Interbedded shales serve as regional and local seals, creating multiple stacked reservoir packages. This vertical stacking of pools explains the complex hydrocarbon distribution patterns across the depobelts (Doust and Omatsola, 1990).

The distribution of oil and gas within the delta shows significant regional variation. Earlier studies recognised an oil rich belt trending across the central portion of the delta and corresponding broadly to the Greater Ughelli and Central Swamp depobelts (Ejedawa, 1981). This belt has low gas to oil ratios and contains many of the largest oil fields in Nigeria. The pattern was initially thought to be linked to the timing of trap formation relative to migration. Later studies, including those by Evamy et al. (1978), demonstrated that structural growth continued during trap development and therefore timing alone could not fully explain the distribution. Other explanations include variations in geothermal gradients, source rock contribution, and basin maturity across the delta.

The **trap types** in the Niger Delta are varied and include fault assisted closures, rollover anticlines, collapsed crest structures, sand filled channels, and stratigraphic pinch outs. Growth faults are the most important controls on trap formation. These faults form due to sediment loading and compactional adjustments within the delta and create numerous petroleum traps in the paralic section of the Agbada Formation (Corredor et al., 2005).

Migration pathways are controlled by the fault systems and vertical pressure gradients within the overpressured Akata Formation. Hydrocarbons migrate upward along fault planes and accumulate where they encounter suitable reservoir and seal combinations (Weber, 1987). Many accumulations within the Greater Ughelli Depobelt, including the region surrounding Well X-1, are related to this type of migration and trapping.

The overall petroleum occurrence in the Niger Delta reflects a combination of favourable source rock potential, high quality reservoir sands, effective seals, and well developed structural traps. These elements continue to support the delta as a major hydrocarbon province.

2.2.7 Sequence Stratigraphic Framework of the Niger Delta

Sequence stratigraphy provides a regional method for understanding how sediment supply, accommodation space, sea level change, and tectonic subsidence influenced the deposition of sediments in the Niger Delta. The stratigraphic architecture of the delta is organised into a series of system tracts that represent recurring patterns of shoreline advance and retreat (Weber and Daukoru, 1975; Doust and Omatsola, 1990).

The Niger Delta succession contains extensive highstand, transgressive, and lowstand deposits that reflect long term progradation and short term relative sea level fluctuations (Reijers, 2011). These sequences are preserved within the Agbada and Akata Formations and play an important role in controlling reservoir distribution, sand body geometry, and the location of key surfaces such as maximum flooding surfaces.

2.2.7.1 Lowstand Systems Tract

Lowstand deposits in the Niger Delta are typically represented by basin floor fans, slope fans, and channelised turbidites in the deeper offshore province (Corredor et al., 2005). These sediments accumulated when sea level was relatively low and siliciclastic sediments bypassed the shelf to be deposited in deeper water settings.

Although lowstand deposits are not often penetrated by shallow onshore wells, they are significant in the offshore depobelts where they form important hydrocarbon reservoirs.

2.2.7.2 Transgressive Systems Tract

Transgressive systems tracts in the Agbada Formation are marked by an increase in marine influence and the deposition of fine grained shales, heteroliths, and lagoonal facies (Reijers, 2011). These units often contain brackish water fauna and are associated with flooding surfaces that can be correlated regionally.

During periods of rising sea level, shoreline retreat produced condensed intervals that contain marine fossils and high gamma ray signatures. These condensed shales commonly serve as effective seals for underlying reservoir sands.

2.2.7.3 Highstand Systems Tract

Highstand deposits form the bulk of the paralic succession in the Agbada Formation. They consist of stacked distributary channel sands, barrier island complexes, mouth bars, and delta front deposits (Weber and Daukoru, 1975).

These deposits accumulate when sediment supply outpaces the creation of accommodation space. As a result, the shoreline advances basinward and successive sand rich units build out over older shales. Many of the hydrocarbon reservoirs in the Greater Ughelli Depobelt, including those likely encountered in Well X-1, belong to highstand system tracts.

2.2.7.4 Maximum Flooding Surfaces

Maximum flooding surfaces are important regional markers in the Niger Delta. They correspond to periods of maximum marine transgression and are associated with condensed sections that contain rich microfossil assemblages (Petters, 1984). These surfaces can be mapped across multiple depobelts and are widely used for well correlation, biostratigraphic interpretation, and sequence boundary identification.

Common maximum flooding surfaces in the Niger Delta include the **Early Miocene, Middle Miocene**, and **Late Miocene** flooding events, which are recognised across the Agbada Formation and have been described in several studies (Reijers, 2011; Obiadi and Obiadi, 2016).

2.2.7.5 Overall Sequence Architecture

The combined effect of repeated cycles of transgression and regression has produced a stratigraphic succession that is strongly progradational. The vertical stacking of highstand sand bodies and transgressive shales produces multiple reservoir–seal pairs that are favourable for hydrocarbon accumulation. Growth faults, shale diapirs, and compactional structures modify this architecture and create numerous structural and stratigraphic traps (Evamy et al., 1978).

The sequence stratigraphic framework is therefore essential for predicting reservoir distribution, understanding sand body geometry, and correlating stratigraphic units within wells drilled across the depobelts of the Niger Delta.

2.2.8 Foraminiferal Biostratigraphy of the Niger Delta

Foraminiferal biostratigraphy plays an important role in the age dating, correlation, and paleoenvironmental interpretation of subsurface sequences in the Niger Delta. Foraminifera are abundant, rapidly evolving marine microfossils that respond sensitively to changes in salinity, water depth, oxygenation, and sedimentation rate. These characteristics make them reliable indicators of depositional environments and stratigraphic age (Petters, 1984).

Biostratigraphic zonations in the Niger Delta are based primarily on the distribution of planktonic and benthonic foraminiferal assemblages recovered from the shales and heteroliths of the Akata and Agbada Formations. Several authors, including Petters (1984), Stacher (1995), and I tijpelaar and Reijers (1993), have refined the zonation schemes that are now widely used in exploration and academic studies.

2.2.8.1 Benthonic Foraminifera

Benthonic foraminifera are highly valuable for interpreting paleoenvironments in the paralic and shallow marine settings of the Agbada Formation. Their distribution reflects variations in salinity, water depth, substrate type, and oxygen levels.

Common benthonic groups found in the Niger Delta include:

i. Bolivina species
ii. Lenticulina species
iii. Miliolina species
iv. Textularia species
v. Quinqueloculina species

Fresh to brackish environments are often indicated by the presence of agglutinated forms such as Ammobaculites and Ammotium, while more open marine conditions are characterised by calcareous benthonic forms (Petters, 1984). These faunas help differentiate delta plain, delta front, and prodelta facies.

2.2.8.2 Planktonic Foraminifera

Planktonic foraminifera occur in the deeper marine environments of the prodelta and offshore areas. They are essential for chronostratigraphy because planktonic species evolve rapidly and exhibit wide geographic distribution (Stacher, 1995).

Key planktonic genera in the Niger Delta include:

i. Globigerinoides
ii. Globorotalia
iii. Globigerina
iv. Orbulina

v. Catapsydrax

These assemblages allow for identification of major chronostratigraphic boundaries and help correlate offshore wells with outcrops in the Anambra Basin and Benue Trough.

2.2.8.3 Foraminiferal Zones in the Niger Delta

The commonly used foraminiferal zonation for the Niger Delta follows the work of Petters (1984) and Stacher (1995). The major zones include:

1. Late Miocene to Recent Zones

Characterised by the Globorotalia menardii complex and other warm water planktonic species.

2. Middle Miocene Zones

Dominated by Globigerinoides trilobus and related species.

3. Early Miocene Zones

Identified by Catapsydrax dissimilis and Globorotalia opima.

4. Oligocene Zones

Defined by the presence of Globigerina ciperoensis and related taxa.

5. Eocene Zones

Marked by the appearance of Morozovella and Acarinina species.

These zones are widely used for dating well sections and correlating reservoir intervals across the depobelts.

2.2.8.4 Applications of Foraminiferal Data

Foraminiferal biostratigraphy supports several aspects of subsurface interpretation, including:

i. Age determination of sedimentary sequences

ii. Correlation of reservoir sands across fault blocks

iii. Identification of maximum flooding surfaces

iv. Reconstruction of paleoenvironments

v. Delineation of marine to marginal marine facies belts

These applications are particularly important in the Greater Ughelli Depobelt where Well X-1 is located, because the area contains thick paralic deposits that require detailed biostratigraphic control for accurate interpretation.

2.2.9 Palynological Biostratigraphy of the Niger Delta

Palynology is one of the most important tools for biostratigraphic dating and paleoenvironmental reconstruction in the Niger Delta. The analysis of pollen, spores, dinoflagellate cysts, algal remains, and other organic walled microfossils helps to unravel the age, depositional conditions, and vegetation history of the delta during the Tertiary. Palynomorphs are particularly valuable because they are abundant in both marine and continental environments and are well preserved in clay rich sediments (Salami, 1983).

Palynological studies in the Niger Delta began with the early works of Germeraad, Hopping, and Muller (1968) who established the tropical palynological zonation scheme. Later contributions by Evamy et al. (1978), Petters (1984), Stacher (1995), Adeigbe and Ochigbo (2017), and Obiadi and Obiadi (2016) refined these zones and adapted them for regional well correlation.

2.2.9.1 Key Palynomorph Groups

The Niger Delta contains a wide variety of palynomorphs that reflect its mixture of continental, marginal marine, and fully marine environments. The most common groups include:

1. Pollen and Spores

Produced by terrestrial vegetation and transported into the delta plain and marginal marine areas. Their abundance reflects proximity to land and the type of vegetation present (Adeigbe and

Ochigbo, 2017).

Common forms include:

1. Monoporites annulatus
2. Retitricolporites irregularis
3. Psilatricolporites crassus
4. Laevigatosporites spp.
5. Cyathidites spp.

2. Dinoflagellate Cysts

Marine palynomorphs that provide reliable age and paleoenvironmental information. They increase in abundance in marine influenced intervals.

Characteristic genera include:

1. Spiniferites
2. Operculodinium
3. Polysphaeridium
4. Achomosphaera

3. Acritarchs and Algal Remains

Indicate offshore or open marine settings and help differentiate prodelta and deeper marine facies.

2.2.9.2 Palynological Zonation

The standard tropical palynological zonation of Germeraad et al. (1968), modified by Evamy et al. (1978) and subsequently applied by several authors, is widely used in the Niger Delta. The major zones include:

1. P860 Zone (Late Miocene to Recent)

Dominated by Zonocostites ramonae, Verrutricolporites spp., and abundant mangrove pollen.

2. P830 Zone (Middle to Late Miocene)

Characterised by the first appearance of Crassoretitriletes vanraadshooveni and key mangrove indicators.

3. P780 Zone (Middle Miocene)

Marked by the presence of Distaverrusporites simplex and increasing marine dinocysts.

4. P720 Zone (Early Miocene)

Identified by Alnipollenites verus and associated pollen species.

5. P660 Zone (Oligocene)

Defined by the appearance of Retidiporites magdalenensis and freshwater swamp pollen.

6. P560 and P540 Zones (Eocene)

Contain characteristic spores and pollen including Praediporites spp. and Psilatricolporites spp.

These zones assist in the correlation of paralic sequences and in distinguishing marine flooding intervals from continental episodes (Obiadi and Obiadi, 2016).

2.2.9.3 Paleoenvironmental Interpretation

i. Palynology provides valuable information on the depositional environments of the Niger Delta.

ii. Abundant mangrove pollen such as Zonocostites ramonae indicates low salinity, tidal swamp, and shoreline settings.

iii. A mix of terrestrial pollen and marine dinocysts suggests marginal marine or lagoonal environments.

iv. High diversity of dinoflagellate cysts reflects open marine or prodelta conditions.

v. Freshwater swamp pollen is associated with delta plain and fluvial environments.

These interpretations support sequence stratigraphic analysis, especially in identifying maximum flooding surfaces where marine palynomorphs reach peak abundance (Reijers, 2011).

2.2.9.4 Application in the Greater Ughelli Depobelt

Many wells in the Greater Ughelli Depobelt, the location of Well X-1, contain rich palynomorph assemblages that make it possible to date reservoir intervals and determine changes in water depth and salinity. Studies by Adeigbe and Ochigbo (2017) and Obiadi and Obiadi (2016) show that palynology is highly effective for correlating sands across fault blocks, especially where lithological similarities make log correlation difficult.

Palynological data from Well X-1 will therefore provide essential support for interpreting the age, depositional environment, and sequence stratigraphic position of the encountered sediments.

2.3 Summary of Literature Reviewed

The literature reviewed in this chapter provides a comprehensive understanding of the geological framework, depositional systems, structural elements, biostratigraphy, and petroleum characteristics of the Niger Delta Basin. The works of Short and Stauble (1967), Weber and Daukoru (1975), Evamy et al. (1978), and Doust and Omatsola (1990) form the foundation for the regional geological interpretation used in this study. These authors established the threefold lithostratigraphy of the delta, described the major structural styles, and defined the depobelt model that explains the progressive basinward progradation of the delta system.

The tectonic evolution of the Niger Delta has been widely studied by authors including Corredor et al. (2005), Reijers (2011), and Tuttle et al. (1999). Their work shows that the deformation patterns in the delta result from the interaction of sediment loading, shale mobility, differential subsidence, and gravity driven processes. These tectonic forces produced the characteristic growth faults, rollover anticlines, diapirs, and toe thrust belts that control reservoir distribution and trap formation.

Stratigraphic studies by Short and Stauble (1967), Corredor et al. (2005), and Reijers (2011) highlight the vertical succession of deep marine, paralic, and continental facies that form the Akata, Agbada, and Benin Formations. These units are central to understanding the lithofacies, reservoir characteristics, and depositional patterns encountered in wells across the various depobelts, including the Greater Ughelli Depobelt where Well X-1 is located.

The depositional environments of the delta have been described by Allen (1965), Weber and Daukoru (1975), and Doust and Omatsola (1990), who demonstrated how fluvial, tidal, delta front, and marine processes interact to produce the complex sedimentary architecture of the Agbada Formation. These environments influence reservoir quality, sand body geometry, and the distribution of shales that form important seals.

The occurrence of petroleum in the Niger Delta has been explained through the Akata–Agbada petroleum system model, which emphasises the role of Akata Formation shales as the primary source rocks and the Agbada Formation as the main reservoir interval (Ekweozor and Daukoru, 1994; Tuttle et al., 1999). The migration and trapping of hydrocarbons are strongly controlled by the fault systems and structural styles described in earlier tectonic studies.

Finally, the biostratigraphic framework of the Niger Delta, based on both foraminiferal and palynological zonations, provides essential tools for dating sedimentary successions, correlating reservoir units, and identifying maximum flooding surfaces. Important contributions by Petters (1984), Stacher (1995), Adeigbe and Ochigbo (2017), and Obiadi and Obiadi (2016) show how microfossil assemblages can be applied in regional and field scale studies.

Overall, the literature reviewed provides the foundation needed to interpret the sedimentology, biostratigraphy, and hydrocarbon potential of Well X-1. The concepts and models discussed support the methodological approach and form the basis for the results and interpretations presented in the subsequent chapters.

CHAPTER THREE

MATERIALS AND METHODS

3.1 DATA AND MATERIALS

The primary data used for this study were derived from the analysis of subsurface samples and biostratigraphic charts. The datasets and materials employed include:

i. **Ditch Cutting Samples:** A total of seventy-two (72) ditch cutting samples were provided by Shell Petroleum Development Company (SPDC). These samples cover the depth interval of 4,500 ft to 11,460 ft (1,372 m - 3,493 m).

ii. **Biofacies Data:** Comprehensive data regarding foraminiferal abundance (planktic, benthic calcareous, and benthic arenaceous).

iii. **Palynological and Foraminiferal Zonation Data:** P-Zone and F-Zone datasets used for sequence stratigraphic definition.

iv. **Chronostratigraphic Charts:** The Niger Delta Cenozoic chronostratigraphic chart (Haq et al., 1988).

v. **Equipment:** A reflected light microscope was used for the visual inspection of sediment samples.

3.1.1 Ditch Cutting Samples

The samples utilized for this research consists of 72 ditch cuttings obtained from SPDC. The samples represent a stratigraphic interval ranging from 4,500 ft to 11,460 ft. These samples form the basis of the lithological and biostratigraphic interpretation.

3.1.2 Biofacies Data

The biofacies data includes the total abundance of foraminifera, subdivided into planktic, benthic calcareous, and benthic arenaceous groups. This data is presented in **Table 4** (see Appendix A for full dataset).

Table 4: Biofacies Data for the Well (Excerpt/Full)

S/N	Depth (ft)	Total Foram	Total Planktic	Total Benthic Calc.	Total Benthic Aren.
1	3960	0	0	0	0
2	4200	0	0	0	0
...	...	...	...	...	...
18	5899	319	91	171	42
...	...	...	...	...	...
22	6265	1794	194	1533	12
...	...	...	...	...	...
112	11500	179	14	162	3

3.1.3 Biostratigraphic Zonation Data (F-Zone and P-Zone)

Foraminiferal (F-Zone) and Palynological (P-Zone) zonations serve as critical tools in sequence stratigraphy for the recognition of Maximum Flooding Surfaces (MFS) and Sequence Boundaries (SB). In cyclic sequence stratigraphy, maximum foraminiferal abundance typically corresponds to the MFS, while minimum abundance corresponds to SBs.

The specific foraminiferal zonation data used for this study are detailed in **Table 5**. These zones were used to establish the biostratigraphic framework of the well.

Table 5: Foraminiferal Zonation (F-Zone) Data

Depth (ft MD)	F-Zone	Confidence
5899	F9300 Top	Fair
6570	F9300 Base	Fair
6688	F7800 Top	Good
11500	F7800 Base	Good

Similarly, the palynological data, which provides complementary stratigraphic control, is summarized in **Table 6**. These datasets were integrated with the chronostratigraphic chart to determine the absolute ages of the identified surfaces.

Table 6: Palynological Zonation (P-Zone) Data

Depth (ft)	P-Zone	Confidence
6265	P620 Top	Fair
7325	P620 Base	Good
10891	P580 Top	Good
11034	P580 Base	Good

3.1.4 Reference Charts

To ensure accurate correlation and dating, standard industry charts were utilized. The Niger Delta Cenozoic Chronostratigraphic Chart, shown in **Figure 6**, provided the global sea-level curve and age context (Haq et al., 1988).

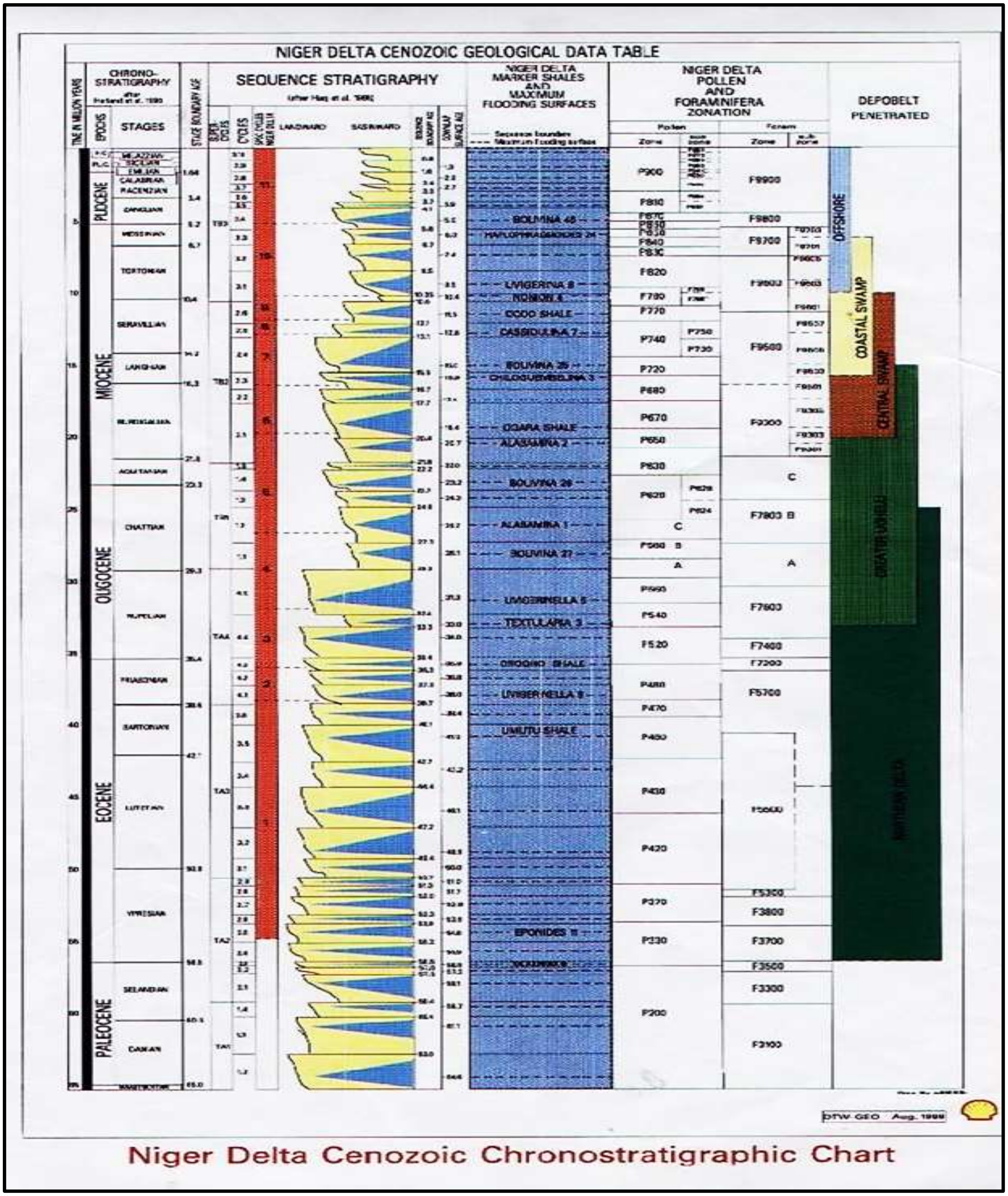


Figure 6: Niger Delta Cenozoic Chronostratigraphic Chart (Source: Haq et al., 1988).

Additionally, the general patterns of foraminiferal distribution relative to depth were interpreted using the association chart displayed in **Figure 7** (Fugro Robertson Research, 1996).

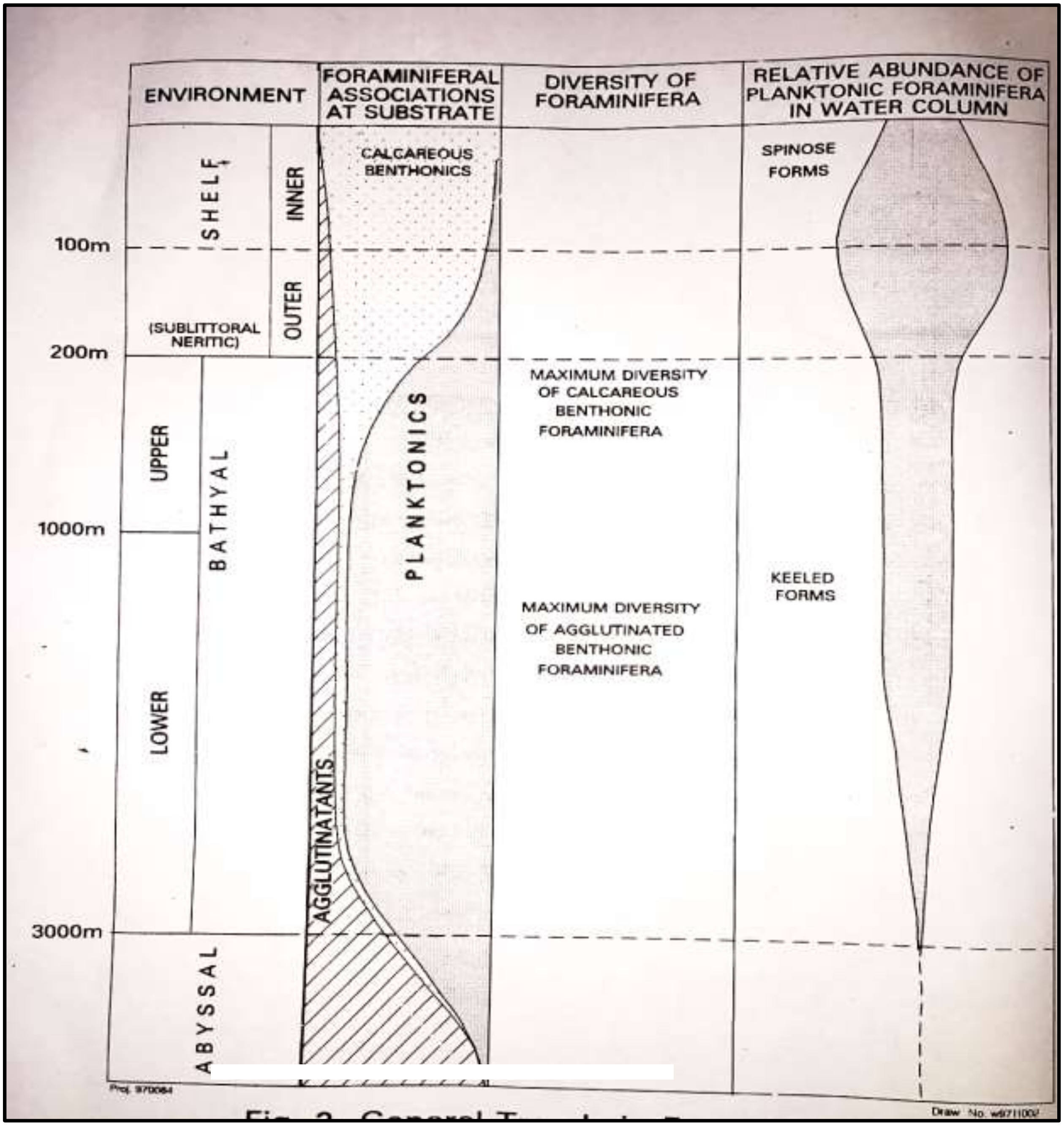


Figure 7: Chart Showing the General Trend in Foraminiferal Association with Depth (Source: Fugro Robertson Research, 1996).

3.2 METHODOLOGY

The methodology adopted for this study involves two primary phases: microscopic examination of lithology and biostratigraphical interpretation involving statistical modeling of foraminiferal abundance.

3.2.1 Microscopic Examination (Lithological Analysis)

Lithology refers to rock units with specific characteristics that depict particular depositional processes or environments. As noted by Allen (1965), paleogeographic studies rely heavily on the analysis of sedimentary units.

The ditch cutting samples were prepared and examined under a reflected light microscope. Sediments were dispersed onto a white background to enhance visibility. The following sedimentological parameters were recorded for each depth interval:

i. Color
ii. Rock type
iii. Sorting
iv. Texture and grain size
v. Sand/Shale percentage

Based on the physical characteristics exhibited by the sediments, lithofacies were delineated. These lithofacies units, representing rock sequences accumulated under similar depositional settings, were correlated vertically to generate a lithostratigraphic model used to identify potential reservoir and source rocks.

3.2.2 Biostratigraphic Interpretation and Modeling

To generate the sequence stratigraphical model, foraminiferal abundance patterns were analyzed against depth.

Data Processing and Graphing: Data analysis was performed using Microsoft Excel. Four distinct abundance curves were generated to visualize biofacies trends as presented in **Table 4**:

1. Total Foraminifera Abundance
2. Total Planktic Foraminifera Abundance
3. Total Benthic Calcareous Abundance
4. Total Benthic Arenaceous Abundance

Plotting Procedure: The abundance data for each category were tabulated against their respective depths. Scatter plots with connecting lines were generated to visualize the fluctuations in fossil abundance relative to depth. The axes were normalized to a uniform scale to facilitate direct comparison between the different abundance curves. The resulting graphs were integrated with the zonation data in **Table 5** and **Table 6** to identify Maximum Flooding Surfaces (MFS) and Sequence Boundaries (SB).

This graphical approach allowed for the identification of peaks (MFS) and troughs (SB) in the foraminiferal distribution, which were then correlated with the standard chronostratigraphic chart (**Figure 6**).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Lithostratigraphic Description

The microscopic examination of the study well (Well X-1) conducted on seventy-two (72) ditch cutting samples spanning the depth interval of 4,500 ft to 11,460 ft. revealed total of forty-nine (49) distinct lithozones. The detailed lithological description of each zone, from bottom to top, is presented below, and the overall stratigraphic model is summarized in **Figure 8**.

4.1.1 Detailed Description of Lithozones (Bottom to Top)

The lithological succession of Well X-1 is divided into three major intervals reflecting a progressive shallowing-upward trend, typical of the Agbada Formation. The dominant mineral throughout the section is Quartz, with minor occurrences of Mica and Feldspar in the transitional intervals.

A. Lower Section (11,460 ft - 7,860 ft): Predominantly Shale

This basal section is characterized by thick, massive shale units, representing the low-energy, prodelta to distal delta-front environment.

Lithozone 1 (11460 ft-11340 ft / 120 ft thick) is light grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 2 (11220 ft) consists of dark grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 3 (11100 ft) is light to dark grey shale; fissile, moderately hard, but notably **calcareous**.

Lithozone 4 (10980 ft-10860 ft / 120 ft thick) is a light to dark grey shale, fissile, non-calcareous, and moderately hard.

Lithozone 5 (10740 ft) is characterized by dark grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 6 (10620 ft) is a brownish grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 7 (10500 ft) consists of dark grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 8 (10380 ft) is characterized by brownish grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 9 (10260 ft-10020 ft / 240 ft thick) is a thick unit of light to dark grey shale, fissile, non-calcareous, and moderately hard.

Lithozone 10 (9900 ft) is brownish grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 11 (9780 ft-9660 ft / 120 ft thick) consists of light to dark grey shale, fissile, non-calcareous, and moderately hard.

Lithozone 12 (9540 ft) is brownish grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 13 (9420 ft) is light to dark grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 14 (9300 ft-9060 ft / 240 ft thick) is a thick unit of dark grey shale, fissile, non-calcareous, and moderately hard.

Lithozone 15 (8820 ft) is composed of light grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 16 (8700 ft-8340 ft / 360 ft thick) is the thickest single unit, consisting of brownish grey shale, fissile, non-calcareous, and moderately hard.

Lithozone 17 (8220 ft) is light to dark grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 18 (8100 ft-8040 ft / 60 ft thick) is light to dark grey shale, fissile, non-calcareous, and moderately hard.

Lithozone 19 (7980 ft-7860 ft / 120 ft thick) is brownish grey shale, fissile, non-calcareous, and moderately hard.

B. Middle Section (7,740 ft - 5,580 ft): Paralic and Reservoir Interval

This section marks the increased influence of fluvial input, characterized by sharp alternations between shaly sand, sandy shale, and thick sandstone bodies, representing the delta-front and channel complexes. The reservoir elements (sandstone units) are concentrated here.

Lithozone 20 (7740 ft) marks the transition with poorly sorted **light grey shaly sand** (90% sandstone, 10% shale). The sand is coarse and angular.

Lithozone 21 (7620 ft-7500 ft / 120 ft thick) is composed of **brownish grey sandy shale** (80% shale, 20% sand) interbedded with brownish grey shale. Minerals include Quartz and Feldspar.

Lithozone 22 (7380 ft) is a dark grey shale; fissile, non-calcareous, and moderately hard. Minerals include Quartz and Mica.

Lithozone 23 (7320 ft) is poorly sorted whitish to dark grey **shaly sand** (70% sandstone, 30% shale); the sand is coarse and sub-angular. Minerals include Quartz and Mica.

Lithozone 24 (7260 ft) is **dark grey sandstone**; coarse, angular to sub-rounded, and **well sorted**. Minerals include Quartz and Mica.

Lithozone 25 (7200 ft–7140 ft / 60 ft thick) is **well sorted light grey sandstone**; coarse and sub-rounded.

Lithozone 26 (7080 ft-7020 ft / 60 ft thick) is a light grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 27 (6960 ft-6900 ft / 60 ft thick) is composed of poorly sorted **shaly sand** (70% sand, 30% shale, grading to 90% sand, 10% shale). The sand is coarse and sub-angular to sub-rounded.

Lithozone 28 (6840 ft) is light grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 29 (6780 ft) is poorly sorted whitish to dark grey **sandy shale** (60% shale, 40% sandstone); the sand is coarse and sub-rounded.

Lithozone 30 (6720 ft-6600 ft / 120 ft thick) is a thick unit of **whitish to colorless sandstone**; coarse, angular to sub-angular, and sub-rounded.

Lithozone 31 (6540 ft) is poorly sorted **light grey shaly sand** (90% sandstone, 10% shale); the sand is coarse and sub-rounded.

Lithozone 32 (6480 ft) is poorly sorted light to dark grey **sandy shale** (90% shale, 10% sandstone); the sand is coarse and sub-rounded.

Lithozone 33 (6420 ft) is light grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 34 (6360 ft) is dark grey **sandy shale** (80% shale, 20% sandstone); fissile, non-calcareous, and moderately hard.

Lithozone 35 (6300 ft) is **whitish to colorless sandstone**; coarse, angular, and **well sorted**.

Lithozone 36 (6240 ft) is poorly sorted whitish to dark grey **shaly sand** (80% sandstone, 20% shale); the sand is coarse and sub-angular. Minerals include Quartz and Mica.

Lithozone 37 (6180 ft) is **well sorted whitish to dark grey sandstone**; coarse and angular. Minerals include Quartz and Mica.

Lithozone 38 (6120 ft) is poorly sorted whitish to dark grey **sandy shale** (60% shale, 40% sandstone); the sand is coarse and sub-rounded. Minerals include Quartz and Mica.

Lithozone 39 (6065 ft) is light to dark grey shale; fissile, non-calcareous, and moderately hard. Minerals include Quartz and Mica.

Lithozone 40 (6000 ft) is poorly sorted whitish to dark grey **shaly sand** (80% sandstone, 20% shale); the sand is coarse and sub-rounded. Minerals include Quartz and Mica.

Lithozone 41 (5940 ft) is **whitish to dark grey sand**; coarse, sub-rounded to sub-angular, and **well sorted**. Minerals include Quartz and Mica.

Lithozone 42 (5880 ft-5580 ft / 300 ft thick) is a thick unit of poorly sorted whitish to dark grey **shaly sands and sandy shale**; the sands are coarse and sub-rounded. Minerals include Quartz and Mica.

C. Upper Section (5,460 ft - 4,500 ft): Seal/Cap Rock Interval

This shallow section is dominated by the cap rock shale, with some basal sand.

Lithozone 43 (5460 ft) is **dark grey shale**; fissile, non-calcareous, and moderately hard. Minerals include Quartz, Mica.

Lithozone 44 (5340 ft) is poorly sorted, whitish to dark grey **shaly sand** (90% sandstone, 10% shale); the sand is coarse and sub-rounded. Minerals include Quartz and Mica.

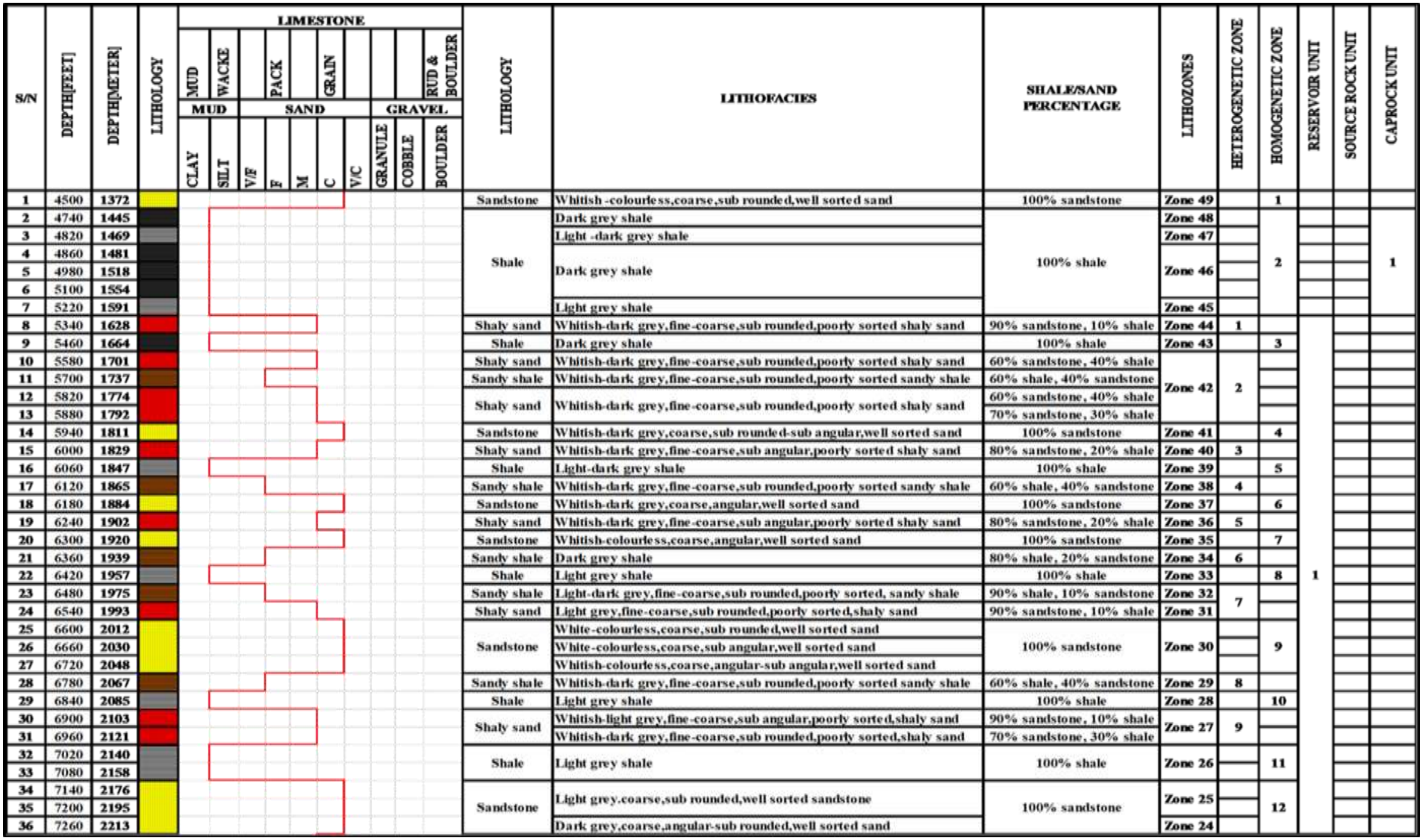
Lithozone 45 (5220 ft) is **light grey shale**; fissile, non-calcareous, and moderately hard.

Lithozone 46 (5100 ft-4860 ft / 360 ft thick) is a major unit of **dark grey shale**; fissile, non-calcareous, and moderately hard.

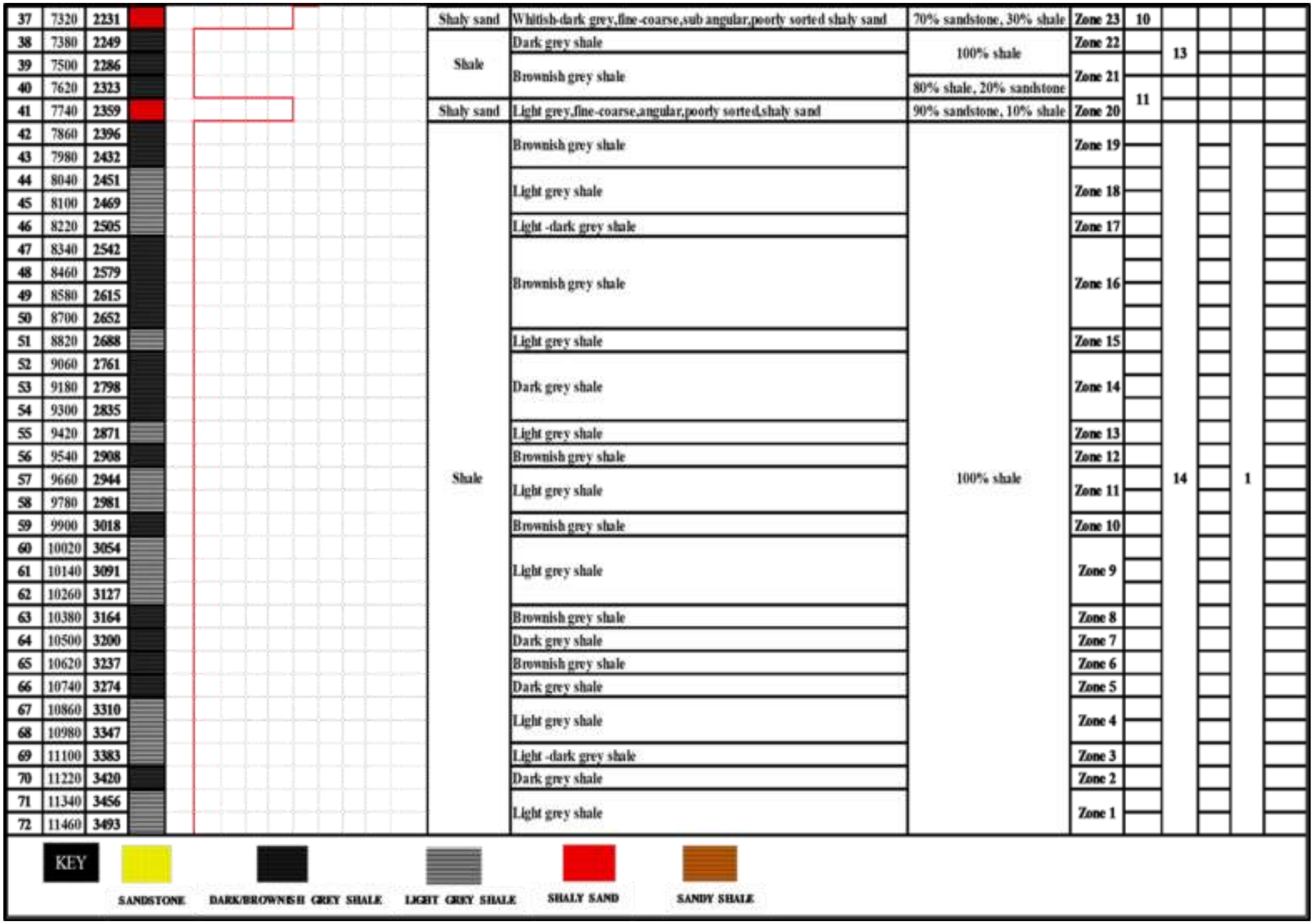
Lithozone 47 (4820 ft) is light to dark grey shale; fissile and moderately hard.

Lithozone 48 (4740 ft) is dark grey shale; fissile, non-calcareous, and moderately hard.

Lithozone 49 (4500 ft) is the uppermost interval studied, characterized by **well sorted whitish to colorless sandstone**; coarse and sub-rounded.



S/N	DEPTH[FEET]	DEPTH[METER]	LITHOLOGY	LITHOLOGY	LITHOFACIES	SHALE/SAND PERCENTAGE	LITHOZONES	HETEROGENETIC ZONE	HOMOGENETIC ZONE	RESERVOIR UNIT	SOURCE ROCK UNIT	CAPROCK UNIT
1	4500	1372	🟨	Sandstone	Whitish -colourless,coarse,sub rounded,well sorted sand	100% sandstone	Zone 49		1			
2	4740	1445	⬛	Shale	Dark grey shale	100% shale	Zone 48		2			1
3	4820	1469	▨		Light -dark grey shale		Zone 47					
4	4860	1481	⬛		Dark grey shale		Zone 46					
5	4980	1518	⬛									
6	5100	1554	⬛									
7	5220	1591	▨		Light grey shale		Zone 45					
8	5340	1628	🟥	Shaly sand	Whitish-dark grey,fine-coarse,sub rounded,poorly sorted shaly sand	90% sandstone, 10% shale	Zone 44	1		1		
9	5460	1664	⬛	Shale	Dark grey shale	100% shale	Zone 43		3			
10	5580	1701	🟥	Shaly sand	Whitish-dark grey,fine-coarse,sub rounded,poorly sorted shaly sand	60% sandstone, 40% shale	Zone 42	2				
11	5700	1737	🟫	Sandy shale	Whitish-dark grey,fine-coarse,sub rounded,poorly sorted sandy shale	60% shale, 40% sandstone						
12	5820	1774	🟥	Shaly sand	Whitish-dark grey,fine-coarse,sub rounded,poorly sorted shaly sand	60% sandstone, 40% shale						
13	5880	1792	🟥			70% sandstone, 30% shale						
14	5940	1811	🟨	Sandstone	Whitish-dark grey,coarse,sub rounded-sub angular,well sorted sand	100% sandstone	Zone 41		4			
15	6000	1829	🟥	Shaly sand	Whitish-dark grey,fine-coarse,sub angular,poorly sorted shaly sand	80% sandstone, 20% shale	Zone 40	3				
16	6060	1847	▨	Shale	Light-dark grey shale	100% shale	Zone 39		5			
17	6120	1865	🟫	Sandy shale	Whitish-dark grey,fine-coarse,sub rounded,poorly sorted sandy shale	60% shale, 40% sandstone	Zone 38	4				
18	6180	1884	🟨	Sandstone	Whitish-dark grey,coarse,angular,well sorted sand	100% sandstone	Zone 37		6			
19	6240	1902	🟥	Shaly sand	Whitish-dark grey,fine-coarse,sub angular,poorly sorted shaly sand	80% sandstone, 20% shale	Zone 36	5				
20	6300	1920	🟨	Sandstone	Whitish-colourless,coarse,angular,well sorted sand	100% sandstone	Zone 35		7			
21	6360	1939	🟫	Sandy shale	Dark grey shale	80% shale, 20% sandstone	Zone 34	6				
22	6420	1957	▨	Shale	Light grey shale	100% shale	Zone 33		8			
23	6480	1975	🟫	Sandy shale	Light-dark grey,fine-coarse,sub rounded,poorly sorted, sandy shale	90% shale, 10% sandstone	Zone 32	7				
24	6540	1993	🟥	Shaly sand	Light grey,fine-coarse,sub rounded,poorly sorted,shaly sand	90% sandstone, 10% shale	Zone 31					
25	6600	2012	🟨	Sandstone	White-colourless,coarse,sub rounded,well sorted sand	100% sandstone	Zone 30		9			
26	6660	2030	🟨		White-colourless,coarse,sub angular,well sorted sand							
27	6720	2048	🟨		Whitish-colourless,coarse,angular-sub angular,well sorted sand							
28	6780	2067	🟫	Sandy shale	Whitish-dark grey,fine-coarse,sub rounded,poorly sorted sandy shale	60% shale, 40% sandstone	Zone 29	8				
29	6840	2085	▨	Shale	Light grey shale	100% shale	Zone 28		10			
30	6900	2103	🟥	Shaly sand	Whitish-light grey,fine-coarse,sub angular,poorly sorted,shaly sand	90% sandstone, 10% shale	Zone 27	9				
31	6960	2121	🟥		Whitish-dark grey,fine-coarse,sub rounded,poorly sorted,shaly sand	70% sandstone, 30% shale						
32	7020	2140	▨	Shale	Light grey shale	100% shale	Zone 26		11			
33	7080	2158	▨									
34	7140	2176	🟨	Sandstone	Light grey.coarse,sub rounded,well sorted sandstone	100% sandstone	Zone 25		12			
35	7200	2195	🟨									
36	7260	2213	🟨		Dark grey,coarse,angular-sub rounded,well sorted sand		Zone 24					



37	7320	2231	🟥	Shaly sand	Whitish-dark grey,fine-coarse,sub angular,poorly sorted shaly sand	70% sandstone, 30% shale	Zone 23	10				
38	7380	2249	■	Shale	Dark grey shale	100% shale	Zone 22		13			
39	7500	2286	■		Brownish grey shale		Zone 21					
40	7620	2323	■			80% shale, 20% sandstone		11				
41	7740	2359	🟥	Shaly sand	Light grey,fine-coarse,angular,poorly sorted,shaly sand	90% sandstone, 10% shale	Zone 20					
42	7860	2396	■	Shale	Brownish grey shale	100% shale	Zone 19		14		1	
43	7980	2432	■									
44	8040	2451	▤		Light grey shale		Zone 18					
45	8100	2469	▤									
46	8220	2505	▤		Light -dark grey shale		Zone 17					
47	8340	2542	■		Brownish grey shale		Zone 16					
48	8460	2579	■									
49	8580	2615	■									
50	8700	2652	■									
51	8820	2688	▤		Light grey shale		Zone 15					
52	9060	2761	■		Dark grey shale		Zone 14					
53	9180	2798	■									
54	9300	2835	■									
55	9420	2871	▤		Light grey shale		Zone 13					
56	9540	2908	■		Brownish grey shale		Zone 12					
57	9660	2944	▤		Light grey shale		Zone 11					
58	9780	2981	▤									
59	9900	3018	■		Brownish grey shale		Zone 10					
60	10020	3054	▤		Light grey shale		Zone 9					
61	10140	3091	▤									
62	10260	3127	▤									
63	10380	3164	■		Brownish grey shale		Zone 8					
64	10500	3200	■		Dark grey shale		Zone 7					
65	10620	3237	■		Brownish grey shale		Zone 6					
66	10740	3274	■		Dark grey shale		Zone 5					
67	10860	3310	▤		Light grey shale		Zone 4					
68	10980	3347	▤									
69	11100	3383	▤		Light -dark grey shale		Zone 3					
70	11220	3420	■		Dark grey shale		Zone 2					
71	11340	3456	▤		Light grey shale		Zone 1					
72	11460	3493	▤									

KEY

🟨 SANDSTONE

■ DARK/BROWNISH GREY SHALE

▤ LIGHT GREY SHALE

🟥 SHALY SAND

🟫 SANDY SHALE

Figure 8: Lithostratigraphic Description of the Succession in Well X-1.

4.1.2 Hydrocarbon Play Elements

The petroleum system encompasses the essential geological elements, source, reservoir, and seal, which is required for hydrocarbon accumulation (Tuttle et al., 1999). Based on the lithostratigraphic model derived from Well X-1, the following play elements were interpreted:

Source Rocks Source rocks are organic-rich sedimentary rocks capable of generating hydrocarbons under thermal maturation (Ekweozor & Daukoru, 1994). In the Niger Delta, the marine shales of the Akata and lower Agbada formations act as the primary source rocks.

Inference: Based on the lithostratigraphic model, the thick shale sequence interpreted between **7,860 ft and 11,460 ft** (Lithozones 1-19 and associated sections) is identified as the primary source rock interval.

Reservoir Rocks Reservoir rocks are characterized by sufficient porosity and permeability to contain and transmit fluids (Kulke, 1995).

Inference: The sand-rich intervals identified between **5,340 ft and 7,260 ft** (including Lithozones 24, 25, 30, 35, 37, and 44) possess the textural maturity indicative of good reservoir quality. This interval is interpreted as the primary reservoir unit.

Seal (Cap) Rocks Seal rocks are impermeable units, typically shales, that prevent hydrocarbon migration (Doust & Omatsola, 1990).

Inference: The thick shale interval interpreted between **4,740 ft and 5,200 ft** (including Lithozones 45, 46, and 48) overlies potential reservoirs and is identified as a probable cap rock.

4.2 SEQUENCE STRATIGRAPHIC ANALYSIS

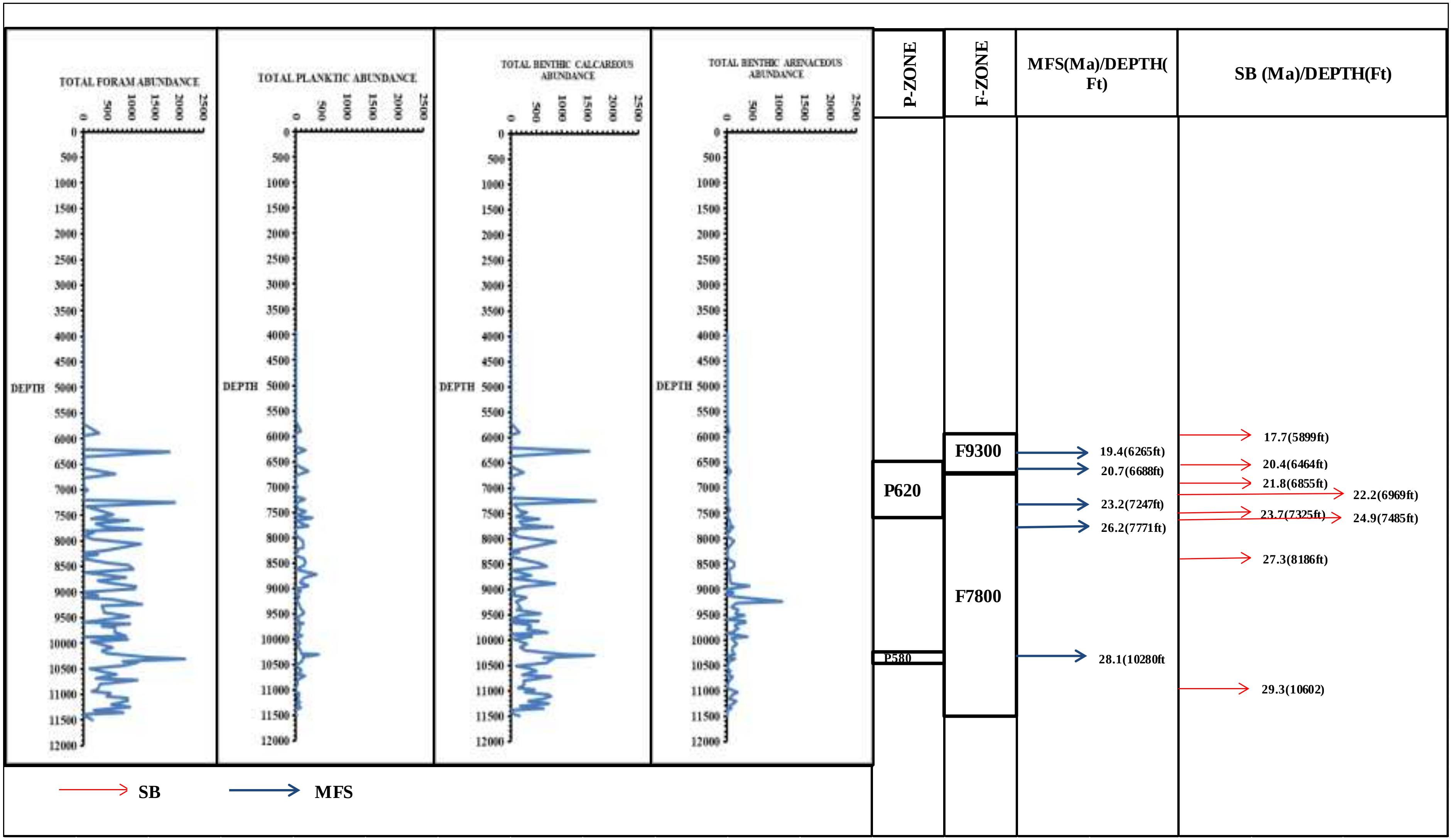
4.2.1 Methodology and Model

Sequence stratigraphy analyzes sedimentary deposits within a chronostratigraphic framework, linking sediment accumulation to changes in accommodation space and sediment supply (Catuneanu, 2006). This study utilized the Exxon Production Research Model (EPRM) as defined by Vail and Wornardt (1990) and Van Wagoner et al. (1988).

The model was constrained using foraminiferal abundance patterns, which are integrated with lithology data for the sequence stratigraphic study. Foraminiferal abundance peaks and high shale content are used to locate the condensed interval, which defines the **Maximum Flooding Surface (MFS)**, and minimum foraminiferal abundance and high sand/low shale content were used to locate **Sequence Boundaries (SB)**.

These surfaces were calibrated against the Niger Delta Chronostratigraphic Chart (Haq et al., 1988; Stacher, 1995) to assign absolute ages. The resulting sequence stratigraphic model, showing the foraminiferal abundance pattern against the interpreted bounding surfaces, is summarized in **Table 7**.

Table 7 Foraminifera Abundance Pattern and Sequence Stratigraphic Model For Well X-1



4.2.2 Sequence Boundaries (SB)

The sequence boundary is an unconformity formed during relative sea-level lowering and during lowstand (Van Wagoner et al., 1988). The SB may be marked by a decrease in both fossil abundance and diversity due to rapid accumulation of sediment or destruction of shell material in shallow, high-energy environments (Armentrout, 1991).

In the study well, minimum foraminiferal abundance is interpreted as sequence boundaries. As shown in **Table 8**, eight (8) Sequence Boundaries were delineated in Well X-1, ranging from 17.7 Ma to 29.3 Ma.

Table 8: Identified Sequence Boundaries and Intervals.

S/N	**Depth (ft)**	**Sequence Boundary Age (Ma)**
1	5,899	17.7
2	6,434	20.4
3	6,688	20.7
4	6,982	22.2
5	7,325	23.7
6	7,485	24.9
7	8,186	27.3
8	10,602	29.3

4.2.3 Maximum Flooding Surfaces (MFS)

The MFS separates the transgressive systems tract (TST) from the highstand systems tract (HST) and represents the maximum landward extent of marine conditions (Emery and Myers, 1996). This surface is often represented by a significant increase in fossil abundance and diversity and by the deepest water biofacies assemblage of the cycle (Armentrout, 1987, 1991).

Five (5) MFS were delineated in Well X-1, ranging in age from the Oligocene to Miocene. These surfaces, along with their associated shale markers, are detailed in **Table 9**.

Table 9: Identified Maximum Flooding Surfaces and Marker Shales.

S/N	Depth (ft)	MFS Age (Ma)	Marker Shales
1	6,265	19.4 (Burdigalian)	Oghara Shale
2	6,688	20.2 (Burdigalian)	Alabamina 2
3	7,247	23.2 (Aquitanian)	Bolivina 26
4	7,771	26.2 (Chattian 2)	Alabamina 1
5	10,280	28.1 (Chattian 1)	Bolivina 27

4.3 BIOSTRATIGRAPHY AND PALEOENVIRONMENT

4.3.1 General Trends in Foraminiferal Association with Depth

Biostratigraphy uses the chronostratigraphic range of fossil species to correlate sections and their paleoenvironmental preferences to provide information on depositional settings (Emery and Myers, 1996). The analysis of foraminiferal distribution revealed depth-dependent trends consistent with established bathymetric zonation (Petters, 1982):

i. **Shelf Environment (5 m - 200 m):** Characterized by an abundance of calcareous benthonic foraminifera. The paleo-shelf edge (~200 m) is marked by an influx of planktic foraminifera.

ii. **Slope Environment (200 m - 3000 m):** Shows an overall abundance of planktonic foraminifera. Maximum diversity of calcareous benthonic forms is found in the upper slope, while maximum diversity of agglutinated or arenaceous benthonic foraminifera is observed in the lower slope.

iii. **Abyssal Environment (3000 m and above):** Characterized by an abundance of arenaceous benthonic foraminifera.

The spinose forms of planktonic foraminifera are relatively abundant in the inner shelf, thriving in high-energy environments, while the keeled forms are relatively abundant in the slope, thriving in low-energy environments.

4.3.2 Paleobathymetry

Palaeobathymetry, interpreted using benthonic foraminifera, is a valuable tool in petroleum exploration for determining the depositional history of a basin (Fleisher and Lane, 1999). Based on the overall biofacies assemblage and the general distribution trends observed, the environment of deposition for the sequence penetrated by Well X-1 is interpreted to be predominantly a Shelf Environment, fluctuating between Inner and Middle Neritic conditions during the periods of maximum transgression (MFS).

CHAPTER FIVE

SUMMARY, CONCLUSION, AND RECOMMENDATIONS

5.1 SUMMARY

The study successfully performed a lithostratigraphic and biostratigraphic analysis on seventy-two (72) ditch cutting samples from the study well (Well X-1) spanning the depth interval of 4,500 ft to 11,460 ft (1,372 m - 3,493 m) within the Greater Ughelli Depobelt of the Niger Delta Basin.

Key Findings:

i. **Lithostratigraphy:** The well penetrates a classic paralic succession of alternating shales and sandstones, characteristic of the Agbada Formation. Forty-nine (49) individual lithozones were identified based on microscopic examination.

ii. **Hydrocarbon Play Elements:** Potential hydrocarbon elements were delineated based on lithology:

    a. **Reservoir Rock:** Sand-dominated intervals between 5,340 ft and 7,260 ft.

    b. **Source Rock:** Thick shale sections interpreted between 7,860 ft and 11,460 ft.

    c. **Seal/Cap Rock:** Shale-dominated unit located between 4,740 ft and 5,200 ft.

iii. **Sequence Stratigraphy:** Through the integration of foraminiferal abundance curves and established biozonation data, a sequence stratigraphic framework was established based on the Exxon Production Research Model (EPRM).

iv. **Bounding Surfaces:** The model identified **eight (8) Sequence Boundaries (SBs)**, ranging in age from 17.7 Ma to 29.3 Ma, and **five (5) Maximum Flooding Surfaces (MFSs)**, ranging from 19.4 Ma (Burdigalian) to 28.1 Ma (Chattian).

v. **Paleoenvironment:** The dominant biofacies assemblage, characterized by an abundance of calcareous benthic foraminifera, indicates that the depositional environment was primarily **Neritic (Shelf)**, fluctuating between Inner and Middle Neritic conditions.

5.2 CONCLUSION

The objectives of the study were achieved by successfully delineating the key lithostratigraphic and sequence stratigraphic units.

The study concludes that:

1. The stratigraphic succession represents a Cenozoic prograding deltaic system, deposited primarily in a fluctuating **shelf-edge to inner-shelf setting**.
2. The maximum abundance peaks in foraminifera correlate precisely with the interpreted MFSs, validating the use of **micropaleontology** as a robust tool for constraining sequence stratigraphic surfaces in the Niger Delta.
3. The alternating lithologies establish a clear framework for the entire **petroleum system**, confirming the presence of vertically stacked source, reservoir, and seal units necessary for hydrocarbon accumulation within the study well.
4. The established MFS and SB ages provide the necessary **chronostratigraphic control** for regional correlation, linking the local depositional cycles to the broader eustatic sea-level history defined by Haq et al. (1988).

5.3 RECOMMENDATIONS

Based on the findings and the sequence stratigraphic model generated, the following recommendations are made for future studies and practical applications:

1. **Field Development:** The identified reservoir zones, particularly within the 5,340 ft to 7,260 ft interval, should be prioritized for petrophysical evaluation (logs and core data analysis) to accurately quantify their **porosity and permeability**.

2. **Seismic Integration:** The interpreted MFSs and SBs should be integrated with **seismic reflection data** to map the lateral extent of the sequences and systems tracts, providing a three-dimensional framework for hydrocarbon exploration within the wider depobelt.
3. **Chemostratigraphy:** Future research should incorporate detailed **geochemical analysis** of the interpreted source rock unit (7,860 ft - 11,460 ft) to determine the type of organic matter present and its thermal maturity.
4. **Deeper Intervals:** Investigation into intervals below 11,460 ft is recommended to determine the potential penetration of the deeper, oil-prone **Akata Formation** shales.

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APPENDICES

Appendix A: Raw Foraminiferal Biofacies Data

This appendix contains the complete, detailed quantitative analysis of foraminiferal abundance across the entire well section. This dataset forms the foundation for the Sequence Stratigraphic Model (Table 7) and the paleoenvironmental interpretations (Chapter Four).

The table below is the complete **Biofacies Data** for Well X-1 (the full dataset corresponding to the excerpt in Table 4).

SN	Depth (ft)	Total Foram Abundance	Total Planktic Abundance	Total Benthic Calcareous Abundance	Total Benthic Arenaceous Abundance
1	3960	0	0	0	0
2	4200	0	0	0	0
3	4320	0	0	0	0
4	4500	0	0	0	0
5	4530	0	0	0	0
6	4710	0	0	0	0
7	4770	0	0	0	0
8	4950	0	0	0	0

SN	Depth (ft)	Total Foram Abundance	Total Planktic Abundance	Total Benthic Calcareous Abundance	Total Benthic Arenaceous Abundance
9	4980	0	0	0	0
10	5125	0	0	0	0
11	5149	0	0	0	0
12	5207	0	0	0	0
13	5344	0	0	0	0
14	5460	0	0	0	0
15	5520	0	0	0	0
16	5580	0	0	0	0
17	5715	0	0	0	0
18	5899	319	91	171	42
19	5940	0	0	0	0
20	6060	0	0	0	0
21	6210	0	0	0	0

SN	Depth (ft)	Total Foram Abundance	Total Planktic Abundance	Total Benthic Calcareous Abundance	Total Benthic Arenaceous Abundance
22	6265	1794	194	1533	12
23	6360	0	0	0	0
24	6434	10	0	6	3
25	6570	0	0	0	0
26	6688	663	239	249	75
27	6765	0	0	0	0
28	6855	0	0	0	0
29	6962	11	1	8	1
30	7005	87	23	61	1
31	7037	10	1	9	0
32	7131	7	0	6	1
33	7193	0	0	0	0
34	7247	1899	176	1659	34

SN	**Depth (ft)**	**Total Foram Abundance**	**Total Planktic Abundance**	**Total Benthic Calcareous Abundance**	**Total Benthic Arenaceous Abundance**
35	7325	56	0	55	1
36	7440	453	42	166	60
37	7485	623	192	314	16
38	7560	156	7	101	2
39	7603	940	326	559	30
40	7663	258	17	161	54
41	7725	430	121	224	54
42	7771	1234	241	828	133
43	7807	33	0	33	0
44	7835	209	5	115	68
45	7900	3	0	1	2
46	7960	179	13	154	6
47	8054	1196	142	882	136

SN	Depth (ft)	Total Foram Abundance	Total Planktic Abundance	Total Benthic Calcareous Abundance	Total Benthic Arenaceous Abundance
48	8186	452	145	245	31
49	8234	0	0	0	0
50	8263	301	45	171	14
51	8291	10	0	0	9
52	8348	0	0	0	0
53	8420	484	161	244	47
54	8476	934	189	554	140
55	8550	1041	164	710	136
56	8625	24	5	2	16
57	8718	877	401	389	66
58	8780	299	159	57	56
59	8820	558	136	324	63
60	8890	1089	81	867	90

SN	Depth (ft)	Total Foram Abundance	Total Planktic Abundance	Total Benthic Calcareous Abundance	Total Benthic Arenaceous Abundance
61	8942	1059	247	227	434
62	9006	10	1	2	2
63	9034	93	4	48	14
64	9065	296	94	71	125
65	9093	3	0	2	1
66	9107	34	5	28	1
67	9150	583	71	303	139
68	9238	1218	11	98	1064
69	9273	382	36	123	178
70	9359	425	77	191	82
71	9397	424	95	109	219
72	9480	955	167	583	168
73	9515	700	118	175	347

SN	Depth (ft)	Total Foram Abundance	Total Planktic Abundance	Total Benthic Calcareous Abundance	Total Benthic Arenaceous Abundance
74	9588	0	0	0	0
75	9623	963	61	546	351
76	9661	378	1	17	360
77	9691	662	146	295	165
78	9720	645	62	399	159
79	9780	640	85	310	221
80	9857	882	56	715	106
81	9877	0	0	0	0
82	9926	927	120	410	390
83	9973	153	4	59	89
84	10080	598	77	310	189
85	10140	381	34	177	109
86	10200	481	84	287	104

SN	Depth (ft)	Total Foram Abundance	Total Planktic Abundance	Total Benthic Calcareous Abundance	Total Benthic Arenaceous Abundance
87	10280	1334	111	1071	152
88	10299	2122	451	1633	13
89	10346	817	131	640	46
90	10363	1140	157	826	151
91	10440	850	111	700	34
92	10505	130	19	94	17
93	10560	424	48	364	11
94	10602	687	106	506	75
95	10686	259	23	224	12
96	10723	1119	173	788	108
97	10800	343	26	240	52
98	10891	292	25	256	11
99	10942	163	4	132	22

SN	Depth (ft)	Total Foram Abundance	Total Planktic Abundance	Total Benthic Calcareous Abundance	Total Benthic Arenaceous Abundance
100	10975	566	7	466	92
101	11034	482	9	269	202
102	11078	915	74	729	111
103	11115	919	51	781	81
104	11160	736	48	635	46
105	11198	573	46	337	185
106	11250	963	86	739	127
107	11310	217	11	180	25
108	11355	827	90	641	85
109	11384	1	0	1	0
110	11425	0	0	0	0
111	11460	96	4	74	11
112	11500	179	14	162	3

Appendix B: Detailed Lithozone Descriptions

This appendix contains the detailed lithological descriptions for the **forty-nine (49) Lithozones** identified in Well X-1, which forms the basis of the lithostratigraphic model and the delineation of hydrocarbon play elements in Chapter Four.

Lithozone	**Depth (ft / m)**	**Thickness (ft / m)**	**Description**
1	11460-11340 / 3493-3456	120 / 37	Light grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
2	11220 / 3420	-	Dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
3	11100 / 3383	-	Light to dark grey shale; fissile, **calcareous**, moderately hard. Mineral: Quartz.
4	10980-10860 / 3347-3310	120 / 37	Light to dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
5	10740 / 3274	-	Dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
6	10620 / 3237	-	Brownish grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.

Lithozone	Depth (ft / m)	Thickness (ft / m)	Description
7	10500 / 3200	-	Dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
8	10380 / 3464	-	Brownish grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
9	10260-10020 / 3127-3054	240 / 73	Light to dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
10	9900 / 3018	-	Brownish grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
11	9780-9660 / 2981-2944	120 / 37	Light to dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
12	9540 / 2908	-	Brownish grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
13	9420 / 2871	-	Light to dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
14	9300-9060 / 2835-2761	240 / 74	Dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.

Lithozone	**Depth (ft / m)**	**Thickness (ft / m)**	**Description**
15	8820 / 2688	-	Light grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
16	8700-8340 / 2652-2542	360 / 110	Brownish grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
17	8220 / 2505	-	Light to dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
18	8100-8040 / 2469-2451	60 / 18	Light to dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
19	7980-7860 / 2432-2396	120 / 36	Brownish grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
20	7740 / 2359	-	Poorly sorted light grey shaly sand (90% sandstone, 10% shale); sand is coarse and angular. Mineral: Quartz.
21	7620-7500 / 2323-2286	120 / 37	Brownish grey sandy shale (80% shale, 20% sand) and brownish grey shale. Mineral: Quartz and Feldspar.
22	7380 / 2249	-	Dark grey shale; fissile, non-calcareous,

Lithozone	Depth (ft / m)	Thickness (ft / m)	Description
			moderately hard. Mineral: Quartz and Mica.
23	7320 / 2231	-	Poorly sorted whitish to dark grey shaly sand (70% sandstone, 30% shale); sand is coarse and sub-angular. Mineral: Quartz and Mica.
24	7260 / 2231	-	Dark grey sandstone; coarse, angular to sub-rounded, well sorted. Mineral: Quartz and Mica.
25	7200-7140 / 2195-2176	60 / 19	Well sorted light grey sandstone; coarse and sub-rounded. Mineral: Quartz.
26	7080-7020 / 2158-2140	60 / 18	Light grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
27	6960-6900 / 2121-2103	60 / 18	Poorly sorted shaly sand (whitish to light grey, 70% sand, 30% shale; whitish to dark grey, 90% sand, 10% shale). Mineral: Quartz.
28	6840 / 2085	-	Light grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
29	6780 / 2067	-	Poorly sorted whitish to dark grey sandy shale

Lithozone	**Depth (ft / m)**	**Thickness (ft / m)**	**Description**
			(60% shale, 40% sandstone); sand is coarse and sub-rounded. Mineral: Quartz.
30	6720-6600 / 2048-2012	120 / 36	Whitish to colorless sandstone; coarse, angular to sub-angular, sub-rounded. Mineral: Quartz.
31	6540 / 1993	-	Poorly sorted light grey shaly sand (90% sandstone, 10% shale); sand is coarse and sub-rounded. Mineral: Quartz.
32	6480 / 1975	-	Poorly sorted light to dark grey sandy shale (90% shale, 10% sandstone); sand is coarse and sub-rounded. Mineral: Quartz.
33	6420 / 1957	-	Light grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
34	6360 / 1939	-	Dark grey sandy shale (80% shale, 20% sandstone); fissile, non-calcareous, moderately hard. Mineral: Quartz.
35	6300 / 1920	-	Whitish to colorless sandstone; coarse, angular, well sorted. Mineral: Quartz.

Lithozone	**Depth (ft / m)**	**Thickness (ft / m)**	**Description**
36	6240 / 1902	-	Poorly sorted whitish to dark grey shaly sand (80% sandstone, 20% shale); sand is coarse and sub-angular. Mineral: Quartz and Mica.
37	6180 / 1884	-	Well sorted whitish to dark grey sandstone; coarse and angular. Mineral: Quartz and Mica.
38	6120 / 1865	-	Poorly sorted whitish to dark grey sandy shale (60% shale, 40% sandstone); sand is coarse and sub-rounded. Mineral: Quartz and Mica.
39	6065 / 1847	-	Light to dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz and Mica.
40	6000 / 1829	-	Poorly sorted whitish to dark grey shaly sand (80% sandstone, 20% shale); sand is coarse and sub-rounded. Mineral: Quartz and Mica.
41	5940 / 1811	-	Whitish to dark grey sand; coarse, sub-rounded to sub-angular, well sorted. Mineral: Quartz and Mica.

Lithozone	**Depth (ft / m)**	**Thickness (ft / m)**	**Description**
42	5880-5580 / 1792-1701	300 / 91	Poorly sorted whitish to dark grey shaly sands and sandy shale; sands are coarse and sub-rounded. Mineral: Quartz and Mica.
43	5460 / 1664	-	Dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz, Mica.
44	5340 / 1628	-	Poorly sorted, whitish to dark grey shaly sand (90% sandstone, 10% shale); sand is coarse and sub-rounded. Mineral: Quartz and Mica.
45	5220 / 1591	-	Light grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
46	5100-4860 / 1554-1481	360 / 109	Dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
47	4820 / 1469	-	Light to dark grey shale; fissile and moderately hard. Mineral: Quartz.
48	4740 / 1445	-	Dark grey shale; fissile, non-calcareous, moderately hard. Mineral: Quartz.
49	4500 / 1372	-	Well sorted whitish to colorless sandstone;

Lithozone	Depth (ft / m)	Thickness (ft / m)	Description
			coarse and sub-rounded. Mineral: Quartz.

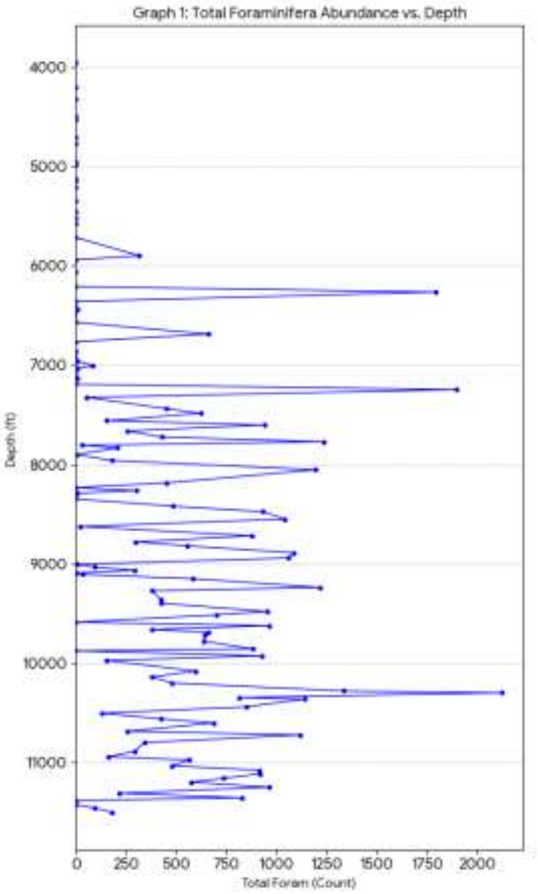
Appendix C: Graphical Outputs

1. This appendix contains the four biostratigraphic charts generated from the Biofacies Data (Appendix A) and utilized for sequence stratigraphic interpretation (Chapter Four)

Graph 1: Total Foraminifera Abundance vs. Depth

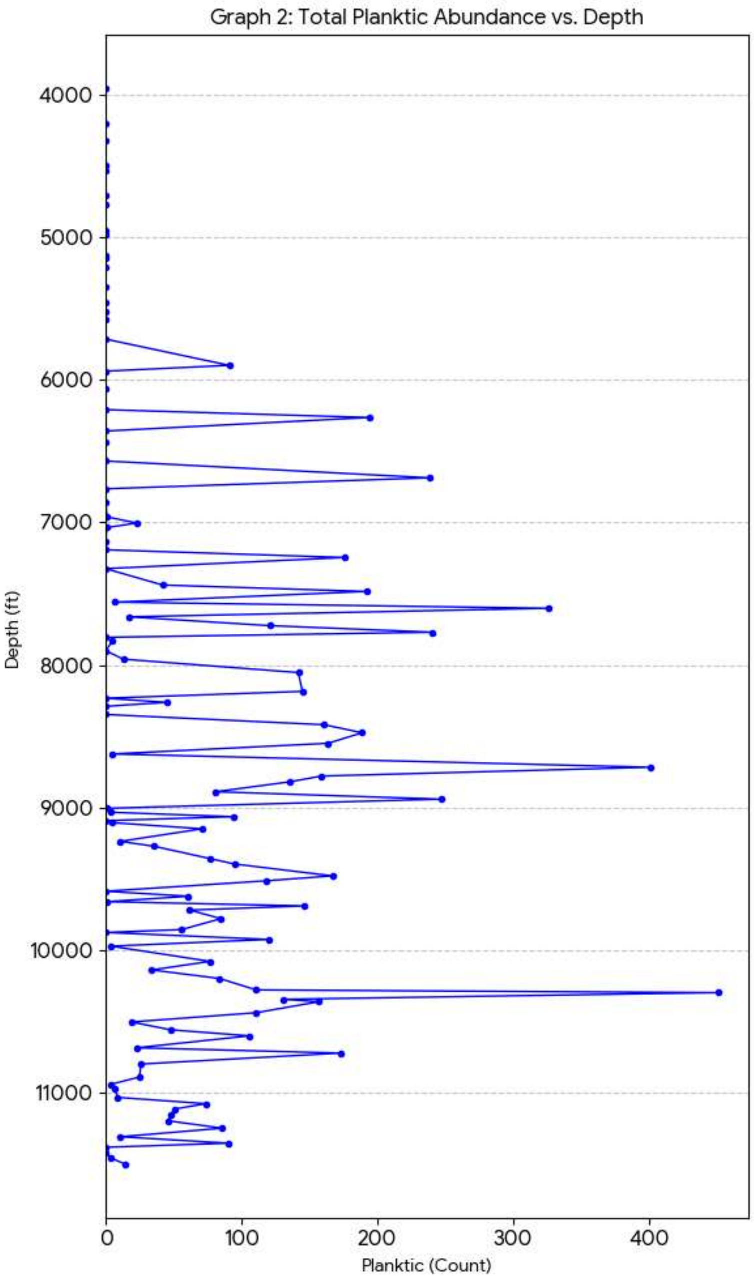
This graph displays the overall concentration of all foraminiferal species. The **peaks in abundance** are strongly correlated with periods of maximum marine transgression, defining the

Maximum Flooding Surfaces (MFS), while troughs suggest potential Sequence Boundaries (SB) or high-energy regimes.



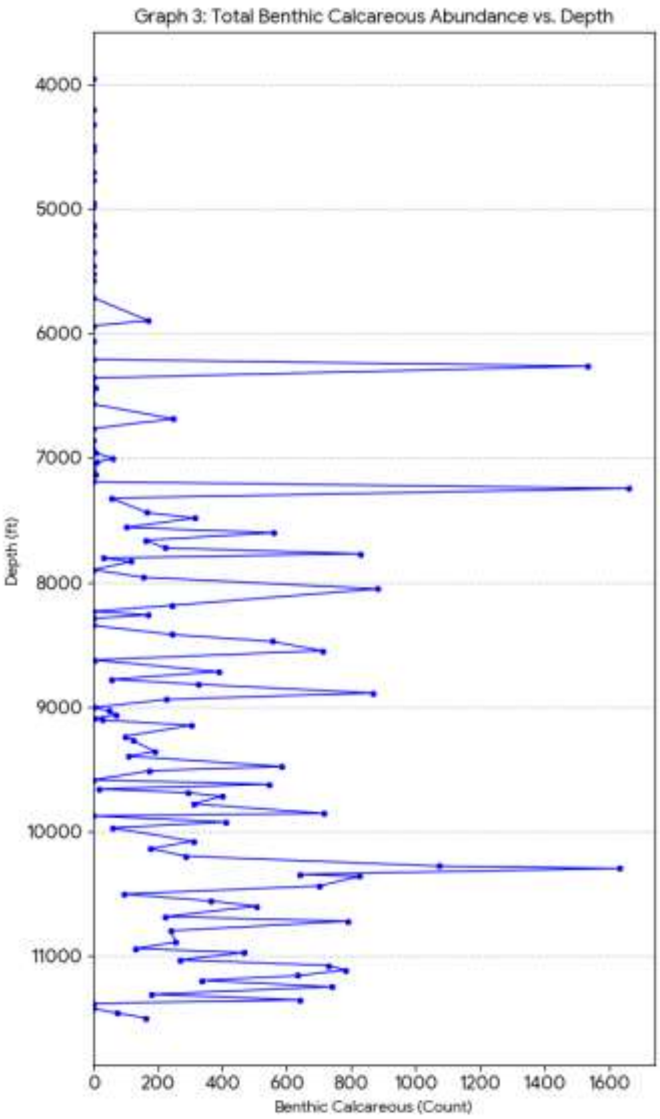
2. Graph 2: Total Planktic Foraminifera Abundance vs. Depth

Planktic foraminifera are crucial for chronostratigraphy and paleoenvironmental interpretation as they are indicative of **open marine influence** and greater water depth. High planktic abundance often confirms the deepest marine conditions and supports the identification of MFS.



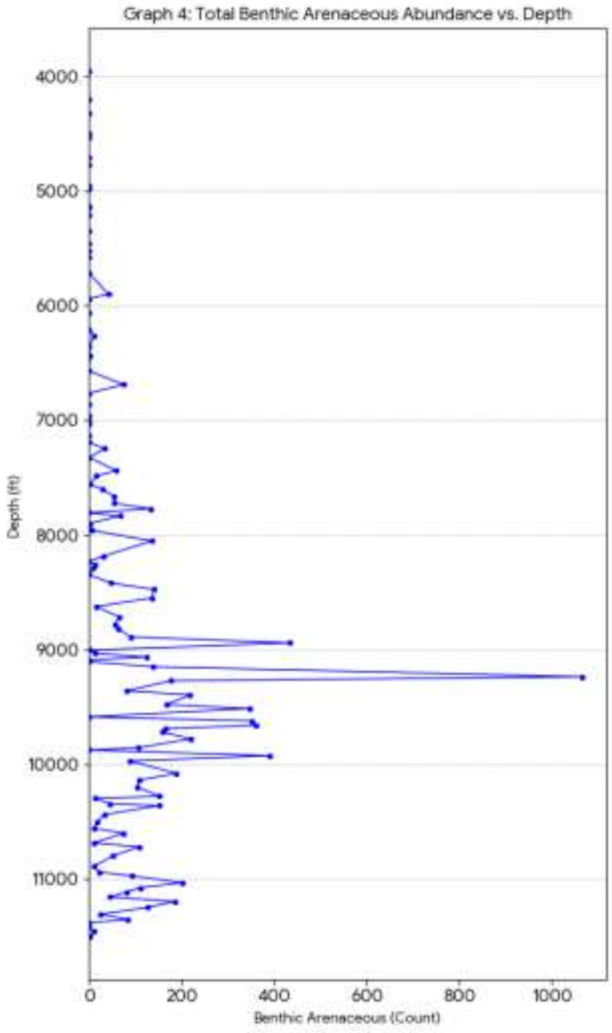
3. Graph 3: Total Benthic Calcareous Abundance vs. Depth

This chart tracks the distribution of calcareous benthic species. High concentrations typically signify well-oxygenated **Neritic (Shelf) environments** with normal marine salinity, supporting the general interpretation that the Agbada Formation was deposited in a shelf setting.



4. **Graph 4:** Total Benthic Arenaceous Abundance vs. Depth

This chart visualizes the distribution of agglutinated forms. High dominance of arenaceous species, especially in the lower slope (bathyal) and abyssal environments , suggests **stressed conditions** such as high sedimentation rates or low oxygenation (dysaerobic/anaerobic conditions).


Graph 4: Total Benthic Arenaceous Abundance vs. Depth
Depth (ft)
4000
5000
6000
7000
8000
9000
10000
11000
0
200
400
600
800
1000
Benthic Arenaceous (Count)