SEQUENCE STRATIGRAPHIC INTERPRETATION OF WELLS 1,2,3 & 4 IN THE "GERA" FIELD, GREATER UGHELLI DEPOBELT, NIGER DELTA BASIN, NIGERIA

By

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CERTIFICATION

This is to certify that this thesis has been read and approved as meeting the requirements of the Department of Geology, School of Sciences, Federal University of Technology, Owerri Imo State.

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DEDICATION

This piece of work is dedicated to God Almighty - My Wonderful Provider and to the loving memory of my late sister- Miss Chibuogu Vivian Onwualu.

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ABSTRACT

A sequence stratigraphic approach was employed to understand sediments penetrated in Gera Field situated in the Greater Ughelli Depobelt, Central Niger Delta Basin. The technique incorporates biostratigraphic and well log data in constructing a high-resolution sequence stratigraphic framework for the field. The analysis of the above data sets enabled the subdivision of the transverse part of the stratigraphic column within the field into sequences and system tracts. Four 3rd order Maximum Flooding Surfaces (MFS) and their intervening sequence boundaries (SB) were interpreted in the area. Three depositional sequences were interpreted within the field and were subdivided into transgressive systems tract and highstand systems tract. Four maximum flooding surfaces correlate with the 28.1Ma, 31.3Ma, 33.0Ma and 34.0Ma of the transgressive marker shales of the Niger Delta Chronostratigraphic Chart. The 28.1 million years (Ma) MFS (G. Opima Opima) with its distinct log signature, constitutes the regional seal rock while the different sequence boundaries act as excellent reservoirs of the field. Of the four sequence boundaries, only one was found to be truly Type-1 sequence boundary, while the other three could not be convincingly attributed to a Type-1 sequence boundary, since a lowstand systems tract does not overlie them. The age of sediments penetrated in Gera field is found to range from Early – Late Oligocene as deduced from the foram zonations of wells in the field.

Key words: Biostratigraphy, Well log, Sequence boundary, Maximum Flooding Surface, Niger Delta.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

As oil and gas reserves diminish around the globe due to excessive exploitation, the need for discovery and development of smaller and more complex reserves to ensure continuity and greater profitability is required. Newly found oil and gas prospects need to be explored and reassessed for additional hydrocarbon resources.

The understanding of the spatial distribution and time of formation of the depositional suites in the Niger Delta Basin is essential to ensure the discovery of additional oil and gas fields and also for the sustainable development of existing fields.

The elements of sequence stratigraphy had been around long before it acquired its modern name, and those elements had their own terminologies that are familiar to most geologists and geophysicists (e.g. depositional cycles, unconformities, beds and bed sets, laminae and laminae sets etc). The publication of Sloss' report of 1963 by Exxon's Stratigraphic Technology in the AAPG Memoir of 1977, has a unique language that excited the geologic community and irritated many that dislike the proliferation of new terminology for long-held concepts. With time, objection faded, perhaps because the new language became more widely used, very familiar, and its usefulness was seen as an unparallel exploration tool for oil and gas as well as a production tool for reservoir development.

Akaegbobi et al. (2007) defined Sequence stratigraphy as an approach that facilitates the subdivision of lithostratigraphic units into packages of sediments that are essentially bounded top and base by chronostratigraphically significant surfaces. Sequence Stratigraphy is therefore an aspect of stratigraphy that subdivides the lithic fill of any given basin into distinct or discrete genetically related sedimentary packages – sequences – bounded by widespread, laterally traceable unconformities and their correlative conformities, (Nwajide, 2010). Posamentier et al (1988) defined Sequence Stratigraphy as the study of rock relationships within a chronostratigraphic framework wherein succession of rocks is cyclic and composed of genetically related stratal units (system tracts). Sequence stratigraphic analysis of successions define key stratal surfaces at abrupt dislocations of system tracts to delineate broad-scale facies trends formed by a long-basin shifts in depositional environments and changes in preservation within system tracts (Vail et al., 1977; Posamentier et al., 1988). It is a data integration technique that puts a vertical succession of strata into a time-constrained spatial framework.

Sequence stratigraphy studies the change in depositional trends in response to the interplay of accommodation and sedimentation, from the scale of the entire sedimentary basins to individual depositional systems. Thus the concept is applicable on scales from an entire basin fill to a reservoir. It is worth noting that the shoreline with its transgressive and regressive shifts represents the central element around which all standard sequence stratigraphic concepts are defined. This is because changes in accommodation largely take place there. Moreover, the interplay of eustasy, subsidence and sedimentation at the shoreline controls the timing of the onset of base level fall and rise, end of regression and end of transgression.

Fundamentally, therefore, sequence stratigraphy analyzes sediment response to base level changes, and depositional trends that emerge from the interplay of accommodation and sedimentation. Base level (accommodation) changes and sedimentation are thus the “structural pillars” of sequence stratigraphic architecture. Sequence Stratigraphic concept of interpretation establishes how sequence of strata accumulated in order in the sedimentary section over a subdividing framework of surfaces. Sequence stratigraphic surfaces are formed in response to base level shifts resulting in transgressions and regressions (forced and normal). Catuneanu (2006) listed seven such surfaces but the major bounding surfaces on the basis they are easily identified in seismic section, outcrops and well logs (Fig. 1) are:

- Maximum Flooding Surfaces (MFS),
- Transgressive Surfaces (TS)
- Sequence Boundaries (SB)

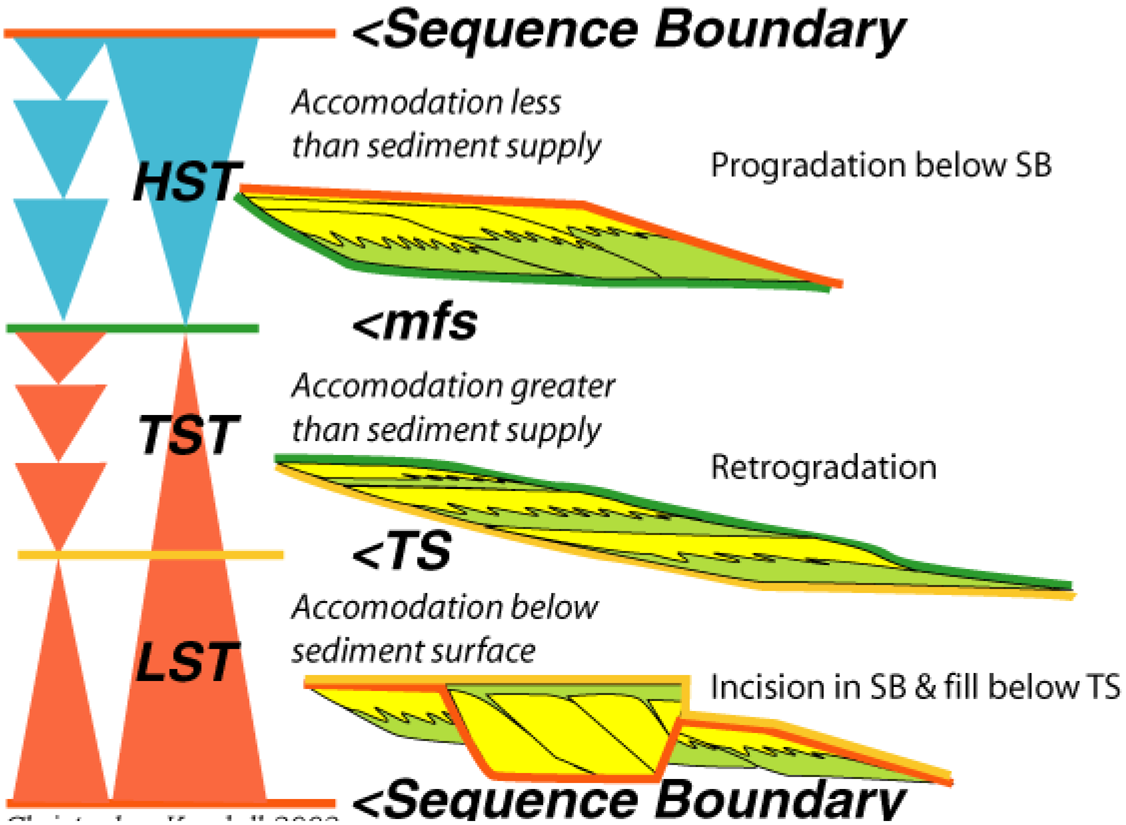

Fig. 1: Schematic diagram of major surfaces and their system tracts (After, Kendall, 2003).

Sequence boundary is a chronostratigraphically significant surface produced as a consequence of a fall of relative sea level. It is usually a subaerial unconformity, *i.e.* a surface of erosion or nondeposition created generally during base level fall by subaerial processes such as fluvial incision, wind degradation, sediment bypass or pedogenesis.

Marine flooding surface is a surface that separates older from younger strata across which there is evidence of an abrupt increase in water depth. The surfaces are typically prominent and mappable. Maximum flooding surface records the maximum extent of marine drowning and separates transgressive (retrograding) units below from regressive (prograding and/or aggrading facies in the early highstand normal regressive) units above.

Transgressive surface is a prominent flooding surface capping the lowstand systems tract. It represents the first major flooding surface to follow the sequence boundary and is usually distinct from the relatively minor surfaces that separate parasequences within the lowstand systems tract. It may be accompanied by significant condensation, especially in nearshore settings which may be starved of sediment. After the lowstand systems tract low rates of accommodation, the sea level begins to rise and following the short term rise that forms a parasequence boundary, a major flooding surface is formed and the first of the series of these flooding surfaces is called the transgressive surface.

This subdivision of the sedimentary section provides the order in which the sediments were laid down (law of superposition), and their relative age. The arrangement of the vertical succession of facies of the sediment geometries bounded by the surfaces (stacking patterns), forms a major element to the interpretation of the depositional settings of stratigraphic section. These stacking patterns (Fig. 2) vary between:

- Progradational
- Retrogradational
- Aggradational

Systems tract is defined as a linkage of contemporaneous depositional systems, where a depositional system is a three-dimensional assemblage of lithofacies, genetically linked by active (modern) or inferred (ancient) processes and environments. Each systems tract is defined by a specific stacking pattern closely associated with a type of shoreline shift (i.e. forced regression, normal regression, or transgression), and represents a specific sedimentary response to the interaction between sediment flux, physiography, environmental energy, and changes in accommodation.

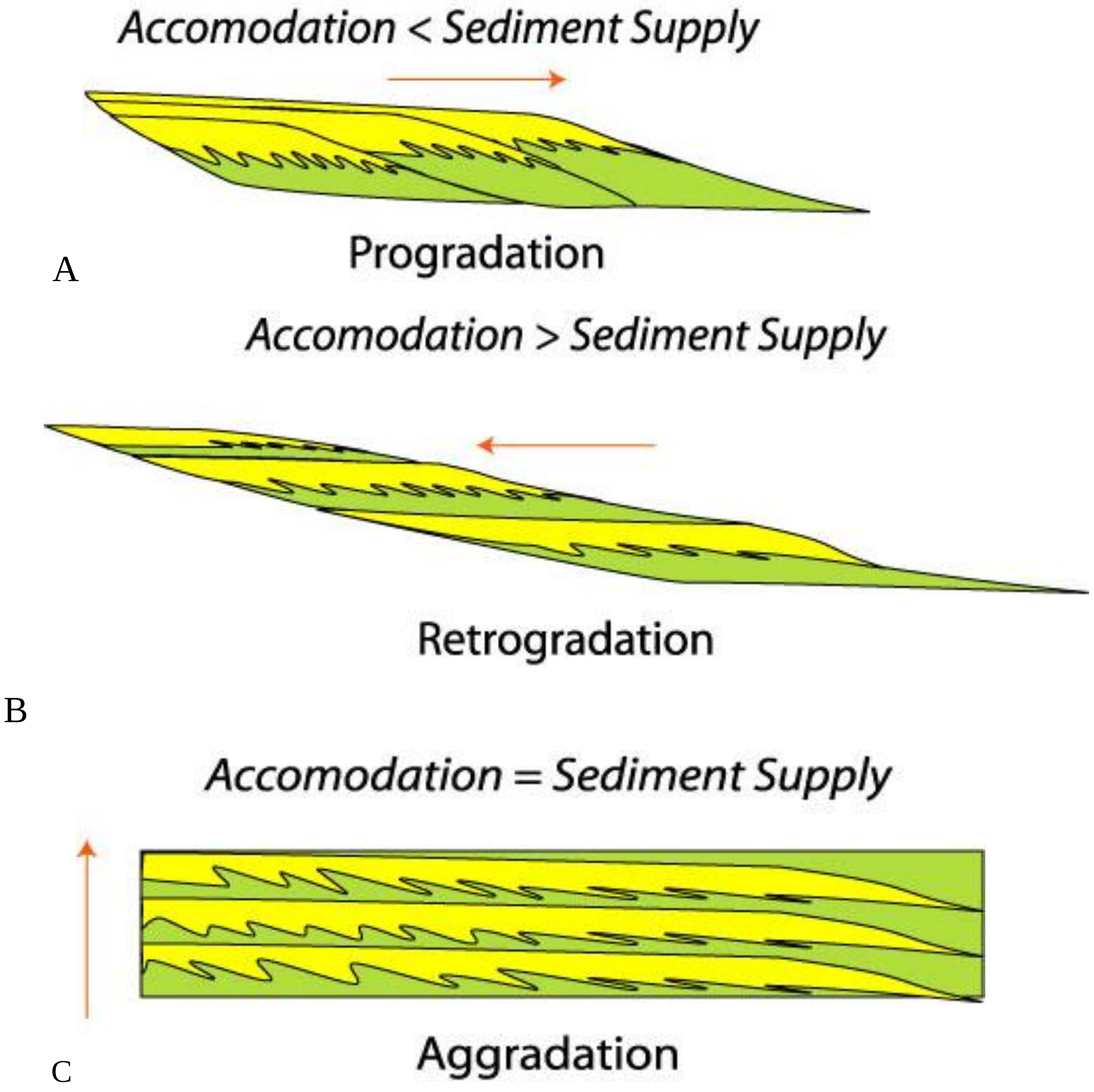

Fig. 2: Schematic Diagram of Retrogradational, Progradational and Aggradational Stacking Pattern(Posamentier and Allen, 1999).

Posamentier and Allen, (1999) categorized system tracts into three groups-

- **Lowstand Systems Tract** (LST)

This consists of deposits of early sea level rise during normal regression. It is bounded at the base by subaerial unconformity and its marine correlative conformity and at the top by a maximum regressive surface. It forms during the early stage of base level rise when the rate of rise is outpaced by the sedimentation rate (Fig. 3a). Thus the depositional processes and stacking patterns are dominated by low-rate aggradation and progradation across the entire basin. As accommodation increases due to rising base level, the lowstand wedge is expected to include the entire suite of depositional systems from fluvial to coastal, shallow marine and deep marine. The deep water portion is dominated by low-density turbidites.

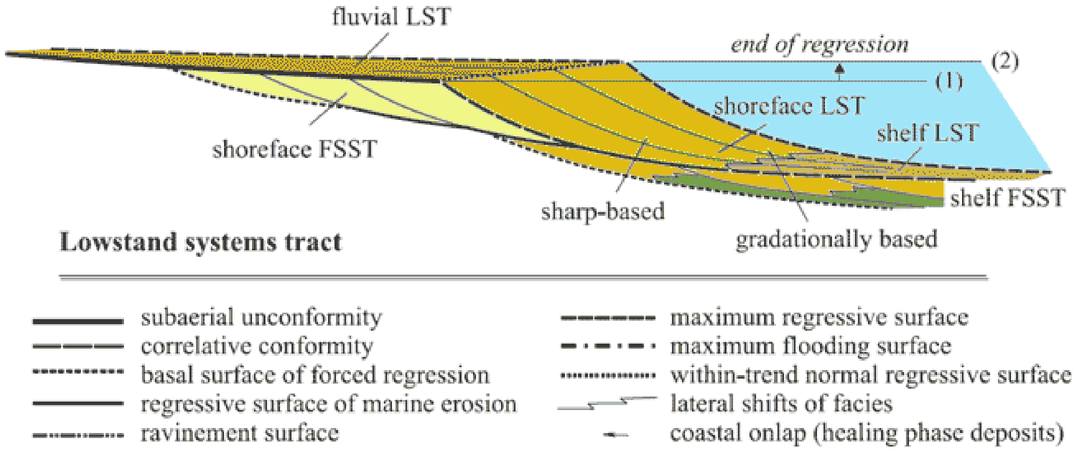

Fig. 3a: **Lowstand Systems Tract (After Catuneanu, 2002)**

- **Transgressive Systems Tract (TST)**

This is bounded by the maximum regressive surface at the base and by the maximum flooding surface at the top. It forms during the stage of base level rise when the rates of rise outpace the sedimentation rates at the shoreline (Fig. 3b). A diagnostic feature is the retrogradational stacking pattern which results in overall fining upward profiles in both marine and nonmarine successions. Since the rates of creation of accommodation is highest during shoreline transgression, the Transgressive Systems Tract is expected to include the entire range of depositional systems formed along the dip of a sedimentary basin, ranging from fluvial to coastal, shallow marine and deep marine.

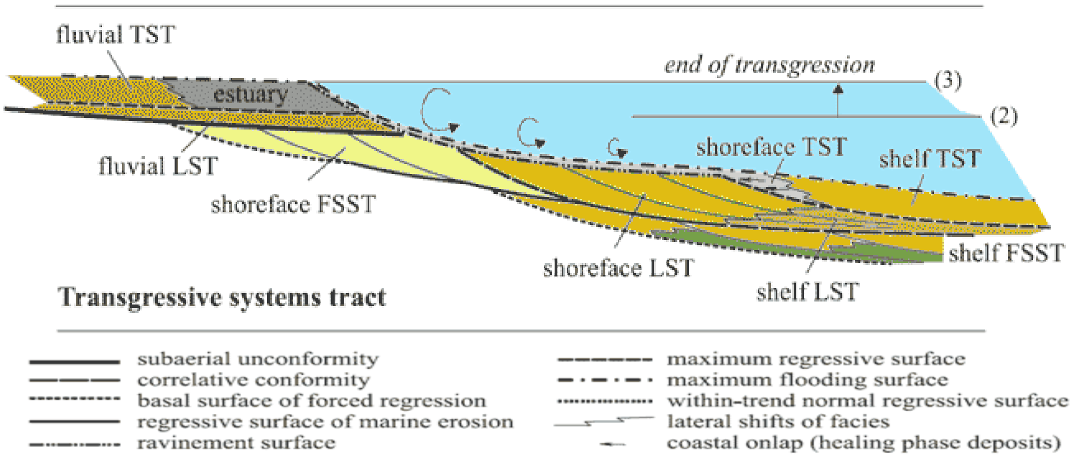

Fig. 3b: **Transgressive Systems Tract (After Catuneanu, 2002)**

- **Highstand Systems Tract (HST)**

This systems tract is bounded by the Maximum Flooding Surface (MFS) at the base, and a composite surface at the top made up of a portion of subaerial unconformity, the basal surface of forced regression, and the oldest portion of the regressive surface of marine erosion (Fig. 3c). Highstand Systems Tract forms during the late stage of base level rise, when the rate of rise drops below the sedimentation rate, generating a normal regression of the shoreline. Thus the stacking patterns are dominated by a combination of aggradation and progradation processes. The bulk of the highstand prism consists of fluvial, coastal and shoreface deposits.

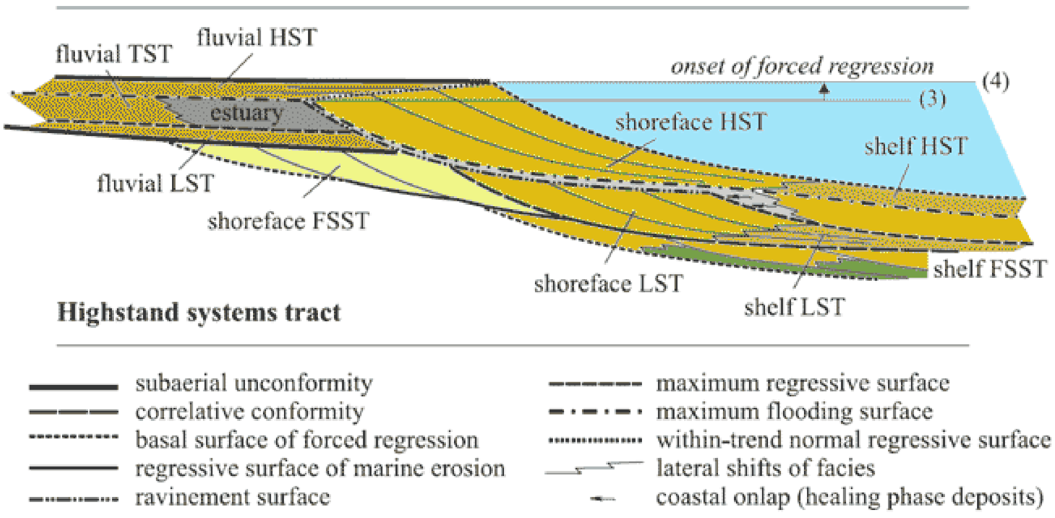

Fig. 3c: Highstand Systems Tract (After Catuneanu, 2002)

Falling-Stage Systems Tract is another category which may be included in systems tractd classification (Catuneanu, 2002); it includes all strata accumulating in a sedimentary basin during the forced regression of the shoreline. It consists primarily of shallow and deep water facies deposited at the same time with the formation of the subaerial unconformity in the nonmarine portion of the basin (Fig. 3).

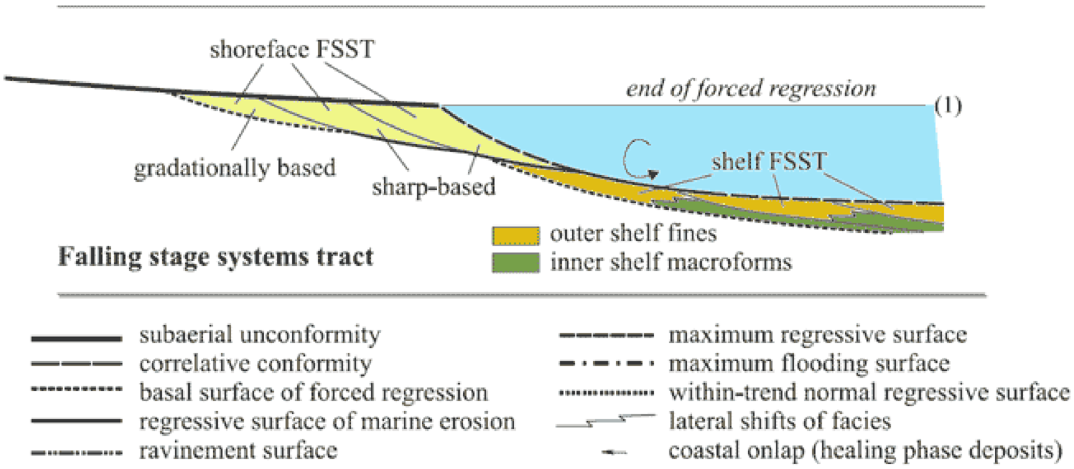

Fig. 3d: Falling Stage Systems Tract (After Catuneanu, 2002)

Diagnostic characteristics of the falling stage systems tract are shallow marine deposits with rapidly prograding and offlapping stacking patterns which are age-equivalent with the bulk of the deep water fans. The most practical feature for identifying Falling Stage Systems Tract is the presence of sharp-based shoreface sand bodies in wave-dominated near-shore areas.

Sequence stratigraphy is a useful alternative to the lithostratigraphic approach, which emphasizes similarity of lithology of rock units rather than time significance; but never a replacement or alternative to sedimentology but offers a framework within which depositional systems can be analyzed. Sequence stratigraphy offers a predictive model in which a series of system tracts within a depositional sequence is interpreted to be deposited in response to a cycle of fall or rise of base level, which is related to eustatic cycle. Each systems tract in a siliciclastic environment has a complex but predictable pattern of distribution of sands and shales and recognizable signatures in well logs and seismic reflection data (Mitchum et al., 1993).

1.2 Statement of Problem

Sequence stratigraphic method of interpretation has not been widely employed to the study of Niger Delta Basin regardless of large database of 2D/3D seismic lines, well logs and biofacies data obtained from oil exploration activities within the basin. Hence, sequence stratigraphic interpretation of “Gera field”, Greater Ughelli Depobelt, Niger Delta Basin, Nigeria will help to reduce the large margin of unstudied fields within the region as the study will enhance an understanding of sequence stratigraphic framework, its impacts and/or relationship on hydrocarbon prospectivity. This is because going with general trend of Niger Delta Basin which has a complex but distinctive structural and stratigraphic zonation, may be misleading thus hindering the discovering of some oil traps.

1.3 Aim and Objectives

The aim of this study is to use well logs, and biostratigraphic data, to delineate the architectural elements in “Gera Field”, Greater Ughelli Depobelt, Niger Delta Basin, in order to ascertain the field’s hydrocarbon prospectivity.

The objectives, therefore, are to utilize the predictive power of sequence stratigraphy to:

- Enhance an understanding of the stratigraphy of “Gera field”,
- Establish a relative time framework for the sedimentary succession in the field,
- Identify source and reservoir rocks,
- Provide an accurate framework for well to well correlation within “Gera field”.

1.4 Justification of Study

Over the last few decades, sequence stratigraphic concept have been utilized in the Niger Delta Basin geological prospect appraisal, and these have achieved awesome result in the areas of predicting sand distribution pattern, and providing a reliable means of correlation. Sequence stratigraphy has become an indispensable tool in hydrocarbon exploration as it provides a chronostratigraphic framework for the analysis and correlation of lithic fills of basins in terms of sea level changes, tectonism and sediment supply. It also enables a better understanding of the linkage between sedimentation patterns in different parts of a basin and the location of reservoirs, their continuity and seal prone (traps) zones in the basin. Sequence stratigraphy, draws from an integrated interpretation of data generated from seismic stratigraphy, biostratigraphy and sedimentology for analysis, correlations and mapping of sedimentary packages.

The hydrocarbon potentials of various fields and depobelts in the Niger Delta Basin are still a matter that deserves consideration and in-depth evaluation for possible greater profitability and sustainability.

The application of sequence stratigraphy in the study of “Gera Field” in the Greater Ughelli Depobelt of Niger Delta Basin will therefore provide a framework for the establishment of sequence stratigraphic interpretation and its impact/ relationship on the hydrocarbon prospectivity of the study area.

1.5 Scope of study

This approach is based upon the interpretation and integration of three inter-dependent basic data sets, including but not limited to the following:

1. Recognizing well-log responses based upon characteristics of deposits, especially sands and shales in each systems tract.
2. Interpretation of acquired high-resolution biostratigraphy and paleoecology of the wells (Gera – 1, 2, 3 & 4) penetrating the stratigraphic section in “Gera field to ascertain paleowater depth,

depositional environments, condensed section from faunal abundance and diversity peaks, and dating of the condensed sections.

3. The use of Niger Delta Chronostratigraphic Chart to assist predicting and dating sequences recognized physically from well logs.

The scope of this study will focus therefore on the area of:

1. Parasequences and parasequence sets delineation from well-logs.
2. Establishment of dominant stacking patterns of parasequence sets.
3. Delineating major bounding surfaces and systems tracts.
4. Correlation of bounding surfaces of same chronologic age across the wells in the study area.

CHAPTER TWO

LITERATURE REVIEW

The Niger Delta Basin, a large arcuate sediment wedge of destruction and mixed energy environment, has attracted a lot of workers from diverse discipline for the reason that it bears the world's most sought economic deposit, petroleum. Studies on the Niger Delta as a whole date back to the early 20th century when exploration for oil began in the area, since then, intensive studies have been done in the area of its geology, tectonics, geochemistry, stratigraphy by diverse authors; among whose work are reviewed this thesis include the work done by Short and Stauble (1967), Vail et al. (1990), Evamy et al. (1978) and a host of others.

Short and Stauble (1967) presented a detailed work on the subsurface stratigraphy of the Niger Delta (i.e. the general geology of the basin), while Adesida et al. (1997), and other authors reviewed the stratigraphy, sedimentation and structures of the Niger Delta. These works were able to establish three lithostratigraphic units in subsurface of Niger Delta and also correlated the units to their surface equivalent (Fig. 4 and Table 1).

Reijers et al. (1977) proposed the division of Niger delta deposits into regional lithostratigraphic megasequences based on an integration of log trends, biostratigraphy and sequence stratigraphic surfaces observed in seismic (their abstract does not provide details of the criteria used in the definition of their stratigraphic divisions)

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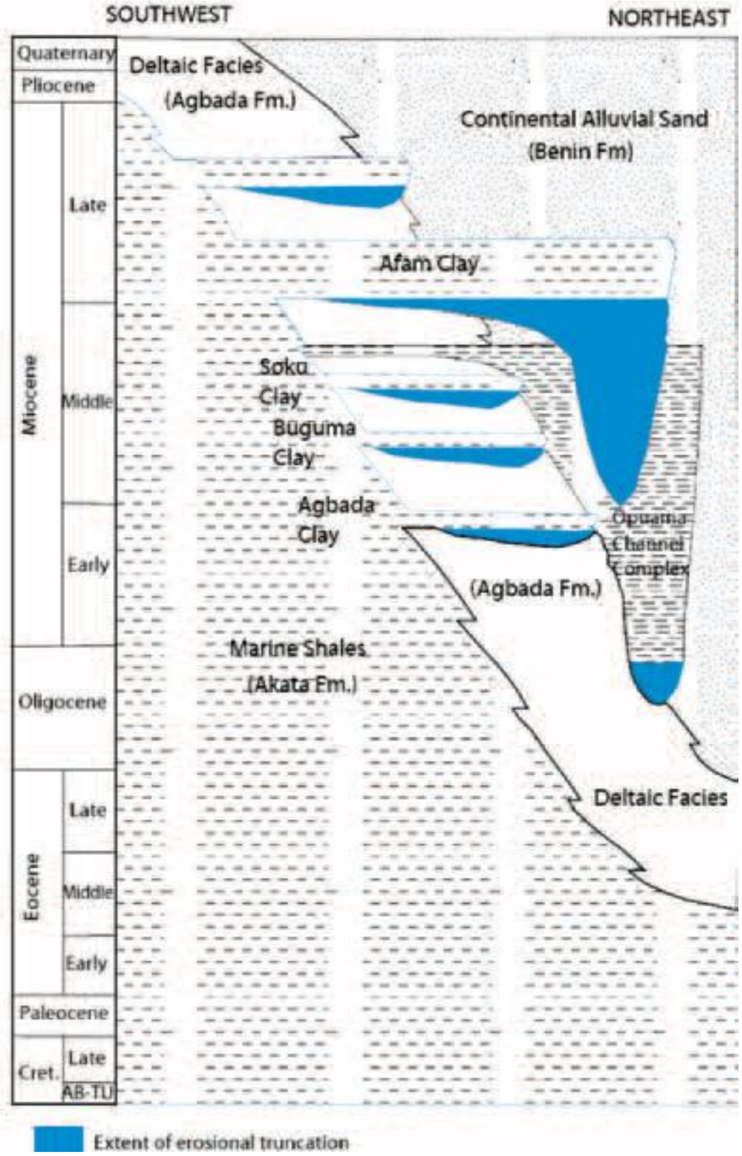


Fig.4: Stratigraphic column showing formations of the Niger Delta (modified from Doust and Omatsola 1990).

Table 1: Table of formations Niger Delta area, Nigeria; modified from Short and Stauble (1967).

Subsurface			Surface Outcrops		
Youngest known Age		Oldest known Age	Youngest Known Age		Oldest Known Age
Recent	Benin Fm Afam Clay Member	Oligocene	Plio / Pleistocene	Benin Fm	Miocene?
Recent	Agbada Fm	Eocene	Miocene Eocene	Ogwashi-Asaba Fm Ameki Fm	Oligocene Eocene
Recent	Akata Fm	Eocene	Lower Eocene	Imo shale Fm	Paleocene
Equivalent Not Known			Paleocene	Nsukka Fm	Maestrichtian
			Maestrichtian	Ajalli Fm	Maestrichtian
			Campanian	Mamu Fm	Campanian
			Camp./Maest.	Nkporo Shale	Santonian
			Coniacian/Santonia	Awgu Shale	Turonian
			Turonian	Eze Aku Shale	Turonian
			Albian	Asu River Group	Albian

Legend: Fm - Formation
Camp.- Campanian
Maest.- Maestrician

The three major lithostratigraphic units defined in the subsurface of the Niger Delta by Short and Stauble (1967) are - Akata, Agbada and Benin Formations;

these formations decrease in age basinward, reflecting the overall regression of depositional environments within the Niger Delta clastic wedge (Nwajide et al., 1997). The environment of deposition is a prograding wave-dominated deltaic system with age ranging from Paleocene to Pliocene. Doust and Omatsola (1989) reviewed that the thickest succession of synrift marine and marginal marine clastics and carbonates were deposited in a series of transgressive and regressive phases.

The petroleum geology and structure of the Niger Delta Basin has been described by Evamy et al. (1978), Knox and Omatsola (1988), Doust and Omatsola (1990).

Evamy et al. (1978) presented a detailed report of the petroleum geology and stratigraphy of the Niger Delta Basin and showed the relationship between depositional patterns, structures and stratigraphy and their influence on oil generation in the Niger Delta Basin. They also documented that the sedimentation in the depobelts was a function of the rate of deposition and the rate of subsidence with syn-sedimentary growth faults upsetting the delicate balance.

Knox and Omatsola (1989) used escalator regression model and impact on hydrocarbon distribution in its development. The escalator regression concept explained the particular association of stratigraphy, lithofacies and structure in the central area of the Cenozoic Niger Delta, with more attention being paid to the degree of mobility of the underlying over-pressured marine shales which move in response to gravity loading of deltaic sediments.

Intensive Biostratigraphic studies have been carried out in the onshore and shallow offshore Niger Delta. While virtually all these studies were done on foraminifera and palynological aspects; only few of these have been made available for publication. Worldwide, foraminifera and calcareous nannofossil have been studied and reports documented in a number of literatures. Boboye et al. (2009) worked on calcareous nannofossils and microfossils biostratigraphic study of some sequences located in the deep offshore area of Niger Delta.

Wood (2001) noted the difference and relationship between the Columbus Basin in Trinidad and that of the Niger Delta Basin which were attributed to the work of Evamy et al. (1978), its relationship lies on the structure and stratigraphy in the geologic evolution. In the Niger Delta model, shale migration establishes a bathymetric high in front of the progradational Niger Delta shelf system, forming a break between paralic / deltaic sedimentation, which has been trapped behind the bulge and slope / bathyal sedimentation outboard of the bulge crest. Beds deposited behind the bulge show progressive downward rotation and steepening of dip along a counter - regional glide plane associated with progressively basinward migration of the mobile shale. Large growth faults develop landward in response to extension and mobile shale withdrawal at depth.

Although similarities between the offshore Nigerian tectonostratigraphic processes and those of Trinidad's Columbus Basin are obvious, a few notable differences exist (Wood, 2001). The most obvious of these differences is the location of the shelf - slope break with respect to the migrating shale bulge, discrepancy in the height of the shale bulge and direction of wedging sediments within the two basins.

Sequence stratigraphy consists of the recognition of stratigraphic surfaces generated by the interaction of sedimentation with shifting base level and the use of such surfaces for correlation and unit definition. It underwent a long gestation period from 1788 when Hutton first recognized unconformities to 1949 when Sloss used unconformities to define the boundaries of a sequence.

Sloss (1963) report in AAPG Memoir of 1977 identified six (6) cratonic sequences (named Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni and Tejas) and their bounding unconformities.

Vail et al., (1979) buttressed the work of Sloss (1963) by using regional seismic data to demonstrate the utility of the discipline. They also revised the definition of a sequence boundary to include a conformable portion and this allowed a sequence to potentially be correlated over most of a basin.

Subsequently, the Exxon scientists demonstrated how their sequence stratigraphic methodologies could be applied to outcrop and well log data. This publication paved way for other authors, such as Siliciclastic Sequence Stratigraphy in Well logs, cores and outcrops: Concept high-resolution correlation of time and facies by Wagoner et al., (1990).

Unfortunately, the Exxon work contains some conceptual flaws and is accompanied by a mind-numbing jargon. In response to these problems, Bill Galloway and Ashton Embry proposed alternate methods of sequence definition. Debate continues regarding the most pragmatic methodology for sequence analysis.

During this long time period numerous geological luminaries made many empirical observations and theoretical postulates on the nature and origin of unconformities and the stratigraphic consequences of base level change.

Vail et al. (1993) documented on the predictive model which sequence stratigraphy offers, a series of systems tracts within a depositional sequence is interpreted to be deposited in response to a cycle of fall or rise of base level, which is related to eustatic cycle. “Each systems tract in a siliciclastic environment has a complex but predictable pattern of distribution of sands and shales and recognizable signatures in well logs and seismic reflection data”.

Weimer and Posamentier (1993) documented on the recent development and application of sequence stratigraphy. They reviewed a more definitive approach to sequence stratigraphic concepts which gave greater emphasis on interpretation of well logs and biostratigraphic information, closely integrated with seismic data to increase the resolution for prediction of reservoir, seal, and source rocks.

This method has been developed in recent years and currently modified and rigorously tested, noting the evolution of the discipline as it shifts from conceptual development to application and documentation, with it being able to answer some questions from the perspective of oil exploration: can this concept be used to decrease risk in petroleum exploration, or applied to better development of reservoir.

Adesida et al (1997) developed a sequence stratigraphic model for the Agbada Formation in the Niger Delta Basin based on a three-dimensional seismic volume and well data from Delta field.

Sequence stratigraphic approach shall be applied to sediments in the “Gera field” for better understanding of prevailing depositional patterns of sedimentation in the Niger Delta Basin with respect to time and space.

CHAPTER THREE
METHODOLOGY

3.1 Data Set

Workers have applied depositional sequence stratigraphic concepts to a variety of data-bases including outcrop, cores, electric logs, multifold seismic data and biostratigraphic data. The sequence stratigraphic analysis and interpretation of depositional processes of four wells in the “Gera Field” Greater Ughelli Depobelt in the central Niger Delta was carried out based on well log (Gamma Ray and Resistivity), Lithologic, Biostratigraphic and Paleobathymetric data.

3.1.1 Well Logs :

Well Logs are continuous measurements or records in the subsurface of some physical parameters with depth by a special logging device (sonde). Sequence stratigraphic analysis is concerned with the influence of depositional controls on sedimentation; sequence analysis of a log suite must therefore concentrate on logging tools that measure depositional parameters.

The Well Log suites used in the Sequence Stratigraphic analysis of four wells (Gera – 1, 2, 3 & 4) of "Gera Field" in the Greater Ughelli Depobelt, Niger Delta Basin comprises of Gamma Ray and Resistivity Logs. The fourth well was only (Gera -4) was used in the correlation panel for key surfaces correlation.

- Gamma Ray Log

Gamma Ray Log records the suite of radioactive activity in the rock. The radioactivity of rocks, measured by the gamma tool is generally a direct function of clay mineral contents and thus depicts grain size and depositional energy. Also, Spectral Gamma Log can be used to distinguish anomalous radioactivity in depositional parameters.

In the scale of 0 - 150 API unit (American Petroleum Institute), even 0 - 200 API unit (depending on company standard), Shales (clay-minerals) generally have relative high gamma count, while sandstone and limestone represent formations with relative low gamma ray count; therefore Gamma Ray Log is a good representation of depositional environment.

The trend or shape of Gamma Ray Log helps to define depositional environment (fig. 5), hence gamma log is one of the most useful logs for sequence stratigraphic analysis, and is run in most wells.

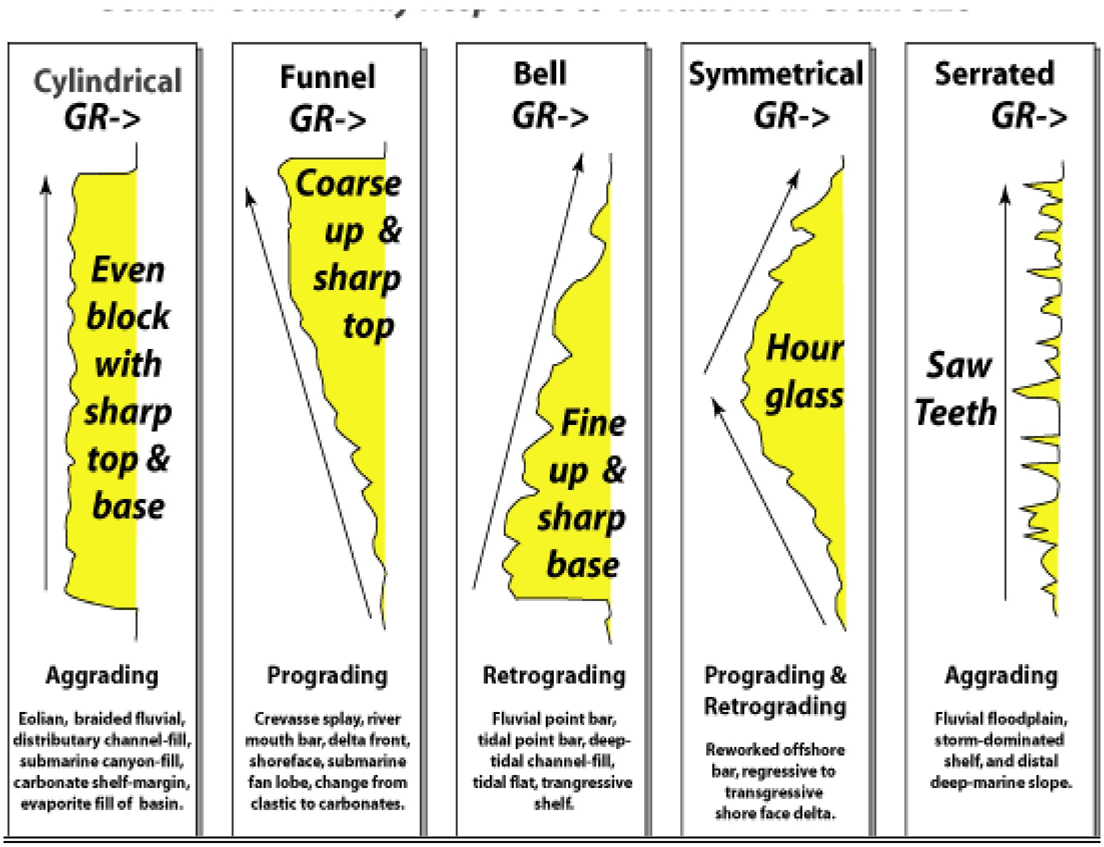


Fig. 5: General Gamma Ray Response to Variations in Grain Size (After, Kendall, 2003)

- Resistivity Log

Resistivity Logs measure the bulk resistivity of the rocks, which is the function of porosity and pore fluid. Resistivity is the reciprocal of conductivity; hence a highly porous rock with a conductive pore fluid (e.g. saline water) will have low resistivity, whereas a non porous rock or a hydrocarbon bearing formation will have a high resistivity.

3.1.2 Biostratigraphic Data

High resolution biostratigraphic data of the wells consisting of foraminifera population / diversity, Benthic diversity / population, planktic diversity / population as well as paleobathymetric data microfaunal and microfloral zonation tables of Gera -1, Gera -2, and Gera -3 wells, which are used to describe the stratigraphic horizons of ‘Gera field’ was generated from ditch cutting samples.

The biostratigraphic analysis and the recognition of a series of biostratigraphically calibrated condensed sections and maximum flooding surfaces provide template for detailed sequence stratigraphic analysis.

Detailed study of the wells in the ‘Gera field’ has illustrated the value of integrating sedimentological, biostratigraphical and biofacies data in the development of a sequence stratigraphic model. Most flooding surfaces are clearly worked by difference in facies change, which is in most cases, is the highlights significant changes for depicting sequence boundaries.

3.1.3 Niger Delta Chronostratigraphic chart:

The Niger Delta Chronostratigraphic Chart is a geological time table which merges the global chronostratigraphic of Haq et al. (1988) with the Niger Delta geologic episode. The use of onlap and eustatic sea level cycles of Haq et al. 1988, and Wornadt and Vail, 1991 have been correlated to the regional chronostratigraphy of Niger Delta Basin assist in predicting and dating sequences recognized physically from well logs and seismic sections. Fig. 6 shows a Niger Delta Cenozoic geological chart which consists of global sequence stratigraphic record with the geologic time, and the corresponding Niger Delta shale markers, P- and F- Zones as well as the depobelts.

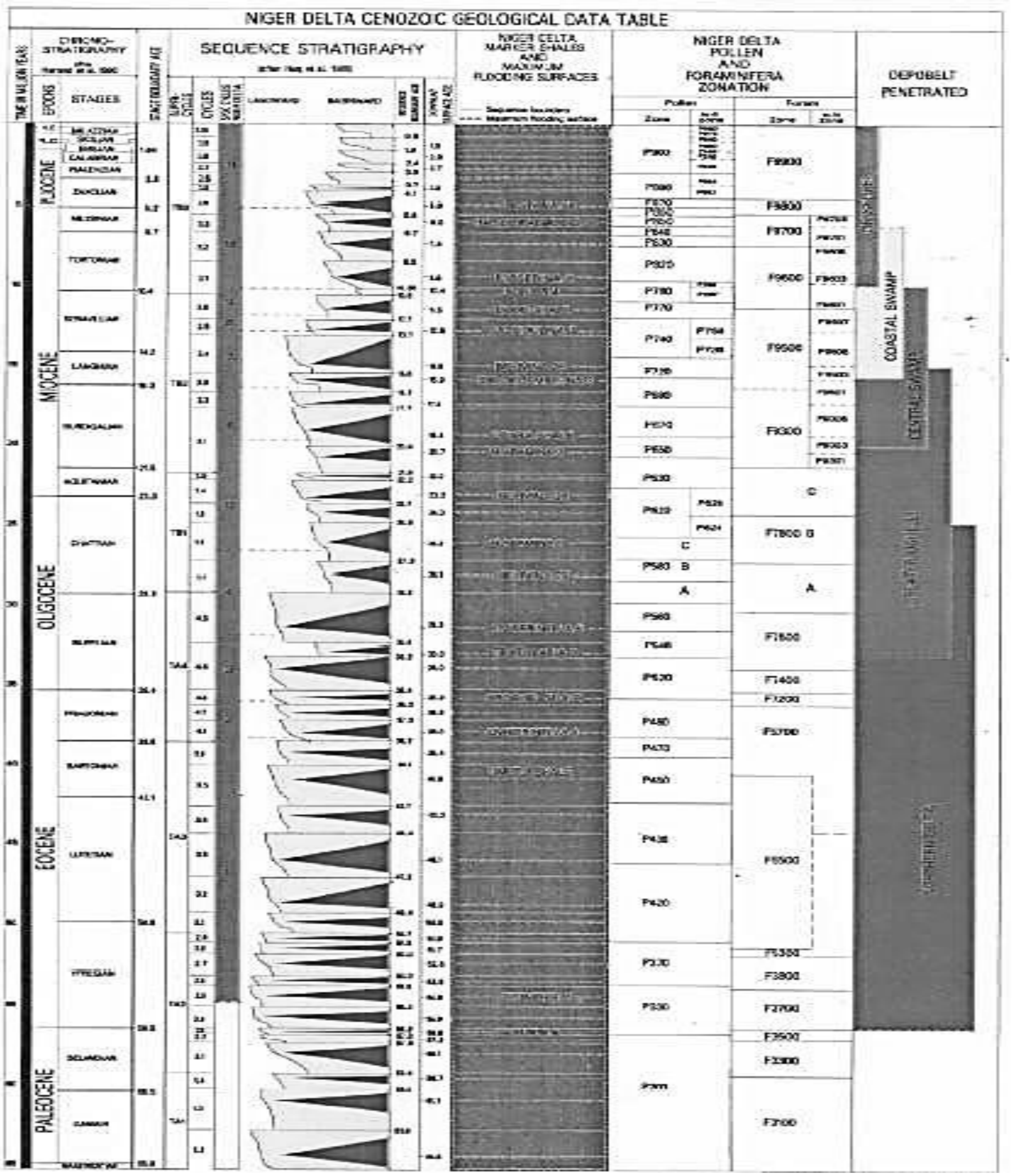


Fig. 6: Chronostratigraphic Chart of Niger Delta Basin.

3.2 Location map of the study area

The area of study is a field named “Gera field” within Greater Ughelli Depobelt of Niger Delta Basin, Nigeria (Fig. 7).

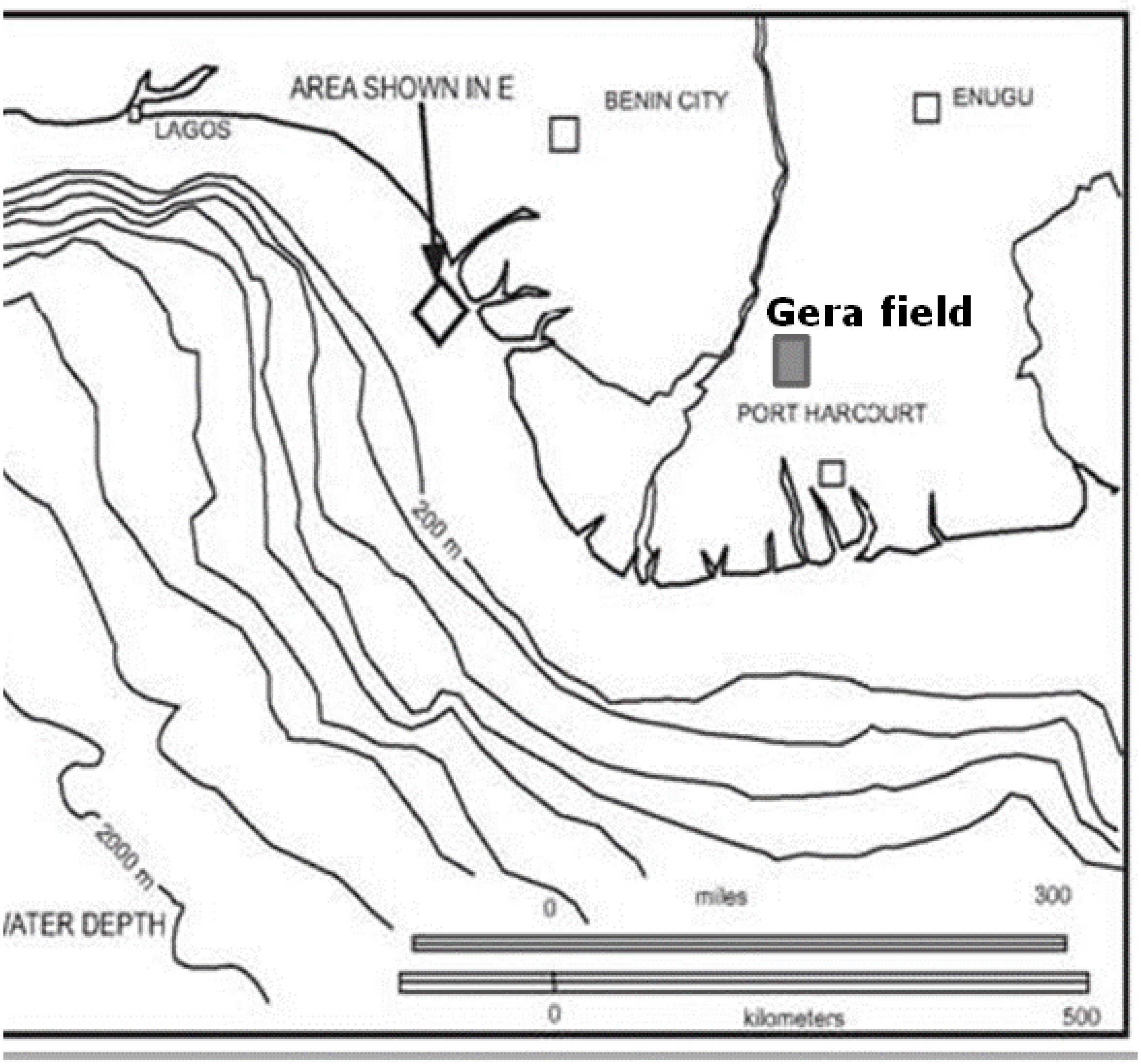


Fig. 7: Map showing the location of the study area in Niger Delta Basin

3.2.1 Geological Setting of Niger Delta Basin

The Niger Delta Basin is situated on the continental margin of the Gulf of Guinea in equatorial West Africa, between latitudes 3° and 6°N and longitudes 5° and 8°E (Fig. 7). It ranks among the world most prolific petroleum-producing Tertiary deltas, comparable to the Alaska North Slope, the Mississippi, the Orionoco, and the Mahakam (Indonesia) deltas.

Fig. 8: Global Position of the Niger Delta Basin

Niger Delta Basin occupies the coastal and ocean-ward part of a much larger and older feature - the Benue Trough, in the southern Nigeria. It is a basin that originated as a result of simultaneous opening of the Gulf of Guinea and the Equatorial Atlantic in Aptian-Albian times, when the equatorial part of Africa and South America began to separate (Nwajide et al., 1997).

"As a sedimentary basin, Niger Delta encompasses a region that is much larger than the geographic extent of the modern delta constructed by Niger-Benue drainage systems" (Nwajide et al., 1997) but embraces other deltas "which are not members of the Niger system" (Allen,1970), notably Cross River Delta and extends into the continental margin of the neighboring Cameroun and Equatorial Guinea, which therefore "have portions of the Niger Delta that contains hydrocarbon" (Evamy et al., 1978).

The Niger Delta Basin is about 75,000km^2 in area and a thickness of about 12,000m in its central part; like other tertiary deltas, its sedimentary fills are entirely clastic. The Niger Delta clastic wedge formed along a failed arm of a triple junction system, the two arms that followed the southwestern and southeastern coast of Nigeria and Cameroon developed into the passive continental margin of West Africa, whereas the third failed arm formed the Benue Trough. Deltaic build-ups in this basin are contribution of other depobelts along the African Atlantic Coast.

In the Tertiary, sediment supply was mainly from the north and east through the Niger, Benue and Cross Rivers, (the Cross and Benue Rivers provided substantial amounts of volcanic detritus from the Cameroon volcanic zone beginning in the Miocene), it prograded into the Atlantic Ocean at the mouth of the Niger-Benue river system at a steadily increasing rate in response to the evolution of these drainage areas and continued basement subsidence. Regression rates increased in the Eocene, with an increasing volume of sediments accumulated since the Oligocene.

The morphology of Niger Delta changed from an early stage spanning the Paleocene to early Eocene to a later stage of delta development in Miocene time. The early coastlines were concave to the sea and the distribution of deposits was strongly influenced by basement topography (Doust and Omatsola, 1989; Reijers et al, 1997) (Fig. 8).

The synrift sediments of Niger Delta Basin started accumulating during the Cretaceous to Tertiary, with the oldest sediments dated to Albian age. Thickest successions of synrift marine and marginal marine clastics and carbonates were deposited in a series of transgressive and regressive phases (Doust and Omatsola, 1989). The end of Synrift phase occurred in Santonian (Late Cretaceous) which was characterized by inversion. Two arms of a triple junction comprising of collapsed margin of south Atlantic gave rise to the Niger Delta following the early Cretaceous subsidence of the African continental margins and deposition of clastic materials. The clastic wedge of the Niger Delta Basin continued to prograde during Middle Cretaceous time into a depobelt located above the collapsed continental margin at the site of the triple junction; during the middle and late Eocene times regional deltaic deposition has been established with sediments largely derived from the weathering flanks of Niger-Benue drainage system (Stacher, 1994). There was an interruption in sediment progradation by episodic transgressions during Late Cretaceous time.

Delta progradation occurred along two major axes, the first paralleled the Niger River, where sediment supply exceeded subsidence rate. The Second, smaller than the first, became active during Eocene to early Oligocene basinward of the Cross River where shorelines advanced into the Olumbe-1 area (Short and Stauble, 1967). This axis of deposition was separated from the main Niger Delta deposits by the Ihuo Embayment, which was later rapidly filled by advancing deposits of the Cross River and other local rivers (Short and Stauble, 1967). Late stages of deposition began in the early to middle Miocene, as these separate eastern and western depocenters merged. In Late Miocene the delta prograded far enough that shorelines became broadly concave into the basin (Fig. 9).

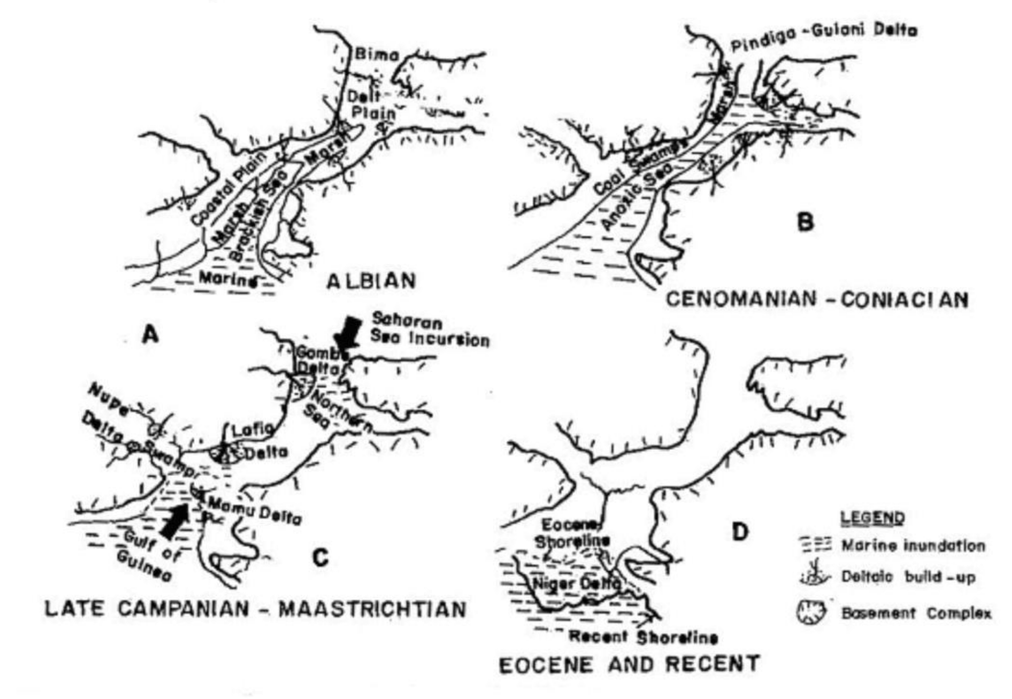


Fig. 9: Cretaceous to Recent paleogeographic evolution of Nigerian rift and continental margin deltas (from Petters, 1978).

Accelerated loading by this rapid delta progradation mobilized underlying unstable shales. These shales rose into diapiric walls and swells, deforming overlying strata. The resulting complex deformation structures caused local uplift, which resulted in major erosion events into the leading progradational edge of the Niger Delta. Several deep canyons (Fig. 10a & 10b), now clay-filled, cut into the shelf and are commonly interpreted to have formed during sea level lowstands. The best known are the Afam, Opuama, and Qua Iboe Canyon fills.

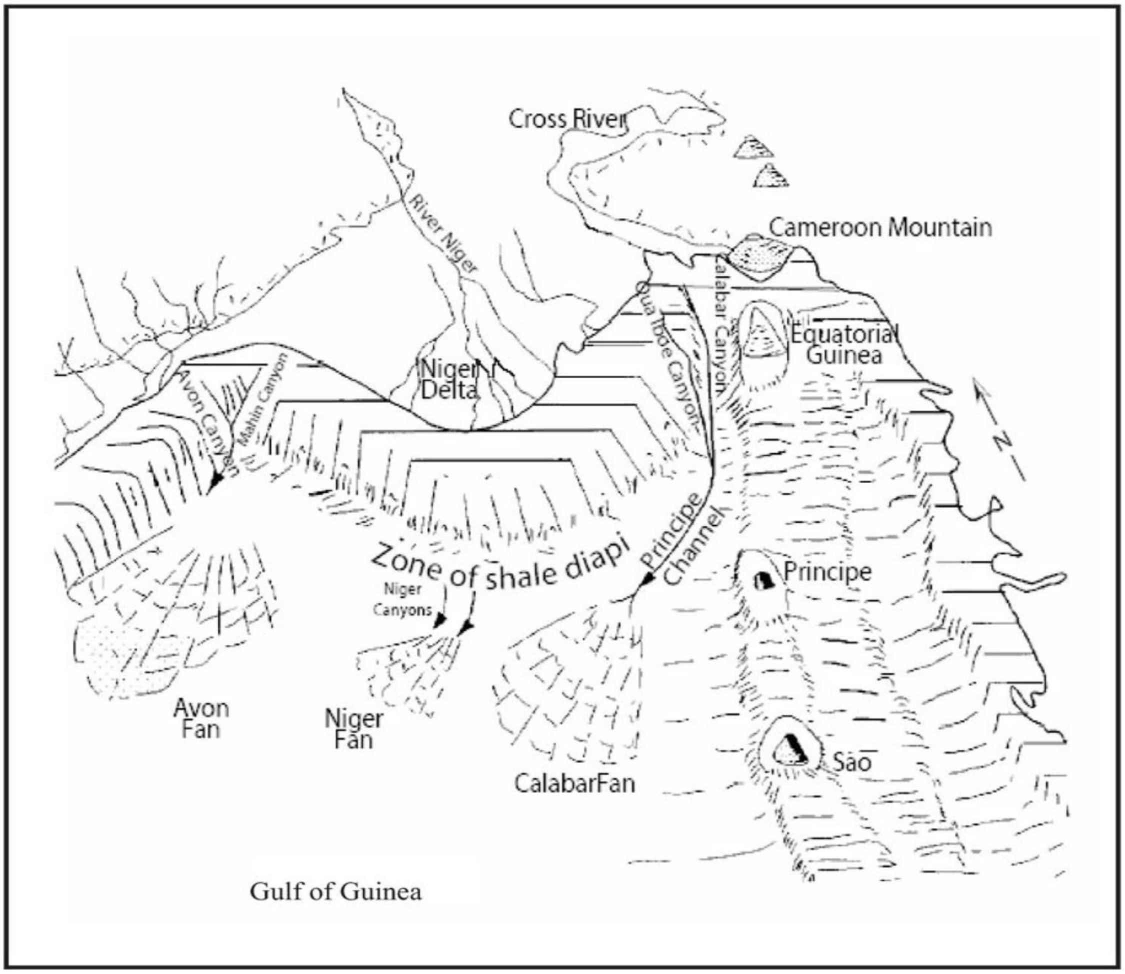


Fig. 10a: Physiographic sketch of the deep marine sediments in the Gulf of Guinea offshore Niger Delta (modified from Reijers et al., 1998).

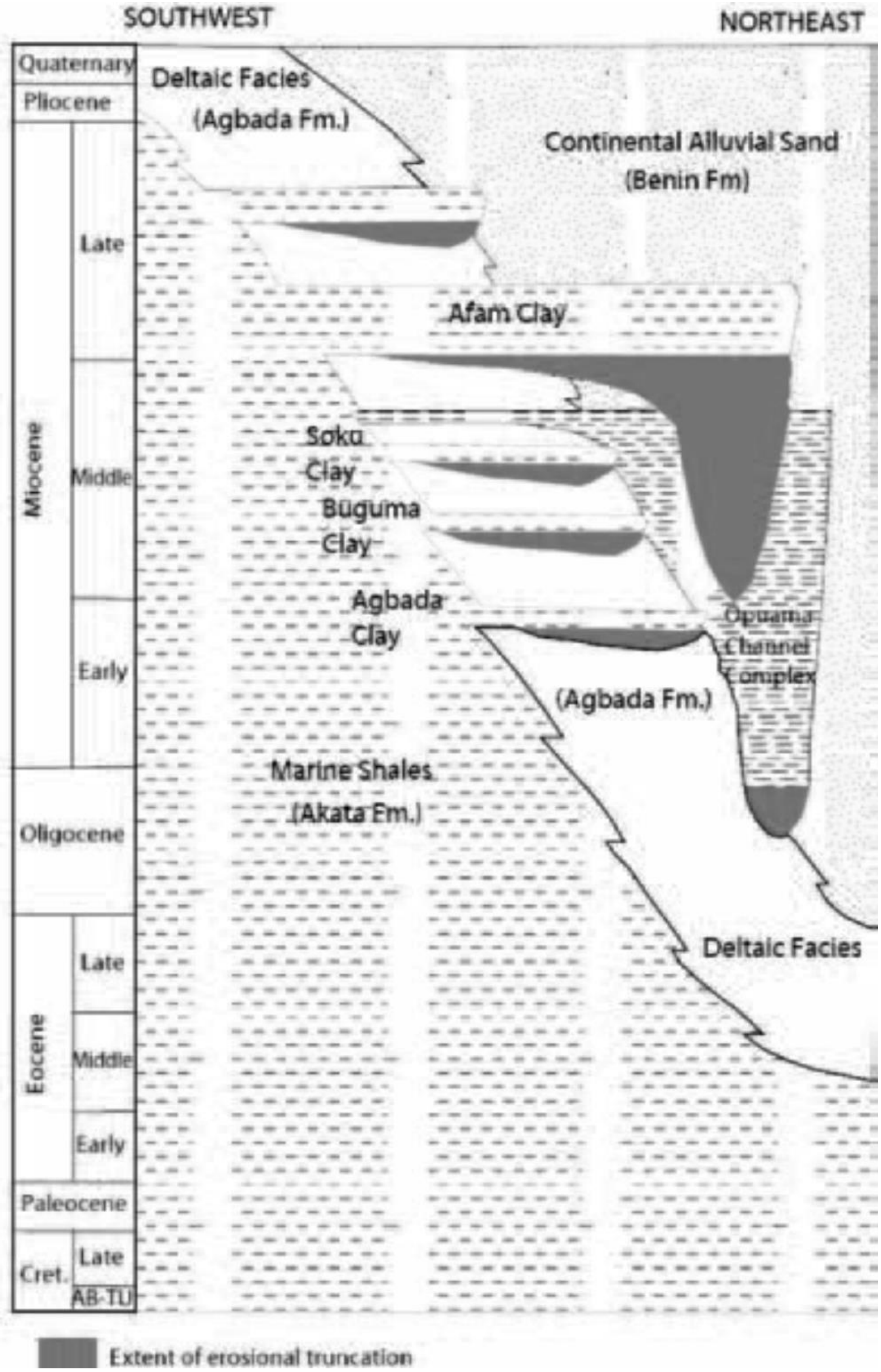


Fig. 10b: Stratigraphic column of formations in Niger Delta Basin, modified from Doust and Omatsola (1990).

3.2.2 Structure of Niger Delta Basin

The progradation of the deltaic sequence has been controlled by syndepositional faults and the interplay between subsidence and sediment supply (Doust and Omatsola, 1990). Niger Delta can be divided into a number of major growth fault bounded sedimentary units or depobelts which as the delta progrades, succeeds one another in a southward direction. In each, the tripartite regressive sequence forms an integral delta unit of a distinct southward direction. In Nigeria, these trends have been referred to in the literature as megastructures (Evamy et al., 1978) or depobelts (Knox and Omatsola, 1989).

Each depobelt contains one or more distinct transgressive shale horizons. This transgressive shale represents interruption in the overall regressive sequence that is probabally related to sea level rises. The fundamental trend however consists of stepwise build up (prograde) of offlap cycles within each depobelt that gradually prograded southward (fig. 11a). This results in a gradual increase in sand percentage upstream. The resultant depobelts are: Northern delta Depobelt, Greater Ughelli Depobelt, Central I and II Depobelts, Coastal swamp I and II Depobelts and Offshore Depobelt; these Depobelts represents successive phases of delta growth (Fig. 11b).

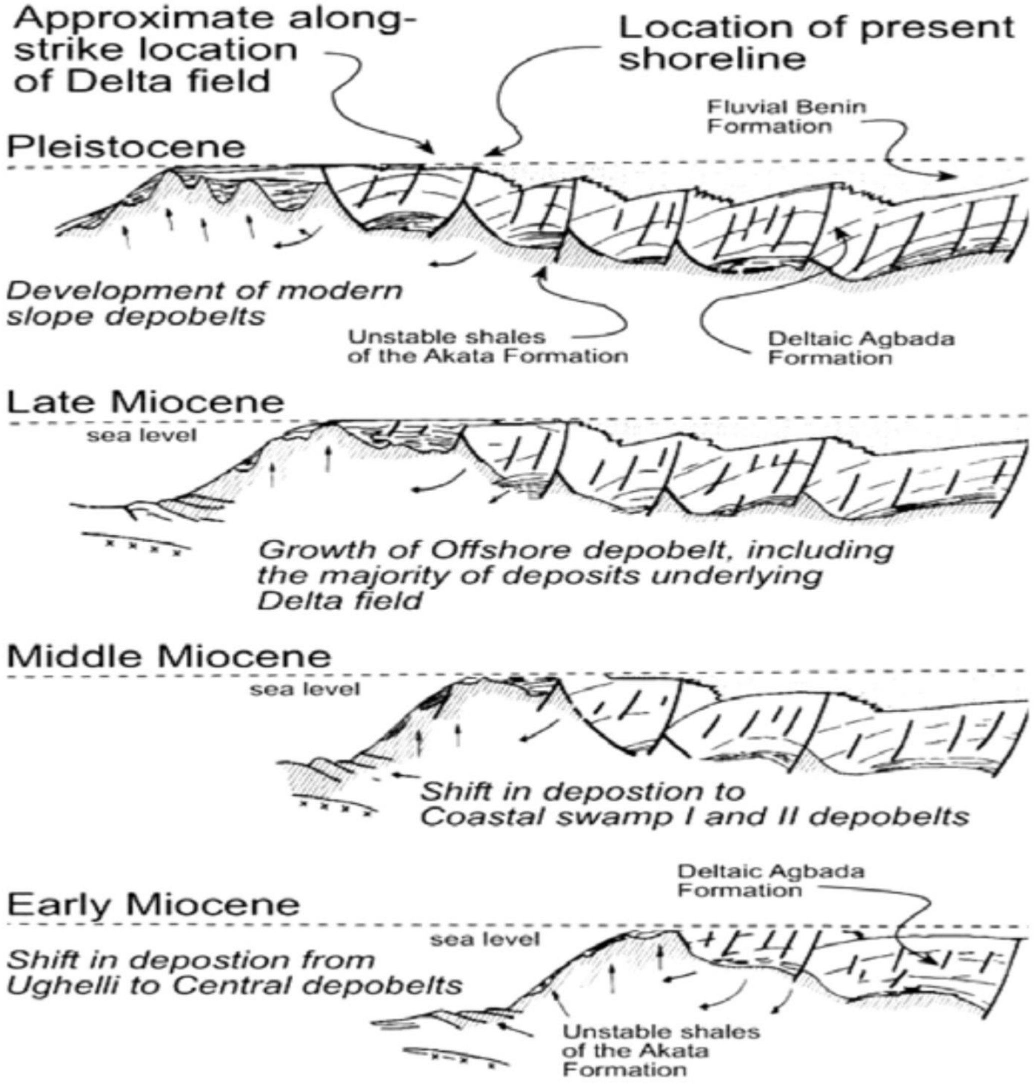


Fig. 11a: Schematic diagram showing the development of successive growth-fault-bounded depobelts during progradation of the unstable Niger Delta clastic wedge (After Knox and Omatsola, 1989).

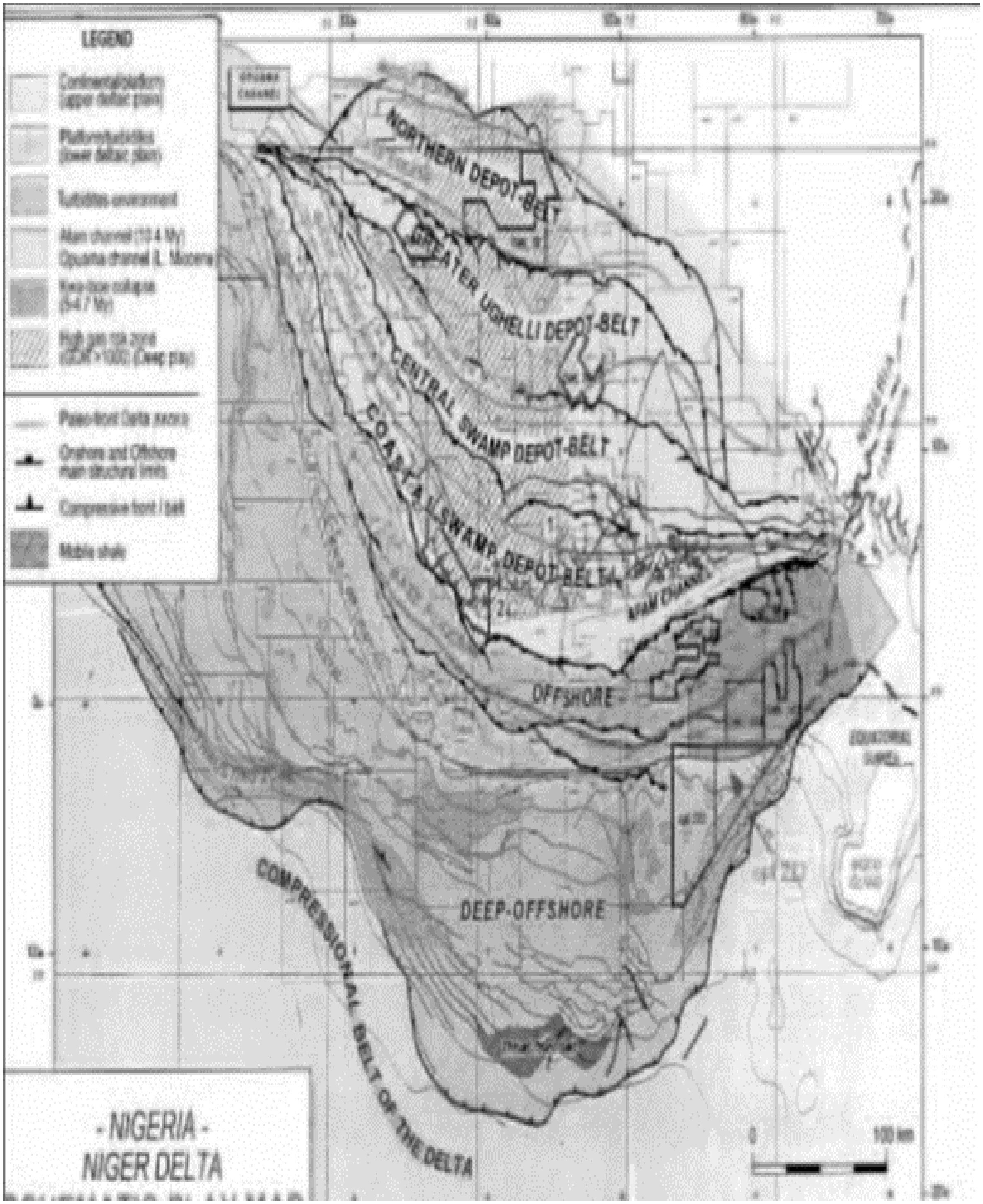


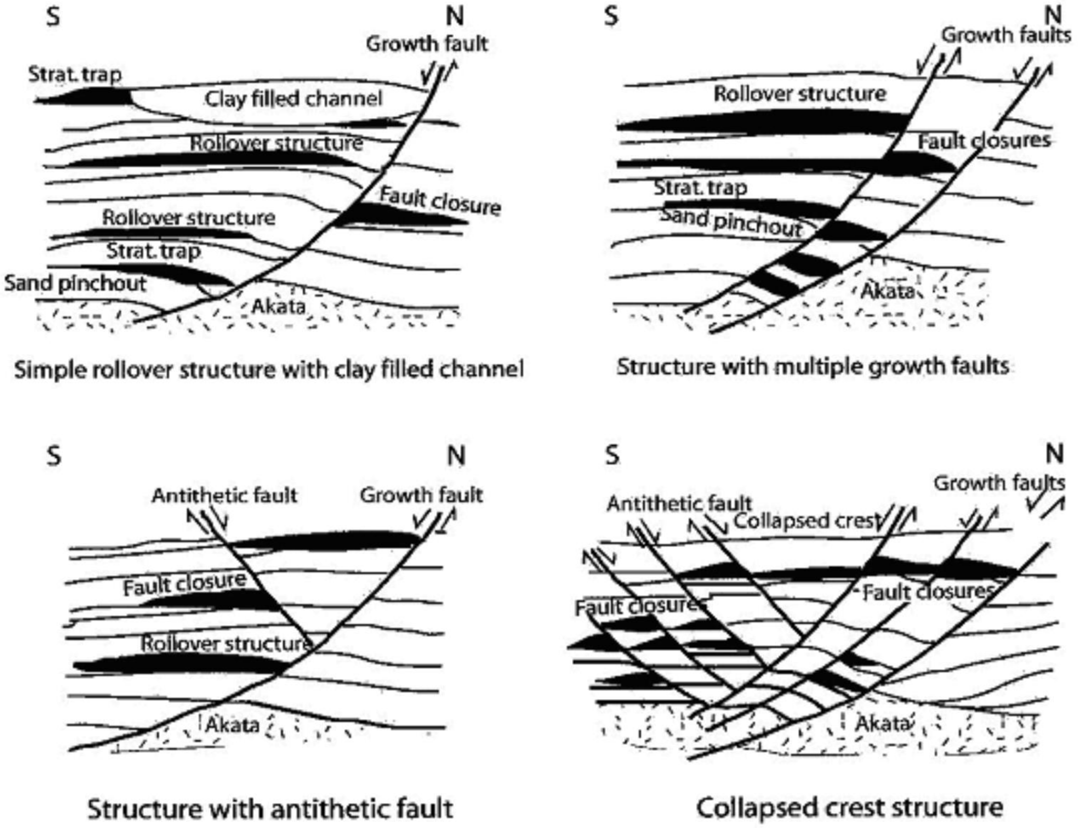
Fig. 11b: Map of Niger Delta showing the different depobelts (After Weber, 1971) (modified from Adesina et al., 2009).

Three major depositional cycles have been identified within Tertiary Niger Delta deposits (Short and Stauble, 1967; Doust and Omatsola, 1990; Nwajide et al, 1997). The first two, involving mainly marine deposition, began with a middle

Cretaceous marine incursion and ended in a major Paleocene marine transgression. The second of these two cycles, starting in late Paleocene to Eocene time, reflects the progradation of a “true” delta, with an arcuate, wave- and tide-dominated coastline. These sediments range in age from Eocene in the north to Quaternary in the south (Doust and Omatsola, 1990). Deposits of the last depositional cycle have be divided into a series of six depobelts (Doust and Omatsola, 1990) separated by major synsedimentary fault zones. These depobelts formed when paths of sediment supply were restricted by patterns of structural deformation, focusing sediment accumulation into restricted areas on the delta. Such depobelts changed position over time as local accommodation was filled and the locus of deposition shifted basinward (Doust and Omatsola, 1990).

Normal faults triggered by the movement of deep-seated, over-pressured, ductile, marine shale have deformed much of the Niger Delta clastic wedge (Doust and Omatsola, 1989). Many of these faults formed during delta progradation and were syndepositional, affecting sediment dispersal. Fault growth was also accompanied by slope instability along the continental margin. Faults flatten with depth onto a master detachment plane near the top of the over-pressured marine shales at the base of the Niger Delta succession. Structural complexity in local areas reflects the density and style of faulting. Simple structures, such as flank and crestal folds, occur along individual faults.

Hanging-wall rollover anticlines developed because of listric-fault geometry and differential loading of deltaic sediments above ductile shales. More complex structures, cut by swarms of faults with varying amounts of thrown, include collapsed-crest features with domal shape and strongly opposing fault dips at depth (Fig. 12).



Simple rollover structure with clay filled channel

Structure with multiple growth faults

Structure with antithetic fault

Collapsed crest structure

Fig. 12: Niger Delta oil field structures and associated traps, modified from Doust and Omatsola (1990) and Stacher (1995).

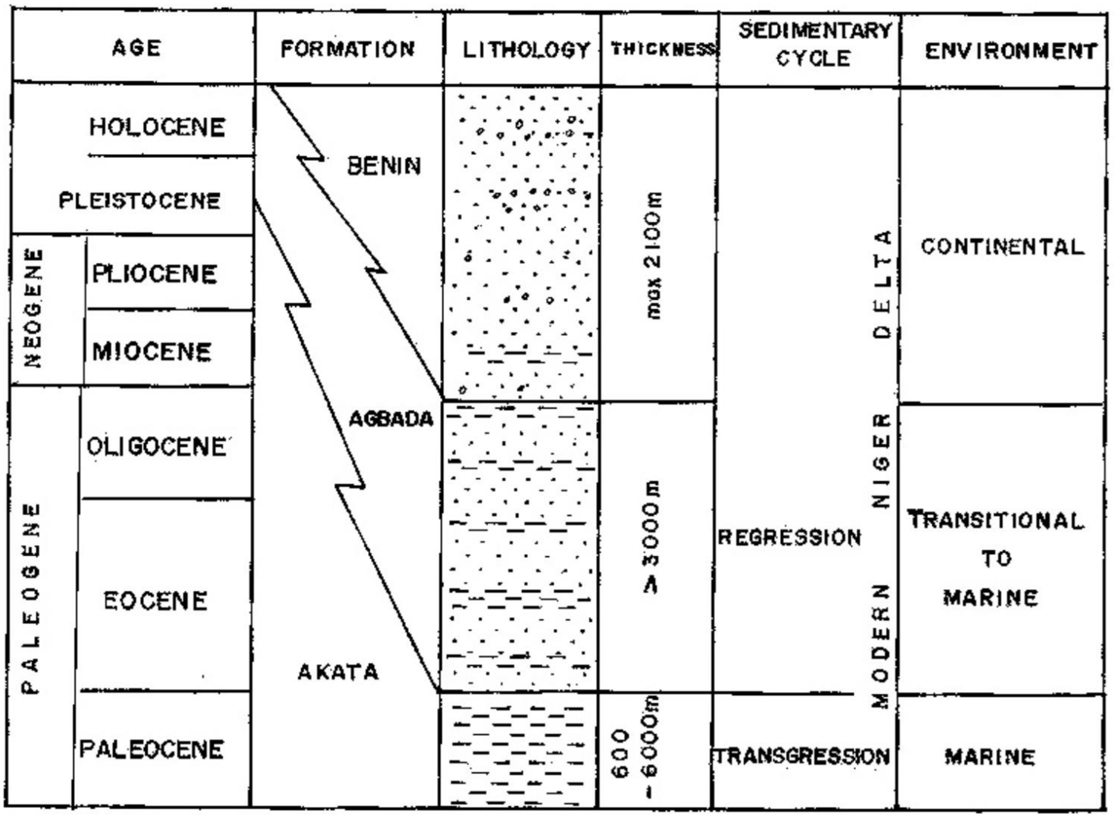
3.2.3 Sediment Fill Niger Delta Basin

Lithostratigraphy of the Cenozoic Niger delta is a direct product of the various depositional environments; the subsurface Tertiary clastic sedimentary fill of Niger Delta Basin decrease in age basinward, reflecting the overall regression of depositional environments within the Niger Delta clastic wedge. It is divided into tripartite diachronous lithostratigraphic units representing prograding depositional facies distinguished mostly on the basis of sand-shale ratios (Table 2 & Fig. 9b). These are the Akata Formation of mostly marine prodelta shales, the Agbada Formation of alternating paralic sands and shales, and the Benin Formation of mostly continental freshwater bearing sands (Short and Stauble, 1967).

These lithostratigraphic units are strongly diachronous in the sense that they began to accumulate since deltaic progradation commenced in the early tertiary;

in which the tripartite formation ranges to recent. Along the northern perimeters of the Niger Delta where the proximal parts of these lithostratigraphic units are exposed, different formation names have been assigned namely: Imo Shale (Akata) Ameki (Agbada), Ogwashi - Asaba (upper Agbada facies) and Benin formation (Nwajide et al, 1997) (Table 1). The formations reflect a gross coarsening-upward progradational clastic wedge (Short and Stauble, 1967), deposited in marine, deltaic, and fluvial environments.

Table 2: Generalized Lithostratigraphy of Niger Delta (from Nwangwu, 1990).



Akata Formation

Akata Formation a marine sedimentary sequence laid down in front of the advancing delta (Short and Stauble, 1967), occur lower in the section of the Basin with occasional sandstone units of deep-sea fan origin (Peters et al, 1997). It is characterize by dark grey shales and silts with a rare streaks of sand of probable turbidite origin; it is estimated to be about 6 400m thick in the central part of this clastic wedge (Doust and Omatsola, 1989). It is of age Paleocene to

Recent and the environment of deposition is believe to be a shallow marine shelf to prodelta setting with the evidence from the marine planktonic foraminifera which make over 50% of the microfauna assemblage (Doust and Omatsola, 1989).

The Akata Formation outcropped at the northeastern part of the delta, referred to as the Imo Shale (Short and Stauble, 1967; Nwajide et al, 1997); also at the offshore in diapirs along the continental slopes. The Akata Formation is typically over-pressured, especially where it is deeply buried; it grade vertically into the overlying Agbada formation.

Agbada Formation

The Agbada formation comprises of alternating sands, silts and shales arranged within ten to hundred feet successions defined by progressive upward changes in grain size and bed thickness. The upper part consists mostly of sands with minor silts and shales while the lower part is about equal proportion in sands and shale alternation. It occurs throughout the Basin, its maximum thickness is about 3 900m and ranges from Eocene to Recent in age (Petters, 1983)). It is probably continuous with the outcrops of the Ogwashi - Asaba and Ameki Formation of Eocene – Oligocene age (Short and Stauble, 1967). The strata are generally interpreted to have formed in fluvial-deltaic environments. The formation ranges in age from Eocene to Pleistocene.

Benin Formation

The Benin Formation comprises the top part of the Niger Delta clastic wedge, from the Benin-Onitsha area in the north to beyond the present coastline (Short and Stauble, 1967). The Benin Formation consists of massive continental sands and gravels, it underlain gradationally by the delta front paralic lithofacies.

The top of the formation is the recent subaerially - exposed delta top surface and its base extend to a depth of 4600 feet. The base is defined by the youngest marine shale. Shallow parts of the formation are composed entirely of non-marine sand deposited in alluvial or upper coastal plain environments during progradation of the delta (Doust and Omatsola, 1989). Although lack of preserved fauna inhibits accurate age dating, the age of the formation is estimated to range from Oligocene to Recent (Short and Stauble, 1967). The formation thins basinward and ends near the shelf edge.

3.2.4 The Petroleum System

The distribution of hydrocarbons in the Niger Delta Basin is complex, there is a general tendency for the ratio of gas to oil to increase southward within individual depobelts (Doust and Omatsola, 1989). Stacher (1995) developed a hydrocarbon habitat model based on sequence stratigraphy of some petroleum-rich belts within the Niger Delta area and provides a short summary of basin, trap, reservoir, source rock and hydrocarbon character (Table 3).

Table 3: Hydrocarbon habitat, (modified from Stacher, 1995).

Geology	Tropical delta at passive continental margin of south Atlantic; Early Tertiary to recent age; Mostly shallow ramp depositional model; Shelf break locally mappable.
Traps	Dip closures (rollover anticline in growth faults); Fault bound traps; Stratigraphic traps (truncation Traps; Stratigraphic traps (truncation traps, tidal Deltas, channels etc.).
Reservoir	Deltaic sandstones (shoreface, beach, channel etc); Stacked sand/shale alternations; Multi-reservoir fields; Reservoir depth 5000-14000 ft.
Source rock	Marine shales (Akata shales) with land plant material (high potential); Type III/II, III vitrinite Liptinite, S.O.M; within well penetrations measured VR less than 0.7; Top oil window variable 9000-14000 ft.
Hydrocarbons	Oil / condensate / gas; Gravity 15-25 API biodegraded; Gravity 25-45 API non-bio-degraded; Low sulphur / nickel; Pristane / Phythane ratio 0.6-1.6; Rich in waxes / resins, other land plant material S.O.M.

In the past, the source rock of Niger Delta Basin was controversial; some authors have it to be the shales of Akata Formation, some the shale units in Agbada formation, and some other, the marine cretaceous sediment beneath the basin. Among the contributors of these notion are Weber and Daukoru, 1975; Evamy et al., 1978; Ejedawe et al., 1979; Ekweozor and Okoye, 1980; Ekweozor and Daukoru, 1984; Lambert - Aikhionbare and Ibe, 1984; Doust and Omatsola, 1990; Stacher, 1995; Frost, 1977; Haack et al., 1997.

The marine source is hypothetical since no well has been drilled to penetrate this section, moreover migration of oil from the Cretaceous into the reservoirs in the Agbada Formation would have required an intricate fault / fracture network as the Akata shale reaches a thickness greater than 6,000 meters, (no available data to support this network). The chemical composition of the oils provides conflicting evidence for the hypothesis of a Cretaceous source rock, especially for an Early Cretaceous one. Nwachukwu et al. 1995 documented low V:V+Ni ratios in Niger Delta crude (0.12), a ratio quite smaller than the ratio in Cretaceous oils in onshore seeps in the northern portion of the province (0.46; Oluwole and others, 1985 as cited in Kulke, 1995).

Ekweozor and Okoye, 1980; Nwachukwu and Chukwura, 1986 proposed that the Agbada Formation has intervals that contain organic-carbon contents sufficient to be considered good source rocks but Evamy et al, 1978; Stacher 1995 argued that these intervals rarely reach thickness sufficient to produce a world-class oil province and are immature in various parts of the delta but the Akata shale is present in large volumes beneath the Agbada Formation and is at least volumetrically sufficient to generate enough oil for a world-class oil province such as the Niger Delta. Evamy et al, 1978 on the basis of organic-matter content and type, therefore proposed both the marine shale of upper part of Akata Formation and the interbedded shale unit within paralic Agbada Formation basically the lower part of the Agbada formation to be the source rocks of the Niger Delta crude. Ekweozor et al. 1979, used ab-hopanes and

oleananes to fingerprint crude with respect to their source the shale of the paralic Agbada Formation on the eastern side of the delta and the Akata marine-paralic source on the western side of the delta. Ekweozor and Okoye (1980) further constrained this hypothesis using geochemical maturity indicators, including vitrinite reflectance data that showed rocks younger than the deeply buried lower parts of the paralic sequence to be immature. Lambert-Aikhionbare and Ibe (1984) argued that the migration efficiency from the over-pressured Akata shale would be less than 12%, indicating that little fluid would have been released from the formation. They derived a different thermal maturity profile, showing that the shale within the Agbada Formation is mature enough to generate hydrocarbons.
Ejedawe et al., 1984 used maturation models to conclude that in the central part of the delta, the Agbada shale sources the oil while the Akata shale sources the gas. In other parts of the delta, it is believe that both shales source the oil. Doust and Omatsola (1990) conclude that the source organic matter is in the deltaic offlap sequences and in the sediments of the lower coastal plain. Their hypothesis implies that both the Agbada and Akata Formations likely have disseminated source rock levels, but the bulk will be in the Agbada Formation. In deep water, they favor delta slope and deep turbidite fans of the Akata Formation as source rocks. The organic matter in these environments still maintains a terrestrial signature; however, it may be enriched in amorphous, hydrogen-rich matter from bacterial degradation. Stacher (1995) proposes that the Akata Formation is the only source rock volumetrically significant and whose depth of burial is consistent with the depth of the oil window.

Evamy et al. (1978) and Doust and Omatsola (1990) reported on the Gas to oil ratios within reservoirs; reservoirs occur along northwest-southeast “oil rich belts” and along a number of north-south trends in the Port Harcourt area. These belts roughly correspond to the transition between continental and oceanic crust within the axis of maximum sediment thickness. Doust and Omatsola, (1990) among other authors attributed oil-rich belts to structural or depositional controls, geothermal gradient increase, and shifts in deposition basinward within subsequent depobelts.

Reservoir intervals in the Agbada Formation have been interpreted to be deposits of highstand and transgressive systems tracts in proximal shallow ramp settings with reservoirs thickness ranging from less than 45 feet to a few with thicknesses greater than 150 feet (Evamy et al., 1978). The most important reservoir units in this region are point bars of distributary channels and coastal barrier bars intermittently cut by sand filled channels. Most primary reservoirs were thought to be Miocene-aged paralic sandstones with 40% porosity, 2 Darcy permeability, and thickness of about 300 feet. Reservoirs thickness may increase towards the down-thrown sides of growth faults. Reservoir units vary in grain size; fluvial sandstones tend to be coarser than the delta front sandstones. Point bar deposits fine upward; barrier bar sandstones tend to have the best grain sorting. Most of the reservoir sandstones are unconsolidated with only minor argillaceous and siliceous cement. Potential reservoirs in the outer portion of the delta complex include deep-channel sands, lowstand sand bodies and proximal turbidite sandstones.

Evamy et al., (1978) and Stacher (1995) suggested that structural traps are formed during synsedimentary deformation of the Agbada Formation; and stratigraphic traps formed preferentially along the delta flanks, define the most common reservoir locations within the Niger Delta complex. The primary seal rocks of the Niger Delta Basin are the interbedded shales of the Agbada Formation; Doust and Omatsola, (1990) categorized these shales into three major types, which include:

- clay smears along faults
- interbedded sealing units juxtaposed against reservoir sands due to faulting, and
- vertical seals produced by laterally continuous shale-rich strata

Major erosion events of early to middle Miocene age formed canyons which filled with shale; these fills provide top seals on the flanks of the delta for some important offshore fields (Doust and Omatsola, 1990).

3.3 Methods

Sequence stratigraphic analysis and interpretations of four wells of “Gera Field” (Gera - 1, 2, 3 and 4) belonging to the Greater Ughelli Depobelt in the Central Niger Delta was carried out based on computer iteration method that used Stratabugs software to present the interpretation in a graphic chart (appendix 2) and Petra panel to show the wells correlation (appendix 4.0).

The steps of the analysis are as follows:

3.1.1 Inspection of well logs and biostratigraphic data

The well logs (Gamma Ray and Resistivity logs) acquired from four wells of “Gera field” (Gera- 1, 2, 3, & 4) as shown in appendix 2.1 – 2.4 are inspected to delineate lithofacies, noting the physical criteria from the logs’ responses (log motif) to determine the trend pattern of response (progradation, retrogradation and aggradation) stacking vertically and their interval.

High-resolution biostratigraphic data acquired from three (3) wells of “Gera field” (Gera - 1, 2 & 3) as shown in appendix 1.1 – 1.3, extracted from ditch cutting samples were used for interpretation. Biofacies interpretation are calibrated with well logs and depth matching was done since mistake tend to arise as a result of time taken for the cuttings to reach the surface differs from the exact timing or corresponding log reading at a particular intervals.

3.1.2 Interpreting Lithofacies and their environment

Gamma Ray log values and its motif (fining and coarsening upward trend) in combination with Resistivity logs’ signature, along with the biofacies data were used to deduce lithofacies and depositional environments of sediments in the “Gera” Field. These deductions were essentially information derived from available biofacies log and paleobathymetry data. Deposition environmental interpretation was aided by the scheme proposed by Allen, 1965 (Fig.12).

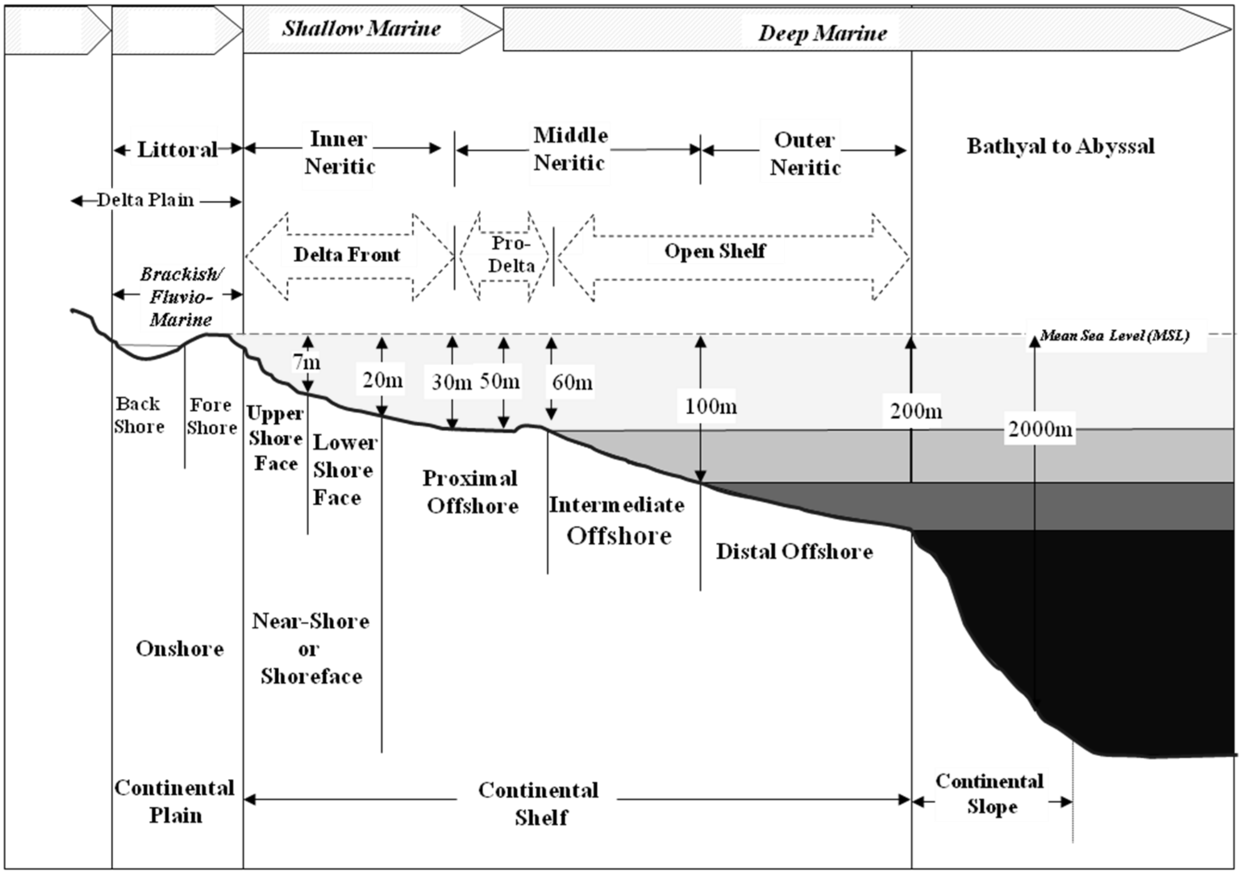


Fig.12: Depositional environments and bathymetric ranges (Modified after Allen, 1965)

Gamma ray log motif can be identified as funnel, blocky or cylindrical and bell shape (fig. 4). Bell shape log motif indicates increase in clay content (fining upward / deepening trend) which denotes an upward increase in gamma ray value and characteristic of a fluvial channel deposit or transgression. Funnel shape motif is an indicator of decreasing clay content (coarsening upward / shoaling trend), which is a feature in deltaic progradational environment; the cylindrical / blocky motif is typical of thick sand-beds. These motifs are important in recognizing a fairly uniform grained-sized sand unit which could be braided channel deposits. Serrated nature of logs suggests a tidal environment, characterized by sand-body with thin shales intercalation.

3.1.3 Recognition of parasequence and stacking pattern

Parasequences are relatively conformable succession of genetically related beds or bedsets bounded top and bottom by flooding surfaces or their correlative surface which are formed as a result of oscillation in the balance between sediment supply rate and the change in accommodation volume and are stacked into progradational, retrogradational and aggradational parasequence stacking pattern.

A progradational parasequence sets can be recognized from well log by an upward increase in the thickness of shallow marine sandstone (shoaling) - upward cycle. Retrogradational stacking pattern is an attribute of facies that are more distal upward while aggradational stacking pattern shows no shift in shoreline but builds up.

The thickness of parasequence is a function of water depth. A rapid rise in sea level is an indicator of increase in accommodation which promotes a thick parasequence. Upward thickening retrogradational parasequence trend indicates accelerating sea level; and the maximum flooding surfaces (MFS) are recognized in the thickest parasequence.

3.3.4 Identification of systems tracts

The systems tracts may include from Lowstand Systems Tract (LST), Transgressive Systems Tract and Highstand Systems Tract (HST) which were delineated based on the stacking patterns expressed by the logs (progradational, blocky or retrogradational), the associated lithofacies, as well as the resultant biofacies (faunal abundance / diversity) / paleobathymetric information.

3.3.5 Identification of Maximum flooding surfaces (mfs)

Maximum flooding surfaces separate the younger from the older and there is evidence of abrupt increase in water depth. It is defined where a relatively high

Gamma ray (GR) and low Resistivity log values associated with a shally lithofacies as well as a high foraminiferal abundance and diversity data.

The Niger Delta fauna and pollen zonation are employed also in the identification of maximum flooding surfaces (MFS), with the aid of Niger Delta chronostratigraphic chart (fig. 4) modified after Haq et al., (1988) and Table 4 showing the chronostratigraphically significant bio-events and their absolute ages in the Niger Delta Basin. The maximum flooding is recognized by maximum abundance of microfossils, which must coincide with the deep water environment.

3.3.6 Identification of sequence boundary (SB)

Sequence boundaries typically represent the time of maximum rate of fall in sea level (Nwajide, 2010). It represents the time of maximum basinward shift of the shoreline position within the deltaic cycles. The SB can be identified by analyzing the stacking pattern between two maximum flooding surfaces. The base of a progradational stacking pattern defines a sequence boundary; it coincides with the shallowest environment associated with the lowest foraminiferal abundance and diversity or complete absence of foraminiferal.

The Sequence Boundary (SB) is defined based on the low Gamma Ray and high Resistivity log values associated with a sandy lithofacies as well as low foraminiferal abundance and diversity data (fauna minima) coinciding with non marine to shallow marine environment..

3.3.7 Surface correlation

The key surfaces with the same geologic age were correlated on a correlation panel using Petrel software, and ensuring that a datum is established.

Correlation of the wells was carried out based on chronostratigraphic datums (MFS and SB) delineated in the various wells. All the identified datums were correlated even though MFS are more reliable than SB. Maximum Flooding Surface is also very easily identified on seismic sections, based on the continuous, medium to high amplitude reflections associated with it, Sequence Boundaries (SB), on the other hand, are generally diachronous and are sometimes non-genetic.

3.3.8 Dating key sequence stratigraphic surfaces

Dating of the key stratigraphic surfaces was by correlation to the third order cycles scheme of Haq, et al., (1988) (Niger Delta Cenozoic Chronostratigraphic chart), with respect to Chronostratigraphically significant bio-events table in Niger Delta (Table 4) and biofacies data. However, where chronostratigraphically significant bio-events were not recorded, dating relied on the Haq, et al., (1988) scheme. Most of these bio-events interpreted using Bolli and Saunders (1985) classification scheme were observed below the delineated datums; this may be attributed to the ditch cutting samples used for the biostratigraphic studies.

CHAPTER FOUR

RESULTS, DATA ANALYSIS, INTERPRETATION AND DISCUSSION

The well sequence stratigraphic analysis techniques as proposed by Vail and Wornardt have been adopted in this study.

4.1 Lithofacies Analysis and Environmental Interpretation

Biostratigraphic and other well data, a combination of Gamma Ray and Resistivity Logs signatures were used to deduce depositional environments based on characteristic sediments in the “GERA” Field. These deductions were essentially complemented by information derived from available biofacies log and paleobathymetry data. Depositional environmental interpretation was aided by the scheme proposed by Allen, 1965 (Fig. 6).

Stratigraphic variations in the units of ‘Gera field’ reflect the regression and transgression of depositional environments within the Niger Delta Basin; changing broadly from finer grained deposits (higher gamma-ray log values) to progressively coarser-grained deposits (lower gamma-ray log values) reflecting the sand and shale units of Agbada formation. Following standard interpretations of the Agbada Formation, log successions that gradually decrease in gamma-ray value and then rapidly increase (gradually coarsen and then abruptly fine) are interpreted to be prograding delta deposits. Those that abruptly decrease in gamma ray value and have “blocky” or gradually increasing trends (abruptly coarsen and remain sandy or gradually fine) are interpreted to be channel deposits.

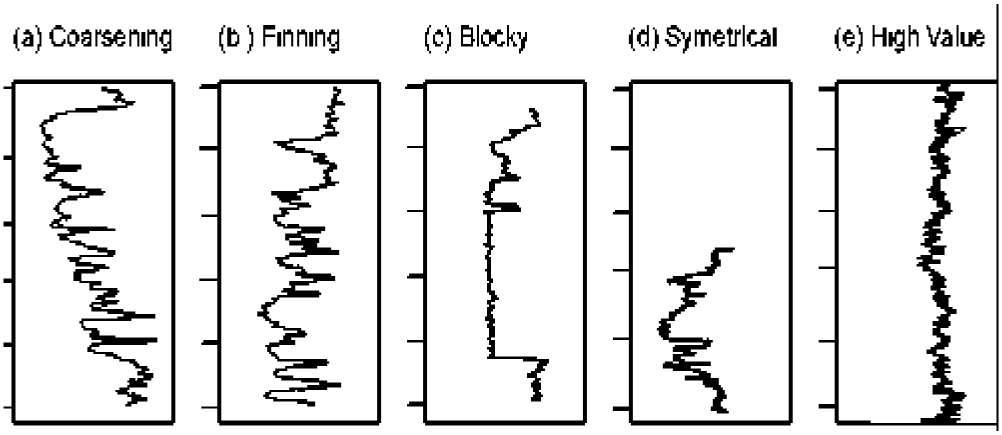


Fig.14: Types of well log patterns observed in ‘Gera field’. (A) Upward-coarsening, progradation log pattern. (B) Upward-fining, retrogradational log pattern. (C) Sharp-based, blocky log pattern. (D) Symmetrical log pattern. (E) High gamma- ray value log pattern.

The shallower part of the Agbada Formation is sandy, while shale becomes progressively thicker at depth, with the sand proportion decreasing.

These attribute suggest that the entire sequence belongs to the transitional / paralic lithofacies zones (SPDC Scheme) of the Agbada Formation.

Hence, the lithology of the studied area is broadly classified as sand and shale and subdivided into three lithofacies (Facies 1, 2 & 3).

Facies 1: Sand Facies

This sandstone facies is characterized by crescent, blocky to funnel Gamma Ray Log motif which is an indicator of coarsening or shallowing upward sequence. The crescent trend describes the cleaning up trend of sand with fine particles at the base. The log motifs suggest a sandy mouth bar, crevasse splay, to braided fluvial environment (Fig. 15); this is supported by the absence of marine fauna and paleobathymetric data of non marine to shallow inner neritic.

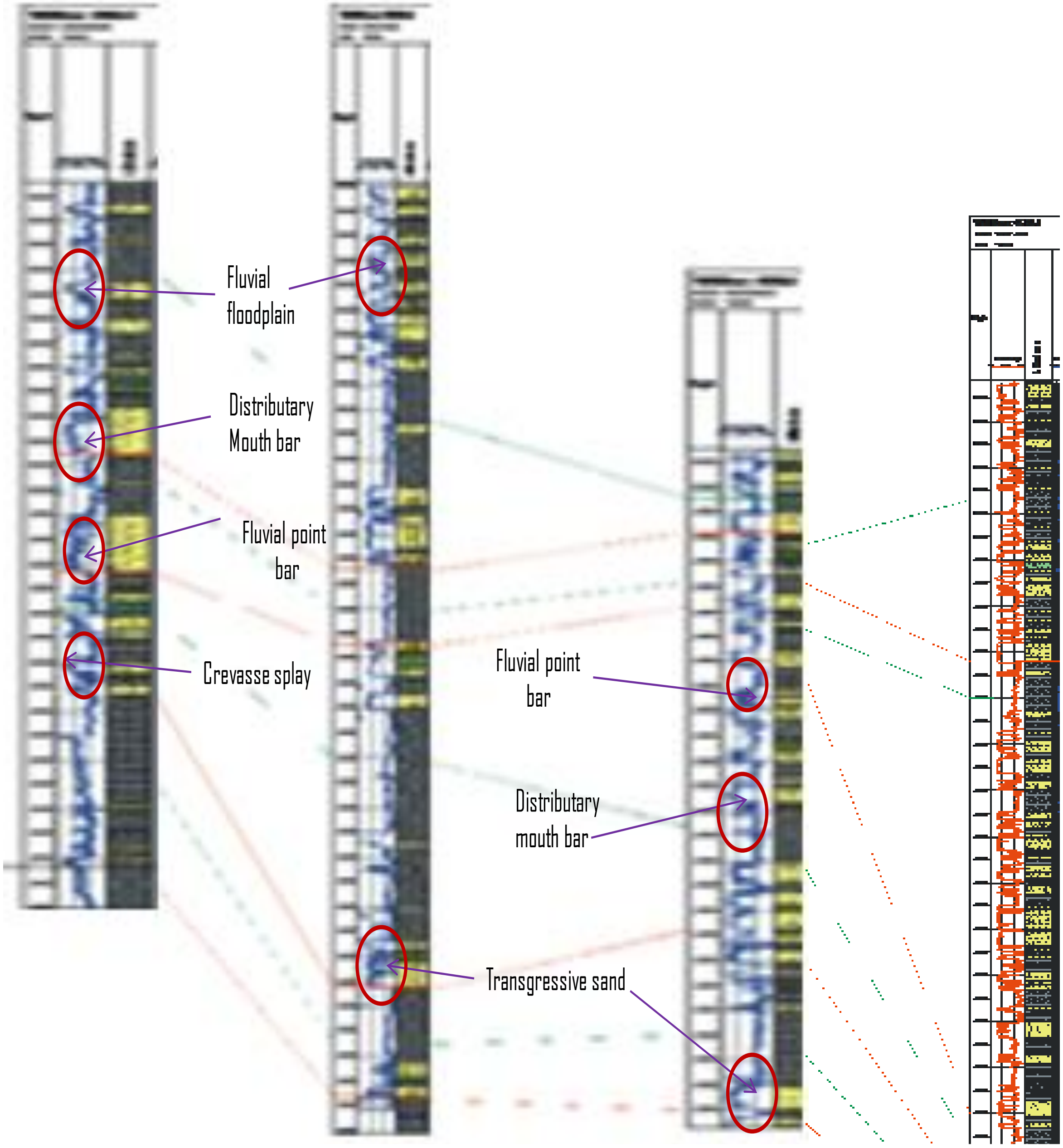


Fig. 15: Environments of deposition from gamma ray response.

Unit 2: Shaly sand Facies

This unit is characterized by bell shape gamma ray log motif with occasional serration which is an indicator of fining or deepening upward sequence. Gamma ray logs show a sharp to gradual deflection from sand to shale. The litholog of this unit comprises of fine grained sandstone / siltstone that grade into a shale unit with paleobathymetric setting of shallow inner neritic to inner neritic.

Unit 3: Shale Facies

This unit comprises of shale with thin mudstone and siltstone intercalation, characterized by retrogradational to aggradational parasequence pattern, high value gamma ray with high diversity and abundance of forams as observed from biofacies. This shale unit is interpreted as suggested by the paleobathymetric data to be of relatively deep setting (middle / outer neritic to upper bathyal).

4.2 Delineation of Constrained Surfaces

4.2.1 Interpretation of Biostratigraphic Data

The biostratigraphic interpretation is focused on the recognition of major faunal abundance and diversity peaks which usually coincide with the Maximum flooding Surfaces and the minima which corresponds to the SB. within the condensed sections of the starved transgressive and highstand systems tracts as well as their minima, which correspond to the sequence boundaries on the biostratigraphic plots (Appendix 1.1-1.3). The biostratigraphic plots and the interpreted well log patterns were then integrated to confirm the identification of key bounding surfaces.

Table 4: The chronostratigraphic significant bio-events and their absolute ages in the Niger Delta (Source: Niger Delta Stratigraphic Commission, 2002).

Bio-event	Absolute age
First Downhole Occurrence (FDO) of *Globorotalia opima opima*	28.1Ma
Acme Occurrence of *Uvigerinella sparsicostata*	31.3Ma
Acme Occurrence of *Spiroplectammina wrightii*	31.3Ma
Last Downhole Occurrence (LDO) of *Globorotalia opima opima*	32.7Ma
LDO of *Spiroplectammina wrightii*	33.0Ma
LDO of *Hopkinsina bononiensis*	34.0Ma

Biostratigraphic studies conducted on the material from the four wells of Gera Field place broad constraints on the age of the 'Gera' Field (table 4). The first down hole occurrence (FDO) of *Globorotalia opima opima* for Gera - 1, 2, 3, and 4 occurred at the depth of 2488m, 2840m, 2960m and 2910m respectively, corresponds to P22/N3 planktonic / nanno foraminifera zone of Bolli and Saunders (1985), indicating a Late Oligocene age.

The Acme Occurrence of *Uvigerinella sparsicostata* for Gera - 2, and 4 occurred at the depth of 3220 and 3320m respectively, and corresponds to the P21/N2 planktonic / nanno foraminifera zone of Bolli and Saunders (1985), indicating a Middle Oligocene age.

Acme Occurrence of *Spiroplectammina wrightii* in Gera - 3 and 4, were at 3176m depth ranging from P20/N1 – P21/N2 in the Bolli and Saunders (1985) planktonic / nanno foraminifera zone, indicative of an Early to Middle age.

The last down hole (LDO) occurrence of *Globorotalia opima opima* for Gera - 1, 2, 3, and 4 is at 3152m, 3300m, 4239m and 4230m respectively and corresponds to P18/N9 of Bolli and Saunders (1985) planktonic / nanno foraminifera zone, indicating an Early Oligocene age.

The last down hole (LDO) occurrence of *Spiroplectammina wrightii* for Gera - 1, 2, 3, and 4 is at 3168m, 3550m, 3704m, and 4290m respectively and corresponds to P18/N9 of Bolli and Saunders (1985) planktonic / nanno foraminifera zone, also indicating an Early Oligocene age.

The last down hole (LDO) of *Hopkinsina bononiensis* Gera - 1, 2, 3, and 4 is at 3544m, 4100m, 4104m and 4150m respectively, corresponding to P18/N9 planktonic / nanno foraminifera zone of Bolli and Saunders (1985), also indicates an Early Oligocene age.

The maximum flooding surfaces in the area correspond to the transgressive marker shales of the Niger Delta chronostratigraphic chart of 28.1Ma, 31.3Ma, 33.0Ma and 34.0Ma transgressive marker shale were identified in all the wells (table 4).

The ages assigned to the four sequence boundaries identified, using the Niger Delta Cenozoic Chronostratigraphic Chart are 29.3Ma, 32.4Ma, 33.3Ma and 35.4Ma. The 29.3Ma, 32.4Ma and 33.3Ma were represented in all the wells, while the 35.4Ma sequence boundary was inconclusive / absent in Gera - 4 well, probably it lie deeper than the logged interval.

Based on the foregoing, only four maximum flooding surfaces and four sequence boundaries were represented in ‘Gera Field’, the key bounding surfaces (MFS and SB) identified in the study area were dated using the foram zone of P22 / N3, P21 / N2, P20 / N1, P18 / N9. These data suggest therefore that Gera Field was deposited over about 28.1- 34.0Ma during the Early to Late Oligocene.

4.2.2 Interpretation of Depositional Sequences and Systems Tracts

Depositional sequences, systems tracts, sequence boundaries and maximum surfaces were identified based on log pattern. The systems tracts were defined by the different stacking patterns (parasequence sets), while the maximum flooding surfaces and the sequences and the sequence boundaries delineated from the wells, coincide with shaly and sandy zones on the well logs respectively.

The depositional environments of the systems tracts within the ‘Gera field’ as interpreted from the well log responses and ditch cuttings description of the sand bodies (extracted from the sedimentological chart) may include inter-distributary bay with crevasse splays, distributary channels, prodelta shelf, fluvial point bar, floodplain, transgressive sand, overbank shales with lagoonal shale; these are based on log characteristics and details as discussed in Adesina (2007). These environments are confined to delta plain – shoreline setting. This indicates that the studied section in the area is essentially a sequence of shoreline (mainly delta plain) deposit of alternating sand and shale.

On the basis of the foregoing, Gera - 1, Gera - 2 and Gera - 3 wells interpreted and the following results were obtained; Gera - 4 well which was integrated solely for well to well correlation within the field is also discussed below.

Gera -1 Well

The thickness of the sediments penetrated by this well is 1483m. The well was logged from 2325m to the total depth (TD) of 3808m. From the well log data, the HST is found to be from 3808m - 3715m, 3500m - 3320m, 3190m - 3115m, 2920m - 2875m, 2500m - 2335m (the top of the logged interval), and the TST is from 3715m – 3500m, 3320m – 3190m, 3115m – 2920m and 2875m – 2500m, four maximum flooding surfaces at 2500m, 2920m, 3190m and 3500m depth and four sequence boundaries at 2875m, 3115m, 3320m and 3715m depth were recognized.

Consequently, three depositional sequences were delineated, namely Sequence - 1, from 3715m to 3320m, Sequence - 2 from 3320m to 3115 and Sequence - 3 from 3115m to 2875m (table 3.1).

Gera -2 Well

The thickness of the sediments penetrated by this well is 1900m and logged from 4250m (TD) to 2350m depth. From the well log data, the HST is from 4250m – 4180m, 4050m - 3980m, 3500m – 3270m, 3200m – 3120m, 2810m – 2350m (the top of the logged interval) and TST from 4180m – 4050m, 3980m – 3500m, 3270m – 3200m and 3120m - 2810m, four maximum flooding surfaces at 2810m, 3200m, 3500m and 4070m and four sequence boundaries at 3120m, 3270m, 3960m and 4180m depth were recognized. Consequently, three depositional sequences were delineated, namely

Sequence - 1, from 4180m to 3960m, Sequence - 2 from 3960m to 3270m and Sequence -3 from 3270m to 3120m (table 3.2).

Gera -3 Well

The thickness of the sediments penetrated by Gera -3 well is 1350m; it was logged from 2880m to the total depth total depth (TD) of 4230m. From the well log responses, the HST was seen at the depth of 4230m (TD) – 4200m, 4050m – 3840m, 3632m – 3190m, 3140 – 3040m and 2972m – 2880m, four maximum flooding surfaces at 2972m, 3140m, 3632m and 4050m and four sequence boundaries depth at 3040m, 3190m, 3632m and 4050m depth were identified. Hence, four sequences were delineated namely Sequence -1, from 4200m to 3840m, Sequence -2 from 3840m to 3190m and Sequence -3 from 3190m to 3040m (table 3.3).

Gera -4 Well

The thickness of sediment penetrated in Gera -4 well is 1950m; it was logged from 2615m to 4260m (TD). From the well log response, the HST is from 4473m -4390m, 4270m – 4205m, 3300m -3220m and 2870m - 2610m, LST is from 4205m – 2370m, four maximum flooding surfaces at 2870m, 3300m, 4270m and 4473m depth and three sequence boundaries 3220m, 4205m and 4390m depth were identified. The base of sequence -1 was inconclusive with the top at depth of 4390m, Sequence - 2 from 4390m to 4205m and Sequence - 3 from 4205m to 3220m (table 3.4).

4.3 Sequence Stratigraphy of Gera Field

The stratigraphic column of ‘Gera field’ penetrated by the three wells (Gera - 1, Gera 2 and Gera 3) is divided from base to the top into three depositional sequences, named; depositional sequence - 1, 2 and 3. Each of them is made up transgressive systems tracts and highstand systems tracts; above sequence 3 is an incomplete sequence denoted as “Above Sequence 3”. Gera - 4 well obtained from the same field was used in the correlation panel as a supporting well, it has a lowstand systems tract. The systems tracts were separated by the key bounding surfaces (MFS and SB), which were used as correlative references (appendix 4.0 and table 6).

- Sequence Stratigraphy of Gera - 1 well

Table 5.1: Sequence Stratigraphic Framework of Gera -1 Well

Sequence	Depth (m) 2535	Systems Tracts	Important Stratigraphic Surfaces and Bioevents	Age (After Haq et al., 1988) (Ma)	Depositional Environment
Above Sequence 3	2500	HST	**MFS**	28.1	MN – ON
	2875	TST	**SB**	29.3	NM –SIN
3	2920	HST	**MFS**	31.3	MN – ON
	3115	TST	**SB**	32.4	NM
2	3190	HST	**MFS**	33.0	MN
	3320	TST	**SB**	33.3	IN
1	3500	HST	**MFS**	34.0	MN – ON
	3715	TST	**SB**	35.4	SIN
		HST			

Legend:
HST – Highstand Systems Tract
MFS – Maximum Flooding Surface
NM – Non marine
MN – Middle Neritic
TST – Transgressive Systems Tract
SB – Sequence Boundary
SIN – Shallow Inner Neritic
ON – Outer Neritic

Highstand Systems Tracts (HST)

Interval: 3800m – 3715m

The lithofacies (shale and sand) in this interval were deposited in middle neritic to non-marine paleoevironments realms and are associated with a progradational (coarsening upward) log pattern (fig. 16a); indicative of regressive phase of deposition. The peak of this regressive phase; the SB, was delineated at 3715m where the low gamma ray and high Resistivity log values are associated with a low foraminiferal abundance and diversity data. The SB is dated 35.4Ma by correlation to the Haq et al., (1988) scheme.

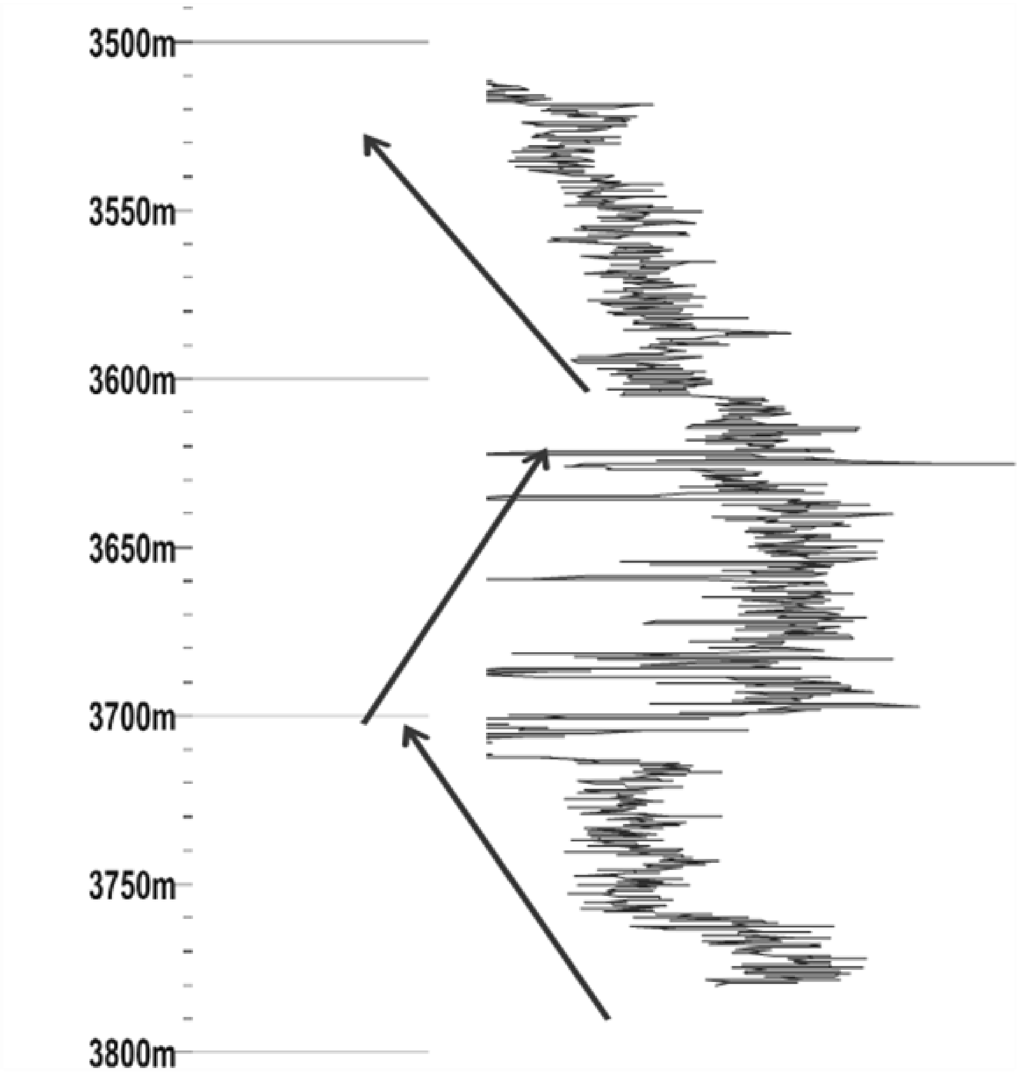


Fig. 16a: Progradational and retrogradational log patterns.

Legend: ↖ Progradational ↗ Retrogradational ↑ Aggradational

Transgressive Systems Tracts (TST)

Interval: 3715m – 3500m

The shale (with sand and silt intercalations) lithofacies in this interval were deposited in non-marine – outer neritic paleoevironments realms and are associated with retrogradational (fining upward) log pattern (fig. 16a); indicative of a transgression. The peak of this phase of deposition; the MFS; was delineated at 3500m where the high GR and low Resistivity log values are associated with a high foraminiferal abundance and diversity data. The MFS is dated 34.0Ma by correlation to the Haq, et al., (1988) scheme. The LDO of *Hopkinsina bononiensis*, dated 34.0Ma and observed at 3544m (about 44m below the defined datum) also confirms the penetration of this shale unit. Its occurrence 44m below may probably be as a result of the sample type (ditch cuttings); which is susceptible to caving.

Highstand Systems Tracts (HST)

Interval: 3500m – 3320m

The shale and sand, with silt intercalation in this interval were deposited in outer neritic – non-marine paleoevironments and are associated with progradational / blocky log patterns (fig. 16b); indicative of a regression. The peak of this regressive phase, the SB, was delineated at 3320m, where low gamma ray and high resistivity log values are associated with the non-recovery of fauna (barren interval); that is, a faunal minima. The SB is dated 33.3Ma by correlation to the Haq et al. (1988) scheme.

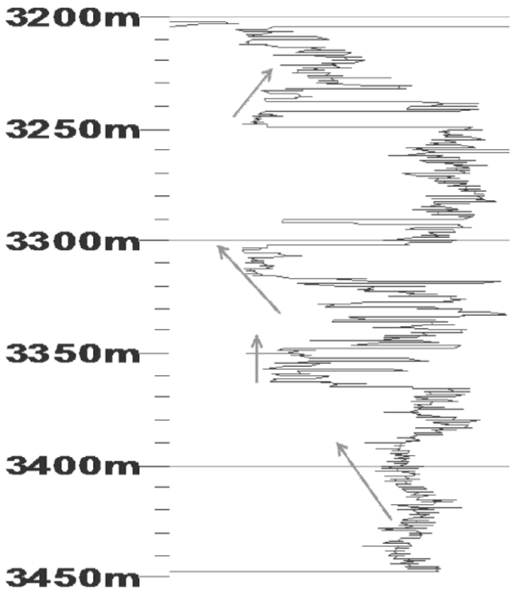


Fig. 16b: Progradational / blocky and retrogradational log patterns.

Legend: ↖ Progradational ↗ Retrogradational ↑ Aggradational

Transgressive Systems Tracts

Interval: 3320m – 3190m

This interval consists of sand, silt and shale litho-units that were deposited in non marine – middle neritic paleoevironments and are associated with stacks of retrogradational log pattern (fig. 16b); indicative of a transgressive phase of deposition. The peak (MFS) of this transgression was defined at 3190m based on the high gamma ray and low resistivity log values associated with a high foraminifera abundance and diversity within interval 3200m – 3208m. This is slightly below the delineated datum at 3190m. This is because the influx of foraminifera is within the proximity of the underlying sand lithofacies. The MFS is thus log-adjusted. This is because the log, being a direct reading of the well borehole is more reliable than the ditch cutting samples from which the foraminifera data was derived.

The MFS is dated 33.0Ma by correlation to the Haq et al. (1988) scheme. Also, the LDO of *Globoratalia opima opima,* dated 32.7Ma and observed at 3152m supports this interpretation.

Highstand Systems Tracts (HST)

Interval: 3190m – 3115m

The litho-units (shale, silt and sand) of this interval were deposited in middle neritic to non-marine paleoevironments and are associated with stacks of progradational to blocky log patterns (fig. 16c), which define a regressive mode of deposition. The peak of the regression, the SB, was delineated at 3115m (the base of a well-developed sand litho-unit) and is characterized by a low gamma ray and high resistivity log values.

The SB is dated 32.4Ma by correlation to the Haq et al. (1988) scheme. Also the LDO of *Globorotalia opima opima* (32.7Ma) observed at 3152m supports the interpretation.

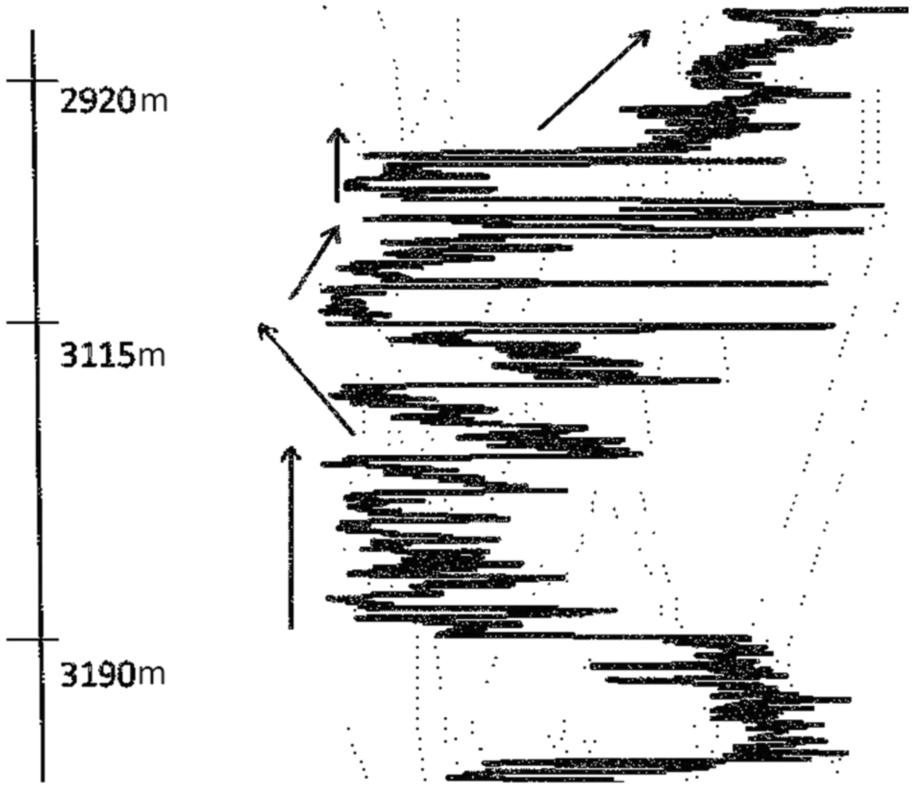


Fig. 16c: Progradational to blocky and blocky to retrogradational log patterns.

Legend: ↖ Progradational ↗ Retrogradational ↑ Aggradational

Transgressive Systems Tracts (TST)

Interval: 3115m – 2920m

This interval consists of transgressive sands overlain by shales. The litho-units were deposited in non-marine to outer neritic paleoevironments and are associated with blocky to retrogradational log patterns (fig. 16c); defining a transgressive mode of deposition. The peak of the transgression (MFS) was delineated at 2920m based on the high gamma ray and low resistivity log values associated with a high abundance and diversity of foraminifera.

The MFS is dated 31.3Ma by correlation to the Haq et al. (1988) scheme.

Highstand Systems Tracts (HST)

Interval: 2920m – 2875m

The shales and sands in this interval were deposited in outer neritic to predominantly shallow inner neritic / non-marine paleoevironments. The sharp drop in paleobathymetric setting alongside coarsening upward (fig. 16d) of the lithofacies typifies a regression. The peak of this regressive phase of deposition (SB) was delineated at 2875m, the base of a well-developed sandbody associated with low GR and high Resistivity log values.

The SB is dated 29.3Ma by correlation to the Haq et al. (1988) scheme.

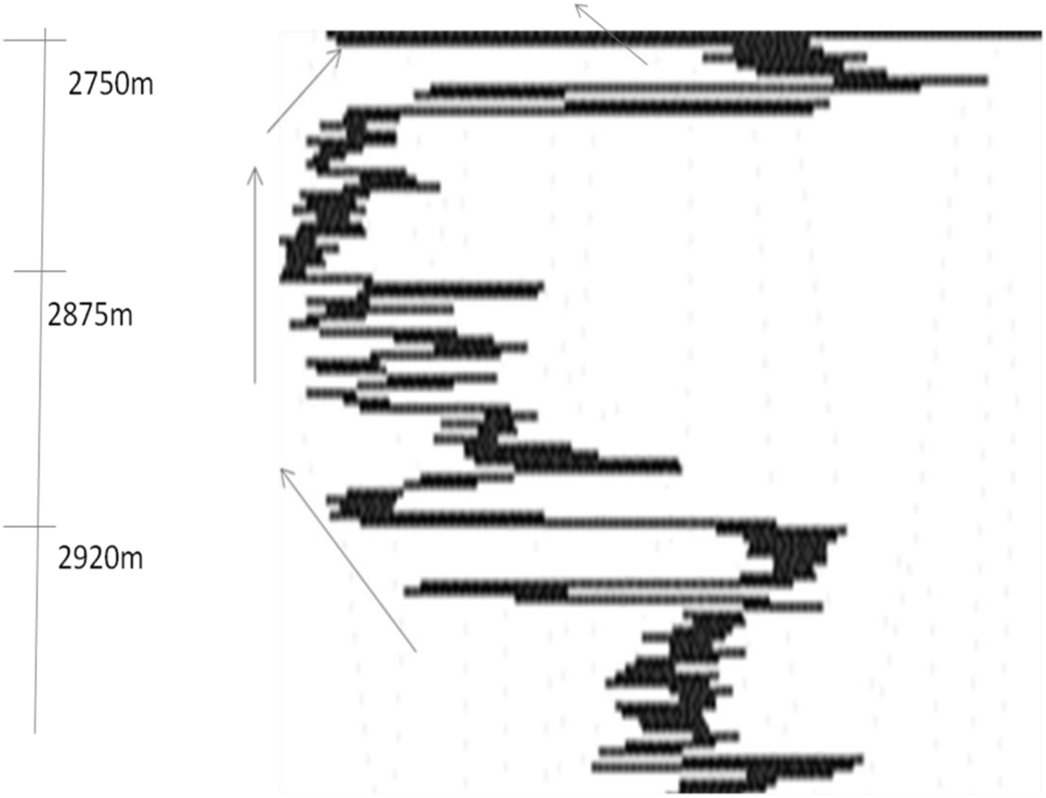


Fig. 16d: Coarsening, blocky to fining upward log patterns.

Legend: ↖ Progradational ↗ Retrogradational ↑ Aggradational

Transgressive Systems Tracts (TST)

Interval: 2875m – 2500m

The sand, silt and shale in this interval were deposited in shallow inner neritic – outer neritic paleoevironments and are characterized by blocky, progradational to retrogradational log patterns (fig. 16d and 16e). This is indicative of a transgressive phase of deposition. The transgression reached its peak (MFS) at 2500m where low gamma ray and high resistivity log values are associated with high abundance of foraminifera. The MFS is dated 28.1Ma by correlation to the

Haq et al. (1988) scheme. The FDO of *Globorotalia opima opima,* dated 28.1Ma and observed at 2488m, supports the interpretation.

Highstand Systems Tracts (HST)

Interval: 2500m – 2325m

The shales and sand intercalations in this interval were deposited in outer neritic to non-marine paleoevironments and are characterized by stacks of progradational log patterns (fig. 16e) indicative of a regressive phase of deposition. The peak of the regression was not penetrated at the top depth (2325m) as depicted by the termination of the log in an aggradational mode.

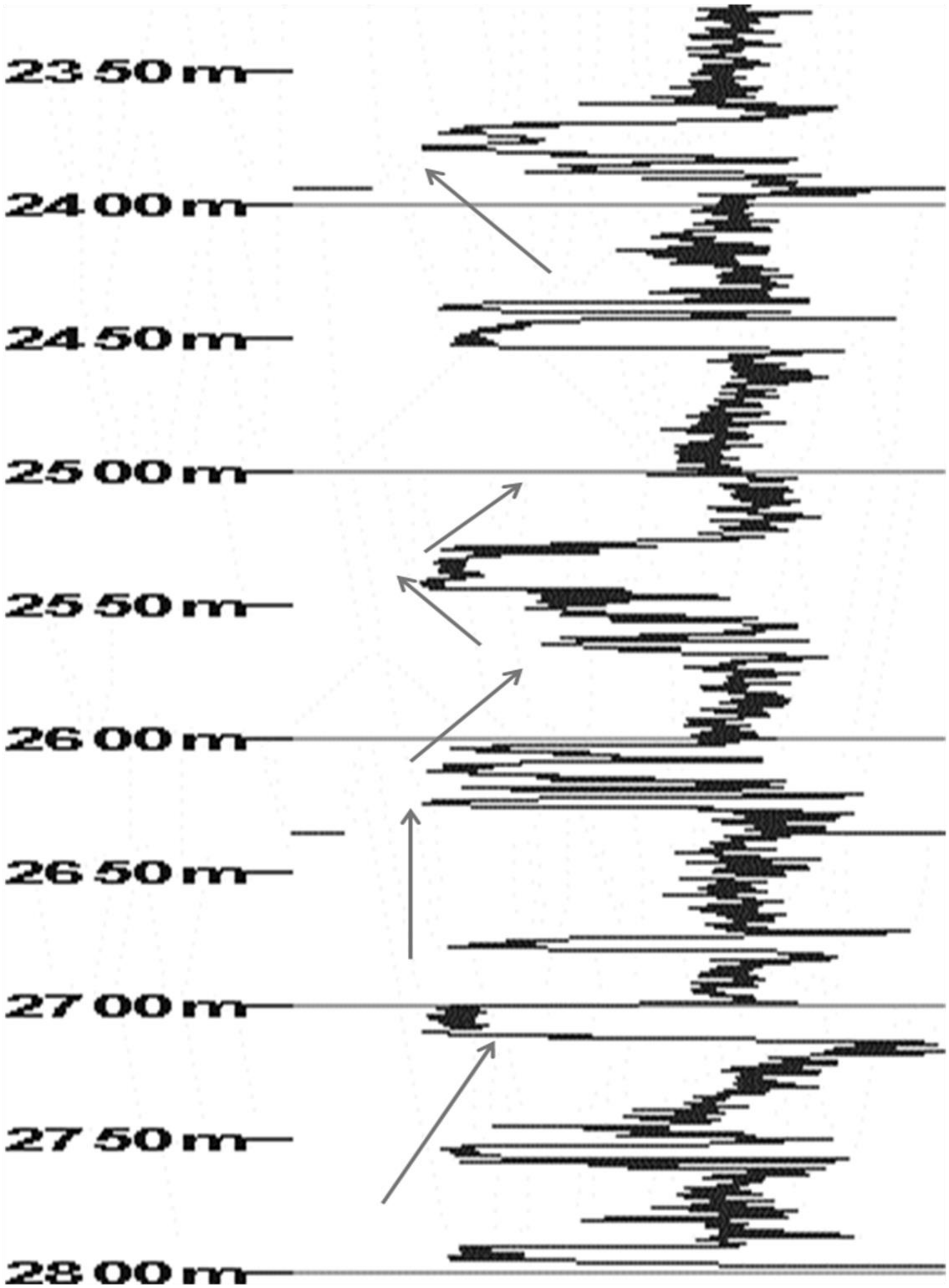


Fig. 16e: Progradational, blocky and retrogradational log patterns.

Legend: ↖ Progradational ↗ Retrogradational ↑ Aggradational

- Sequence Stratigraphy of Gera - 2 Well

Table 5.2: Sequence Stratigraphic Framework of Gera -2 Well

Sequence	Depth (m)	Systems Tracts	Important Stratigraphic Surfaces and Bioevents	Age (After Haq et al., 1988) (Ma)	Depositional Environment
	2350				
Above Sequence 3	2810	HST	**MFS**	28.1	ON – UB
	3120	TST	**SB**	29.3	IN – MN
3	3200	HST	**MFS**	31.3	ON – UB
	3270	TST	**SB**	32.4	IN
2	3500	HST	**MFS**	33.0	ON
	3960	TST	**SB**	33.3	NM
1	4070	HST	**MFS**	34.0	MN - ON
	4180	TST	**SB**	35.4	NM – SIN
		HST			

Legend:
HST: Highstand Systems Tract
MFS: Maximum Flooding Surface
NM: Non marine
MN: Middle Neritic
IN: Inner Marine
TST: Transgressive Systems Tract
SB: Sequence Boundary
SIN: Shallow Inner Neritic
ON: Outer Neritic
UB: Upper Bathyal

Highstand Systems Tracts (HST)

Interval: 4250m – 4180m

The shale and sand with silt intercalation in this interval were deposited in inner / shallow inner-neritic to non-marine paleoevironments and are characterized by progradational log units (fig. 17a); indicative of a regression. The peak of this regressive phase of deposition (SB) was delineated at 4180m where the relatively low GR and high Resistivity log values are associated with a low foraminiferal abundance.

The SB is dated 35.4Ma by correlation to the Haq et al., (1988) scheme.

Transgressive Systems Tracts (TST)

Interval: 4180m – 4070m

The shales (underlain by sands) in this interval were deposited in shallow inner - outer neritic paleoevironments and are characterized by a retrogradational log pattern (fig. 17a). This transgressive phase of deposition reached its peak (MFS) at 4070m, where the shale unit is associated with relatively high GR and low Resistivity log values; with an accompanying relatively high abundance and diversity of foraminifera.

The MFS is dated 34.0Ma by correlation to the Haq et al., (1988) scheme. The LDO of *Hopkinsina bononiensis,* dated 34.0Ma and observed at 4100m supports this interpretation.

Highstand Systems Tracts (HST)

Interval: 4070m – 3960m

The shale and sand litho-units in this interval were deposited in outer neritic to non-marine paleoevironments and are characterized by progradational to blocky log patterns (fig. 17a); suggestive of a regression. The regression reached its peak at 3960m, where low GR and high Resistivity log values are associated with the non-recovery of foraminifera (barren interval).

The SB is dated 33.3Ma by correlation to the Haq et al., (1988) scheme.

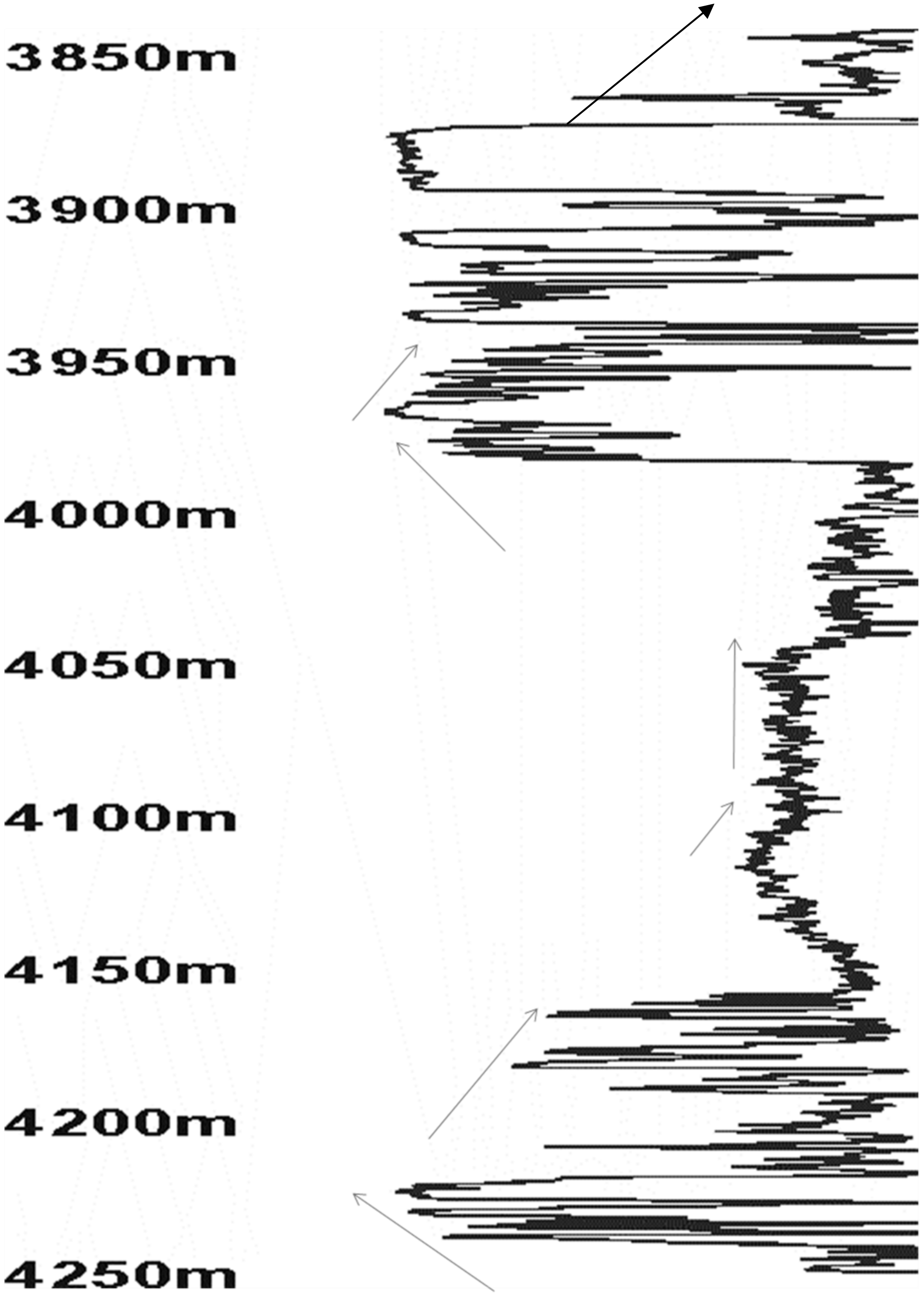


Fig. 17a: Progradational, retrogradational and blocky log patterns.

Legend: ↖ Progradational ↗ Retrogradational ↑ Aggradational

Transgressive Systems Tracts (TST)

Interval: 3960m – 3500m

The sand and the shale in this interval were deposited in non-marine – middle neritic paleoevironments and are characterized by a retrogradational log pattern (fig. 17a). The fining / deepening upward episodes observed from the data are indicative of a transgression that reached its peak (MFS) at 3500m. The MFS is characterized by high GR and low Resistivity log values associated with relatively high abundance and diversity of foraminifera. It is dated 33.0Ma by correlation to the Haq et al., (1988) scheme. The LDO of *Spiroplectammina wrightii,* dated 33.0Ma and observed at 3550m supports this interpretation.

Highstand Systems Tracts (HST)

Interval: 3500m – 3270m

The shale, silt and sand in this interval were deposited in outer – inner neritic paleoevironments and are characterized by progradational / blocky log patterns (fig. 17b). The association of the lithofacies with these log patterns as well as the drastic drop in paleobathymetry (from predominantly outer neritic/upper bathyal directly to an inner neritic setting) typifies a regressive phase of deposition. The regression reached its peak at 3270m, where the relatively low gamma ray and high resistivity log values are associated with low abundance and diversity of foraminifera.

The SB is dated 32.4Ma by correlation to the Haq, et al., (1988) scheme. The LDO of *Globorotalia opima opima*, dated 32.7Ma and observed at 3300m supports this interpretation.

Transgressive Systems Tracts (TST)

Interval: 3270m - 3200m

The sand and shale in this interval were deposited in predominantly outer neritic – upper bathyal paleoevironments and are characterized by a retrogradational log pattern (fig. 17b); indicating a transgression. The peak of this transgressive phase (MFS) was delineated at 3200m where the high GR and low Resistivity log values are associated with a high abundance and diversity of foraminifera.

The MFS is dated 31.3Ma by correlation to the Haq et al., (1988) scheme. The Acme occurrence of *Uvigerinella sparsicostata*, dated 31.3Ma and observed at 3220m supports this interpretation.

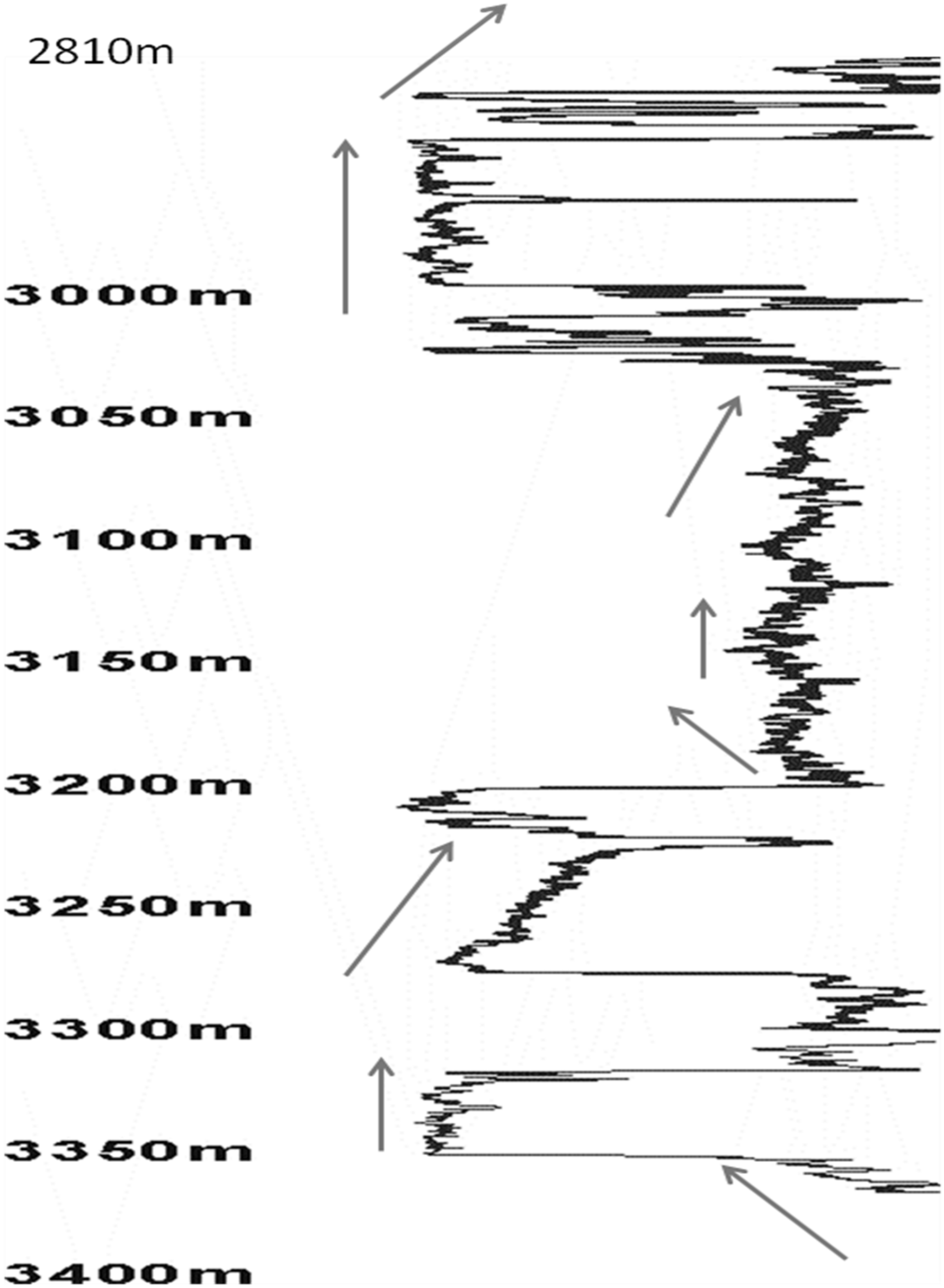


Fig. 17b: Retrogradational, progradational and aggradational log patterns.

Legend: ↖ Progradational ↗ Retrogradational ↑ Aggradational

Highstand Systems Tracts (HST)

Interval: 3200m – 3120m

The shale and sand in this interval were deposited in upper bathyal – inner neritic paleoevironments in a typical shallowing / coarsening upward sequence associated with progradational / blocky log patterns (fig. 17b). This regressive phase reached its peak at 3120m, where low GR and high Resistivity log values are associated with a relatively low foraminiferal abundance.

The SB is dated 29.3Ma by correlation to the Haq et al., (1988) scheme.

Transgressive Systems Tracts (TST)

Interval: 3120m – 2810m

The sand and shale in this interval were deposited in inner neritic – upper bathyal paleoevironments and are characterized by a retrogradational / aggradational log patterns (fig. 17b); indicative of a transgression. The peak of this transgressive phase was delineated at 2810m based on the high GR and low Resistivity log values associated with high abundance and diversity of foraminifera.

The MFS is dated 28.1Ma by correlation to the Haq *et al.,* (1988) scheme. The FDO of *Globorotalia opima opima,* dated 28.1 Ma and observed at 2840m supports this interpretation.

Highstand Systems Tracts (HST)

Interval: 2810m – 2350m

The shale, silt and sand in this interval were deposited in upper bathyal to non-marine / shallow inner neritic paleoevironments and are characterized by stacks of progradational / blocky log patterns (17c). The peak of this regressive phase was probably not penetrated at the top depth (2350m) where the log is still in a progradational mode.

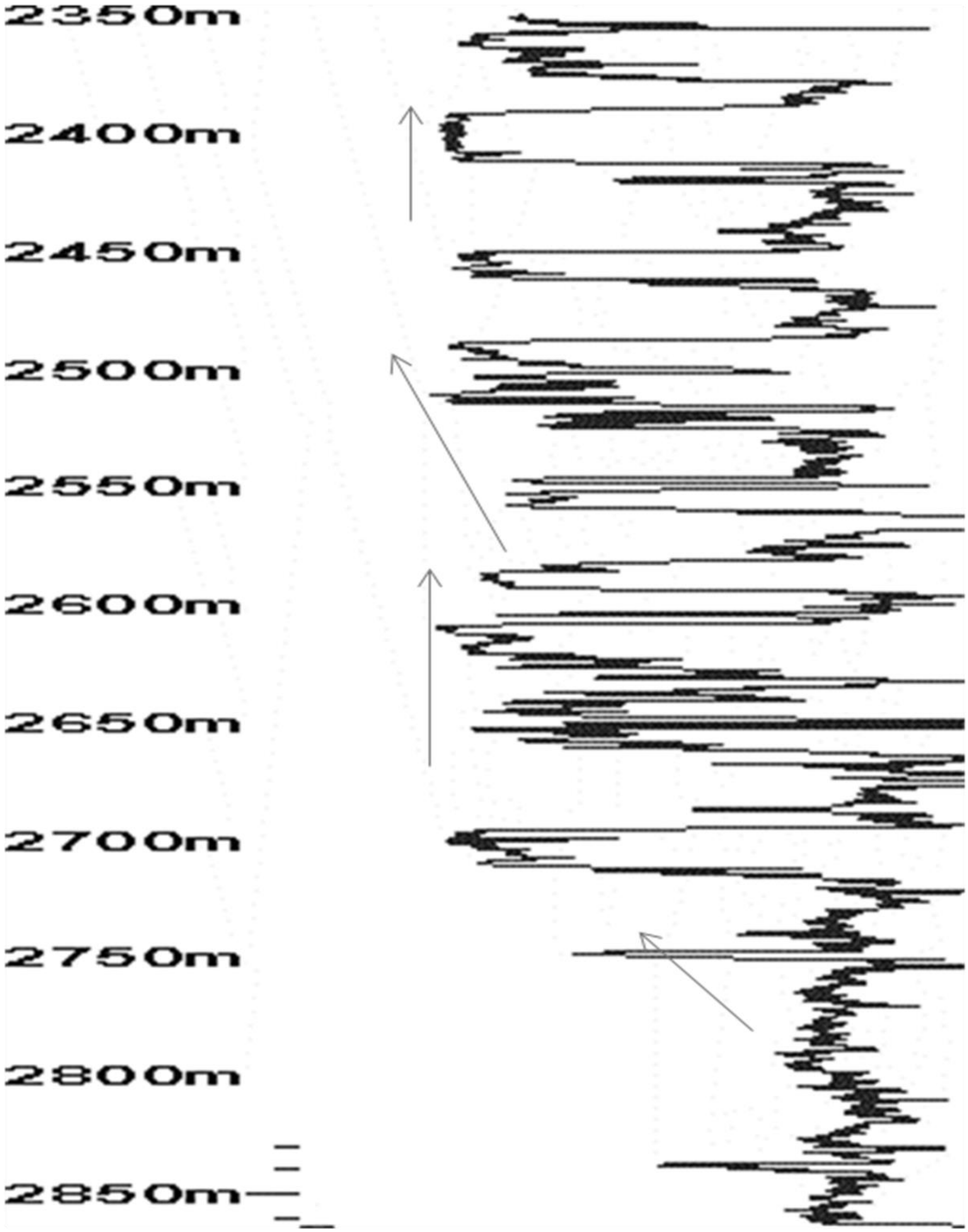


Fig. 17c: **Retrogradational, progradational and aggradational log patterns.**

Legend: ↖ Progradational ↗ Retrogradational ↑ Aggradational

- Sequence Stratigraphy of Gera - 3 well

Table 5.3: Sequence Stratigraphic Framework of Gera -3 Well

Sequence	Depth (m)	Systems Tracts	Important Stratigraphic Surfaces and Bioevents	Age (After Haq et al., 1988) (Ma)	Depositional Environment
	2850				
Above Sequence 3	2972	HST	**MFS**	28.1	IN – MN
	3040	TST	**SB**	29.3	SIN – IN
3	3140	HST	**MFS**	31.3	MN – ON
	3190	TST	**SB**	32.4	NM
2	3632	HST	**MFS**	33.0	MN – ON
	3840	TST	**SB**	33.3	NM
1	4050	HST	**MFS**	34.0	MN – ON
	4200	TST	**SB**	35.4	IN
		HST			

Legend:
HST – Highstand Systems Tract
MFS – Maximum Flooding Surface
NM – Non marine
MN – Middle Neritic
TST – Transgressive Systems Tract
SB – Sequence Boundary
SIN – Shallow Inner Neritic
ON – Outer Neritic

Highstand Systems Tracts (HST)

Interval: 4230m – 4200m

The sand (with shale intercalation) in this interval was deposited in inner neritic paleoevironments and is characterized by a blocky log pattern (fig. 18a). This regressive phase reached its peak at 4200m where low GR and high Resistivity log values are associated with a low foraminiferal abundance and diversity.

The SB is dated 35.4Ma by correlation to the Haq et al., (1988) scheme.

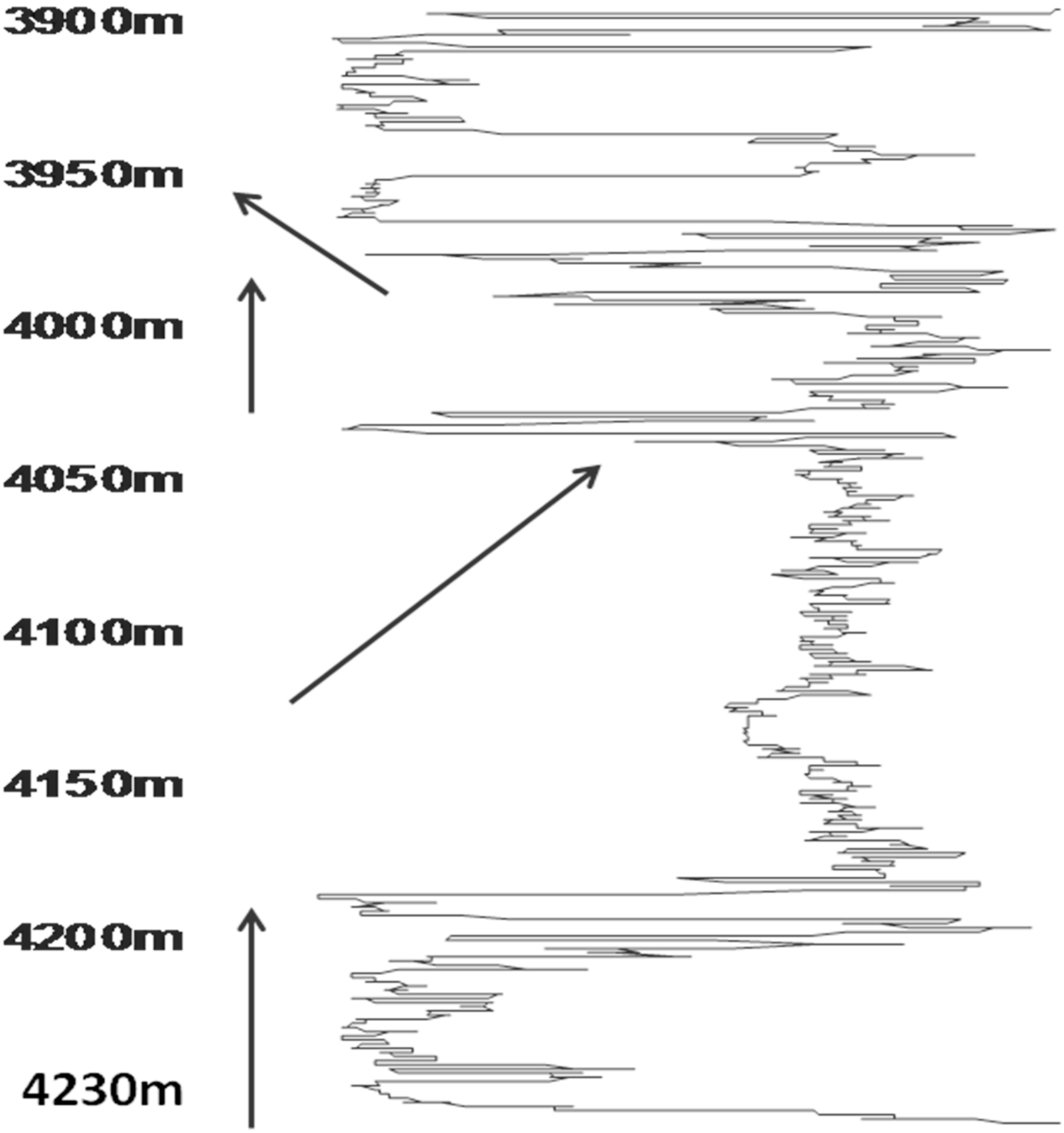


Fig. 18a: Retrogradational, progradational and blocky log patterns.

Legend: ↖ Progradational ↗ Retrogradational ↑ Aggradational

Transgressive Systems Tracts (TST)

Interval: 4200m – 4050m

The sand and shale in this interval were deposited in inner-outer neritic and are characterized by an overall retrogradational log pattern (fig. 18a); indicative of a transgression. The peak of this transgressive phase was delineated at 4050m where high GR and low Resistivity log values are associated with a high foraminiferal abundance and diversity data.

The MFS is dated 34.0Ma by correlation to the Haq *et al.,* (1988) scheme. The LDO of *Hopkinsina bononiensis,* dated 34.0Ma and observed at 4104m supports this interpretation.

Highstand Systems Tracts (HST)

Interval: 4050m - 3840m

The shale and sand (with silt intercalation) were deposited in outer neritic – non-marine paleoevironments and are characterized by progradational / blocky log patterns (fig. 18b). This regressive phase reached its peak at 3840m where low GR and high Resistivity log values are associated with the non-recovery of foraminifera. The SB is dated 33.3Ma by correlation to the Haq et al. (1988) scheme.

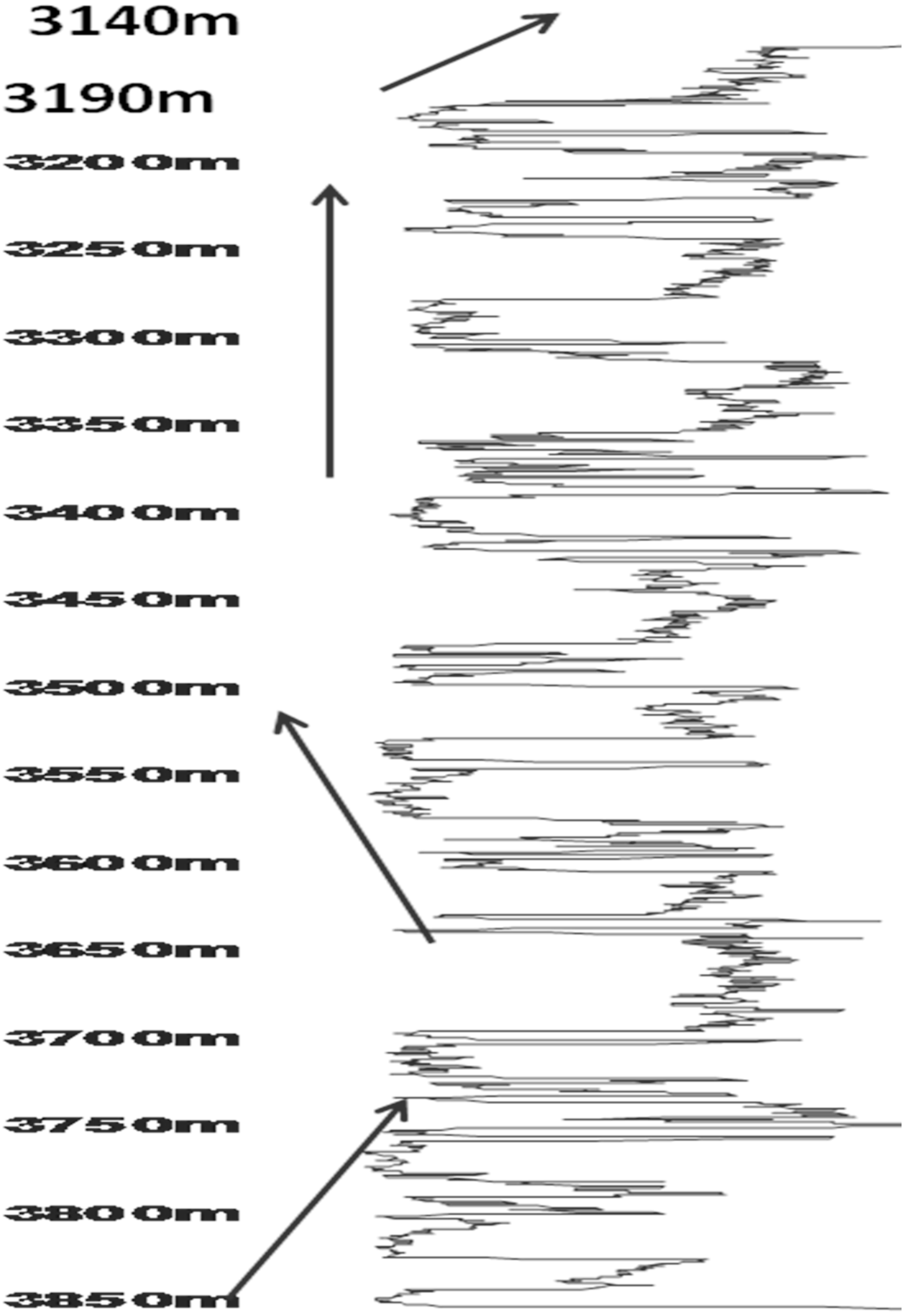


Fig. 18b: Retrogradational, progradational and blocky log patterns.

Legend: ↖ Progradational ↗ Retrogradational ↑ Aggradational

Transgressive Systems Tracts (TST)

Interval: 3840m – 3632m

The sand, silt and shale in this interval were deposited in non-marine – outer neritic paleoevironments and are characterized by stacks of retrogradational log patterns (fig.

18b). The peak of this transgressive phase was delineated at 3632m where high GR and low Resistivity log values are associated with a high foraminiferal abundance and diversity data.

The MFS is dated 33.0Ma by correlation to the Haq et al. (1988) scheme The LDO of *Spiroplectammina wrightii,* dated 33.0Ma and observed at 3704m supports this interpretation.

Highstand Systems Tracts (HST)

Interval: 3632m – 3190m

The shale silt and sand in this interval were deposited in outer neritic – non-marine paleoevironments and are characterized by stacks of blocky / progradational log patterns (fig. 18b); suggestive of a regression.

The peak of the regression was delineated at 3190m where low GR and high Resistivity log values are associated with the non-recovery of foraminifera.

The SB is dated 32.4Ma by correlation to the Haq et al., (1988) scheme.

Transgressive Systems Tracts (TST)

Interval: 3190m – 3140m

The sand and shale in this interval were deposited in predominantly middle – outer neritic and are characterized by a retrogradational log pattern (fig. 18b). This transgressive phase reached its peak at 3140m where high GR and low Resistivity log values are associated with a high foraminiferal abundance and diversity data. The MFS is dated 31.3Ma by correlation to the Haq et al., (1988) scheme. The Acme occurrence of *Spiroplectammina wrightii,* dated 31.3Ma and observed at 3176m supports this interpretation.

Highstand Systems Tracts (HST)

Interval: 3140m – 3040m

The shale, silt and sand in this interval were deposited in outer – inner/shallow inner neritic paleoevironments and are characterized by progradational / blocky log patterns (fig. 18c). This regressive phase reached its peak at 3040m where low GR and high Resistivity log values are associated with a low foraminiferal abundance and diversity data. The SB is dated 29.3Ma by correlation to the Haq, et al., (1988) scheme.

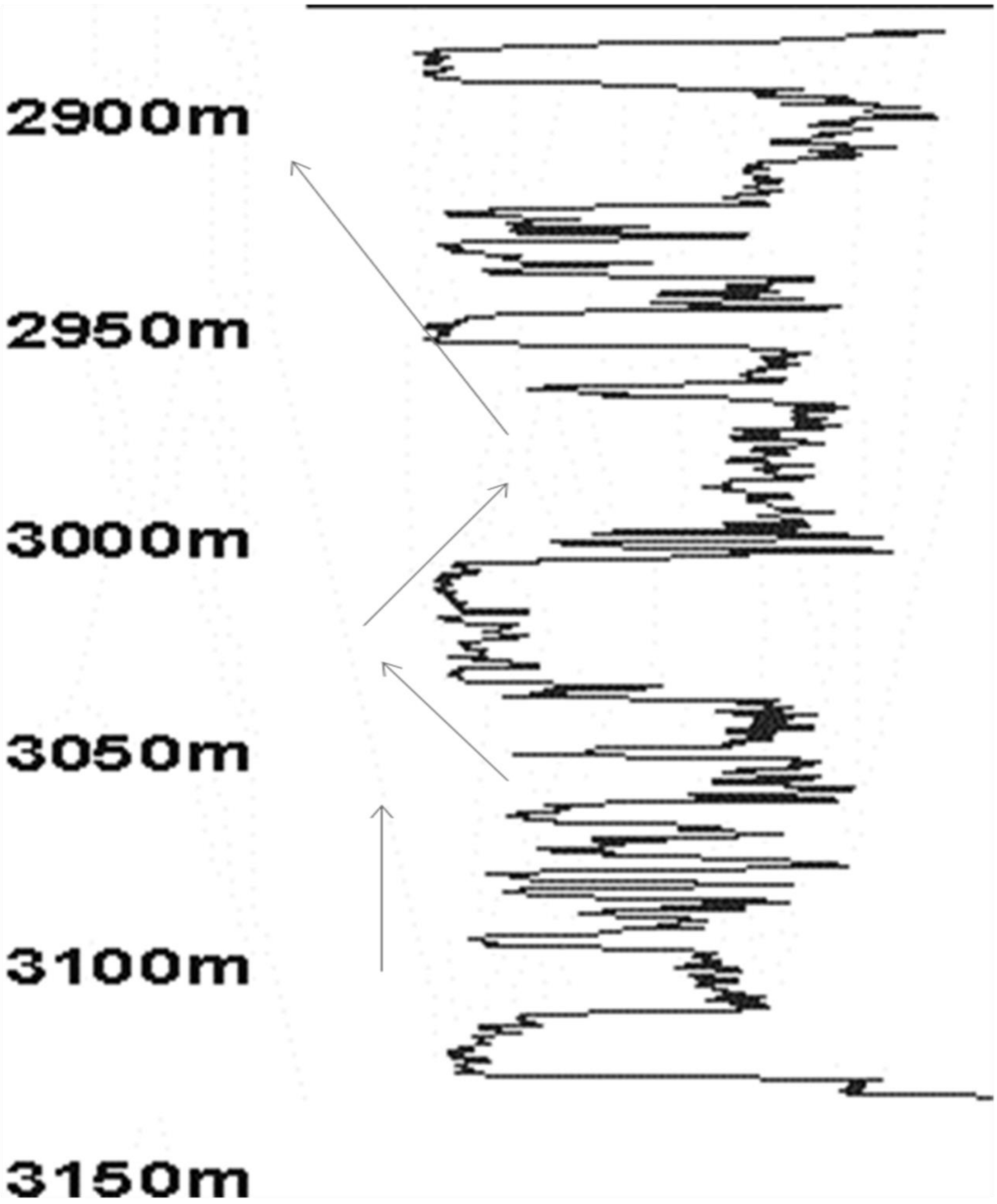


Fig. 18c: Retrogradational and progradational log patterns.

Legend: ↖ Progradational ↗ Retrogradational ↑ Aggradational

Transgressive Systems Tracts (TST)

Interval: 3040m – 2972m

The sand and shale in this interval were deposited in Shallow inner – outer neritic paleoevironments and are characterized by an overall retrogradational log pattern (fig.

18c); indicative of a transgression that reached its peak at 2972m; based on the high GR and low Resistivity log values associated with high foraminiferal abundance and diversity data.

The MFS is dated 28.1Ma by correlation to the Haq, et al., (1988) scheme. The FDO of *Globorotalia opima opima*, dated 28.1Ma and observed at 2980m supports this interpretation.

Highstand Systems Tracts (HST)

Interval: 2972m – 2880m

The shale, silt and sand in this interval were deposited predominantly inner-middle neritic paleoevironments and are characterized by stacks of progradational log pattern (fig. 18c). This phase of regression did not reach its peak at the top depth (2880m) as shown by the progradational mode of the log.

Table 5.4: Sequence Stratigraphic Framework of Gera -4 Well

Sequence	Depth (m)	Systems Tracts	Important Stratigraphic Surfaces and Bioevents	Age (After Haq et al., 1988) (Ma)	Depositional Environment
Above Sequence 3	2870	HST	MFS	28.1	ON – UB
	3220	TST	SB	29.3	NM
3	3300	HST	MFS	31.3	ON – UB
	4205	TST LST	SB	32.4	NM
2	4270	HST	MFS	33.0	ON – UB
	4390	TST	SB	33.3	NM – SM
1	4473	HST	MFS	34.0	ON – UB
	4560	TST	SB	35.4	?
		HST			

Legend:

HST:	Highstand system tract	TST:	Trangressive system tract
LST:	Lowstand system tract	MFS:	Maximum flooding surface
SB:	Sequence Boundary	ON:	Outer Neritic
UB:	Upper Bathyal	NM:	Non marine

4.3.1 Depositional Sequences of Gera Field

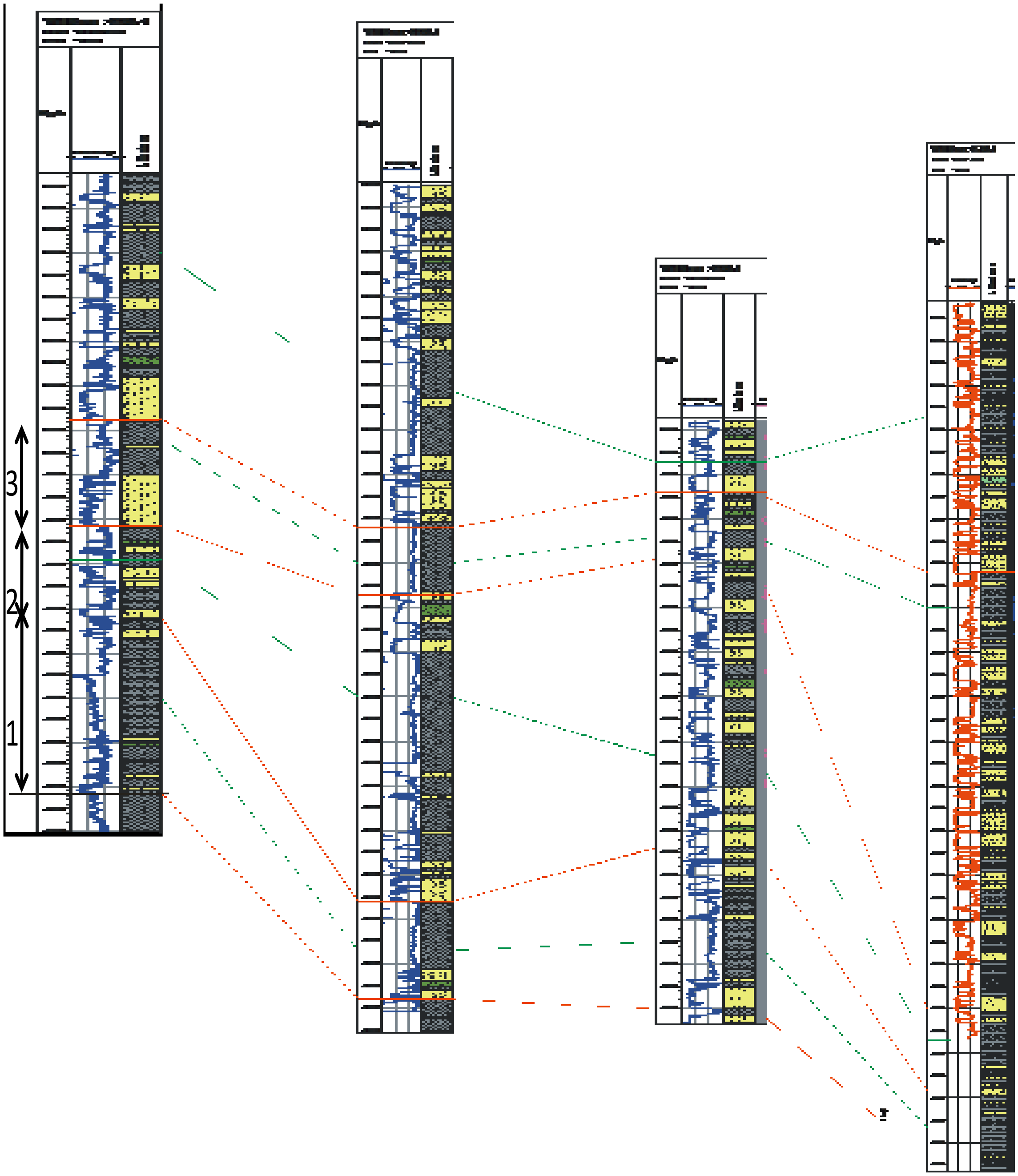


Fig. 19: Depositional Sequences encountered in Gera Field.

Sequence 1:

The first Sequence has an average thickness of about 361m with erosional coarse base, bounded top and base by sequence boundary 35.4 and 33.3 Ma, in the middle by 34.0Ma maximum flooding surface (fig. 19). Gamma ray log shows an abrupt increase above the coarse base with blocky/ retrogradational log motif, occasionally interrupted vertically by few meter thick high gamma ray values and at the top a retrogradational to progradational pattern ensues. The environment of deposition of sequence 1 as deduced from paleowater depth ranges from shallow inner neritic to outer neritic, this is interpreted to be period of shalestone deposition with few sandstone interbeds.

Sequence 2:

The second Sequence with an erosional base has an average thickness of 472m, bounded by sequence boundary 33.3 and 32.4Ma (fig. 19). The gamma ray log shows a crescent (bow trend) to blocky pattern at the basal part and subsequently followed by equal amounts of high and low values which grades vertically into sand and shale beds. The abrupt gamma ray increase towards the middle of the sequence corresponds to the lowest resistivity values indicating a 33.0Ma maximum flooding surface. Depositional environment ranged from Non marine to Outer Neritic and interpreted to be period of deposition of equal amounts of shalestones and sandstones.

Sequence 3:

The third sequence with an average thickness of 180m has an erosional coarse base (fig. 19). Gamma ray log shows a retrogradational pattern at the top of the coarse base with subsequent equal amounts of high and low values of sand and shale grading vertically. This sequence is bounded by top and base by sequence boundary 32.4 and 29.3Ma, with 31.3Ma maximum flooding surface at the middle. The environment of deposition from palaeowater depth is Non marine to Upper Bathyal, interpreted to be time of relative sea level fall with deposition of sandstone and occasional interbeds of mudstones.

Above Sequence 3:

Above sequence 3, there is an evidence of another sequence which consists of an erosional base lying above sequence boundary 29.3Ma (fig. 19). Gamma ray logs shows a blocky to progradational pattern at the basal part, subsequently followed by thick high value shale occasionally interrupted vertically by few meter thick sandstone, with 29.1Ma maximum flooding surface. The top of this sequence is not within the logged area.

Surface Correlation of Wells in the Gera Field

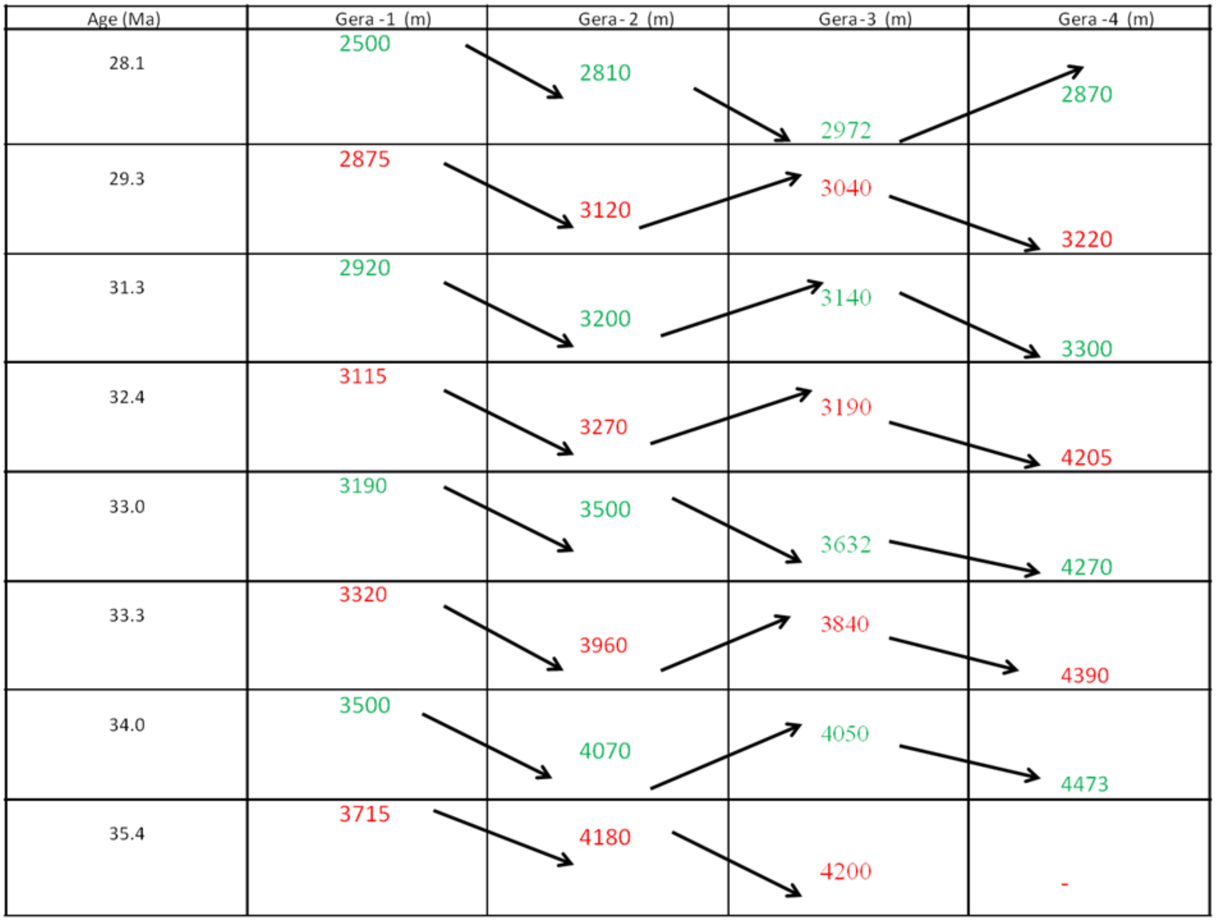
The four wells of Gera field are correlatable as can be seen in table 6 and appendix 3.0. From this correlation, it could be observed also that a major subsidence or a fault took place in the study area; there is a down-dip displacement between Gera-1 and Gera-2 on the entire identified datum, whereas there is a reversal between Gera-2 and Gera-3 on the 29.3Ma, 31.3Ma, 32.4Ma, 33.3Ma and 34.0Ma datum.

Table 6a: The chronostratigraphic datums and depths of penetrated wells.

Chrono - Datums	Wells			
	GERA -1	GERA -2	GERA -3	GERA -4
28.1 Ma (MFS)	2500m	2810m	2972m	2870m
29.3 Ma (SB)	2875m	3120m	3040m	3220m
31.3 Ma (MFS)	2920m	3200m	3140m	3300m
32.4 Ma (SB)	3115m	3270m	3190m	4205m
33.0 Ma (MFS)	3190m	3500m	3632m	4270m
33.3 Ma (SB)	3320m	3960m	3840m	4390m
34.0 Ma (MFS)	3500m	4070m	4050m	4473m
35.4 Ma (SB)	3715m	3715m	4200m	-

From the table 6 above, it is observed that there is a down-dip displacement between Gera -1 and Gera -2 on the entire identified datum, whereas there is a reversal between Gera-2 and Gera-3 on the 29.3Ma, 31.3Ma, 32.4Ma, 33.3Ma and 34.0Ma datum. However, a further down-dip displacement is observed on the 28.1 Ma, 33.0Ma and 35.4Ma datum. The relationship between Gera -3 and Gera -4 wells is such that there is a down-dip displacement on the 29.3Ma, 31.3Ma, 32.4Ma, 33.0Ma, 33.3Ma and 34.0Ma datum. The only reversal between these two wells is on the 28.1Ma datum.

Table 6b: Chronostratigraphic datums of penetrated wells



Age (Ma)	Gera -1 (m)	Gera- 2 (m)	Gera-3 (m)	Gera -4 (m)
28.1	2500	2810	2972	2870
29.3	2875	3120	3040	3220
31.3	2920	3200	3140	3300
32.4	3115	3270	3190	4205
33.0	3190	3500	3632	4270
33.3	3320	3960	3840	4390
34.0	3500	4070	4050	4473
35.4	3715	4180	4200	-

From the foregoing, it can be inferred that there is a general trend of a normal growth fault displacement across the field as generally known in the Niger Delta. The reversals observed between Gera -2 and Gera -3 wells may have been as a result of a slight adjustment of the deposition / displacement axis due to sediment loading. They also may have resulted as a result of localized minor displacement events on the major growth fault axis.

One major problem that can be solved from this correlation is the ability to predict the location of equivalent payzone facies as mere conjectures based on the general trend are sometimes misleading. However, the integration of seismic data will avail a much clearer picture and therefore enhance a more accurate identification of exploration targets.

4.5 Petroleum Potential of the Gera Field

The absence of petrophysical logs (neutron and density) hindered the reservoir evaluation but a minor evaluation using gamma ray and resistivity logs was done.

Reservoir rock

A clastic petroleum reservoir is a subsurface formation containing gas, oil, and water in varying proportions. These fluids are contained in the pore spaces of rock formations, among the grains of sandstones. The reservoir rock of Niger Delta lies within the porous and permeable sandstone unit of Agbada formation, therefore the fine to coarse sand units of HST, TST and LST of Gera -1, 2, 3 and 4 acts as reservoir rocks of ‘Gera Field’ (fig. 20).

Lateral continuity

These reservoirs exhibit lateral continuity, as can be seen in the well correlation (fig. 20 and appendix 4.0), e.g. the clean sandstone unit at the base of sequence 4 in Gera -1 well, is seen progressing laterally into Gera -2, 3 and 4 wells. The reservoir sand are interpreted to be transgressive sand, point bars, channel sand, crevasse splay sand on the basis of their gamma ray log motif.

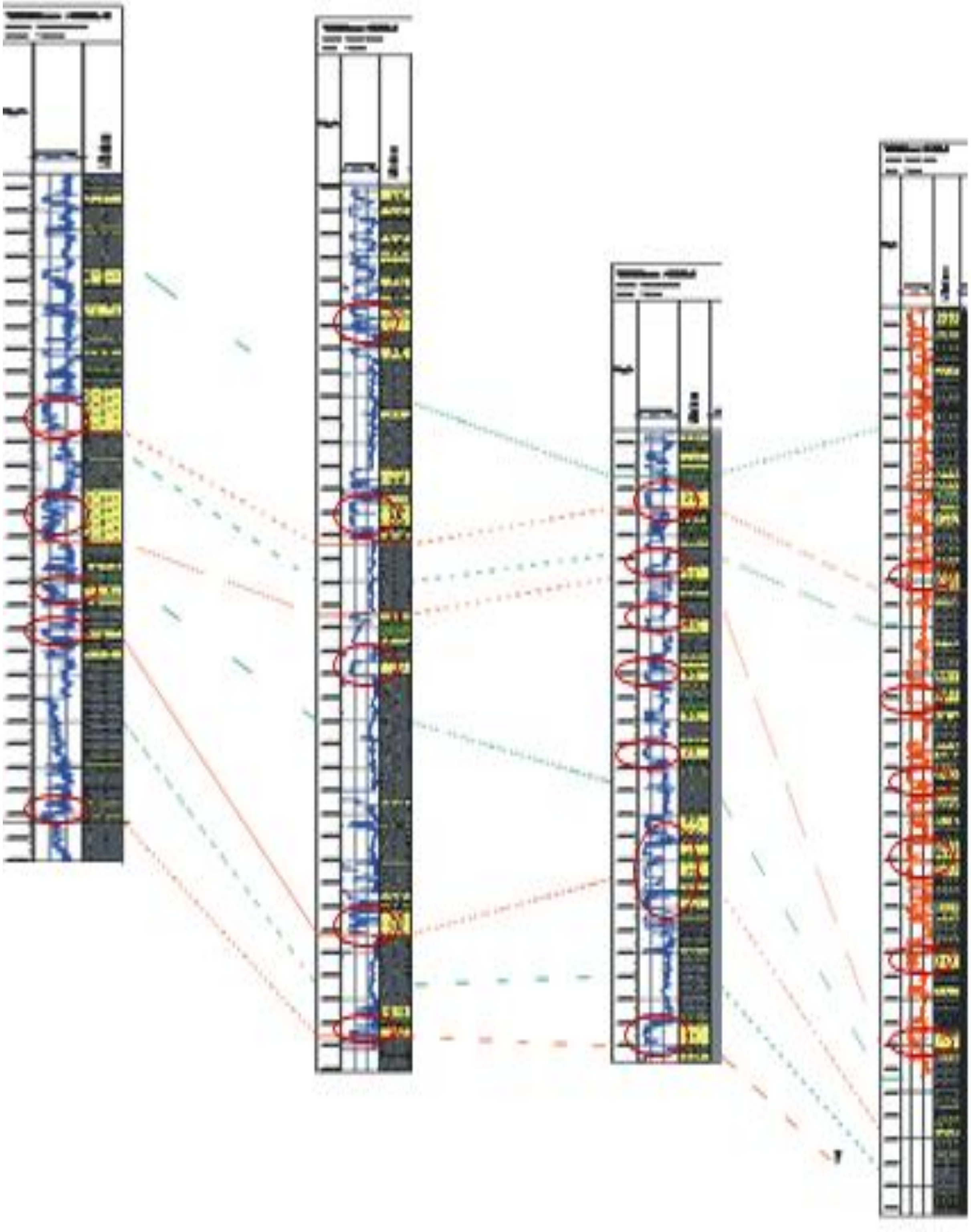


Fig. 20: Correlatable reservoir rocks of 'Gera field'.

Legend: ⬭ Reservior Sandstone.

Source rock

Source rocks are rocks that contained right organic matter, buried within the right temperature and pressure (oil window) to generate hydrocarbon. In Niger Delta Basin, the source rock lies within the shale unit of the Agbada formation and top of the Akata. The source rock of Gera field is considered to be the thick shale of TST found to be rich in organic matter (fig. 18).

Trapping system

The Niger Delta Basin is associated with structural traps that formed the syndepositional deformation of the paralic sequence of Agbada formation; stratigraphic traps are uncommon (Evamy et al, 1995). Doust and Omatsola (1990) described a variety of structural trapping elements, this include those associated with simple roll – over structures, clay filled channel structure with multiple growth faults, structures with antithetic faults and collapsed crest structures.

From the surface correlation framework, structural and stratigraphic traps were recognized in Gera field, this was established from the down dip displacement of the major surfaces of the four wells (table 6) in the field and by facies change respectively.

For a trap to have integrity, it must be overlain by an effective seal (Selly, 1998), therefore the shale of TST and shales within the HST forms the top and bottom seal of the reservoir sand of the system tracts, hence the reservoir rock in the HST and LST combines with the seal shale of the TST to form a stratigraphic trap.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.0 Conclusion

This study developed a sequence stratigraphic interpretation for “Gera Field” in Greater Ughelli Depobelt of the Niger Delta Basin based on well logs and biostratigraphic data of four wells (Gera -1, 2, 3 and 4), which enabled the subdivision of the stratigraphic column within the Gera Field into depositional sequences and systems tracts and recognition of the key bounding surfaces. This has aided the understanding of the processes that generated the vertical succession of sediments and lateral facies changes, which are the characteristic features of the systems tracts; and the following conclusion were was reached.

- Sands and shale make up the lithology of the study area, delta plain sedimentation, represented essentially by transgressive sand, mouth bar, distributary channels, crevasse splays and inter- distributary bays prevailed throughout the period represented in the studied sections of the wells.
- Depositional sequences and systems tracts interpreted from the well logs and biostratigraphic data identified three major depositional sequences (Depositional Sequence - 1, 2 and 3) in the field (table 5.1 – 5.4).

Four maximum surfaces characterizing periods of maximum flooding (late retrogradation) across the shelf were recognized. Also, four sequence boundaries characterizing periods of late falling of relative sea-level (late progradational) were delineated.

- Cyclical depositional patterns marked by regional isochronous transgressive surfaces identify 28.1Ma, 31.3Ma, 33.0Ma and 34.0Ma marker shales.

The shales have high faunal content and correspond to maximum flooding surfaces in the study area. The correlation of the key bounding surfaces depicts the correlative nature of the laterally persistent isochronous surfaces across the field of the study and this has shown that subsidence or major faulting took place in the study area.

- The hemipelagic - pelagic condensed sections of the transgressive systems tracts and shales associated with the early progradation in the field are excellent potential source rocks. Potential stratigraphic traps are also identified in all the depositional sequences.

This study thus may enhance the understanding of the study area. The alternation of highstand sands and transgressive shales provides the desired combination of reservoir and seal rocks, essentially for accumulation and stratigraphic trapping of hydrocarbons. The lowstand systems tract observed in Gera -4 well is excellent reservoir. One major problem that can be solved from this correlation is the ability to predict the location of equivalent payzone facies as mere conjectures based on the general trend are sometimes misleading. However, the integration of seismic data will avail a much clearer picture and therefore enhance a more accurate identification of exploration targets.

From the results obtained, it is concluded therefore that the application of sequence stratigraphic technique has enhanced good correlation between wells, interpretation of stratigraphic build-ups, recognition of isochronous surfaces and identification of prospects and leads; and discovery of stratigraphic traps.

5.1 Recommendation

This integrated study of Sequence Stratigraphy of ‘Gera Field’ in the Greater Ughelli of Niger Delta Basin, will no doubt enhance a better and precise understanding of the depositional sequences and the system tracts in time and space, which will ensure proper delimitation of the basin; and the hydrocarbon habitat of the study area; but it is of utmost importance to integrate the seismic sections and well logs with Petrophysical properties to improve and understand the reservoir characteristics.

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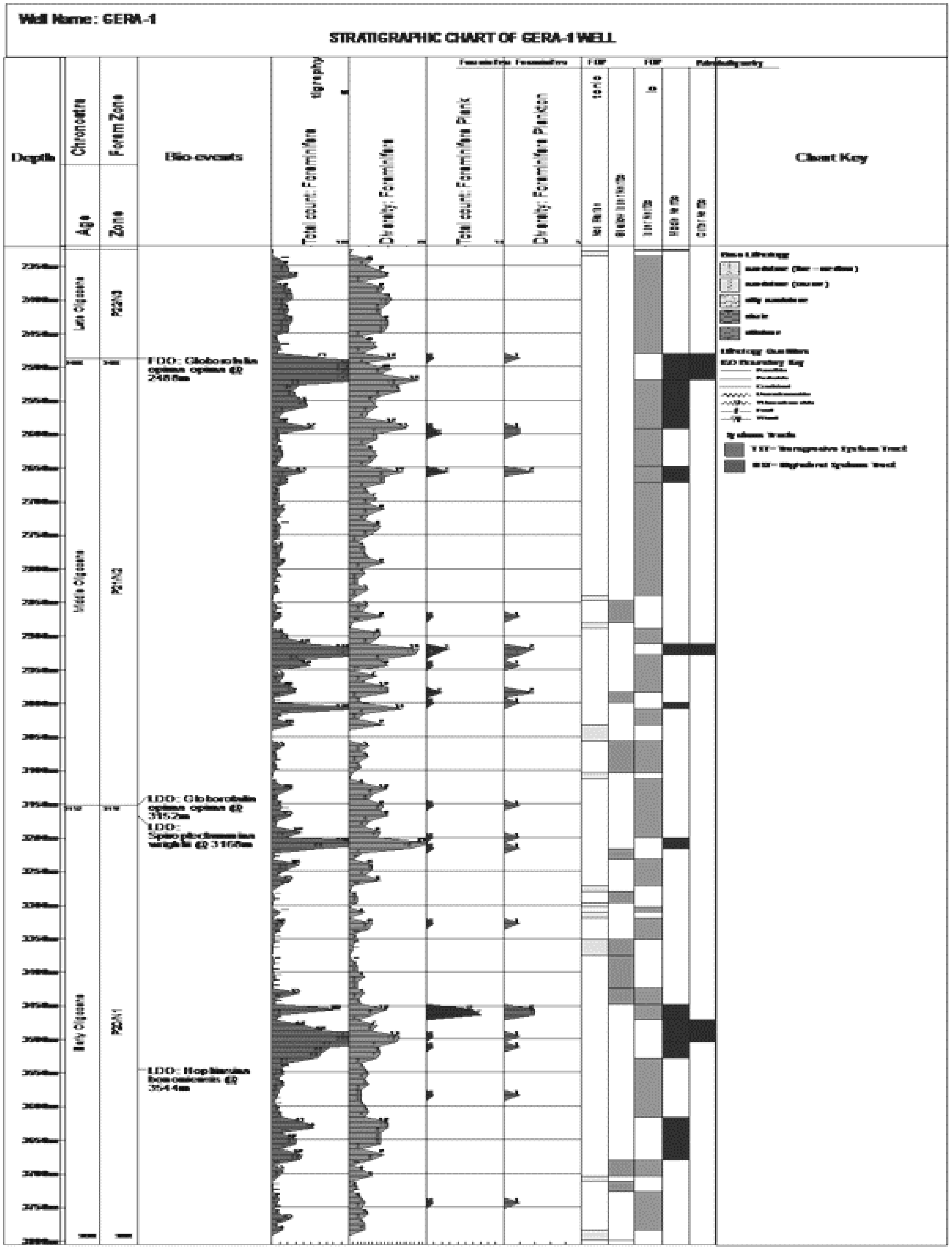
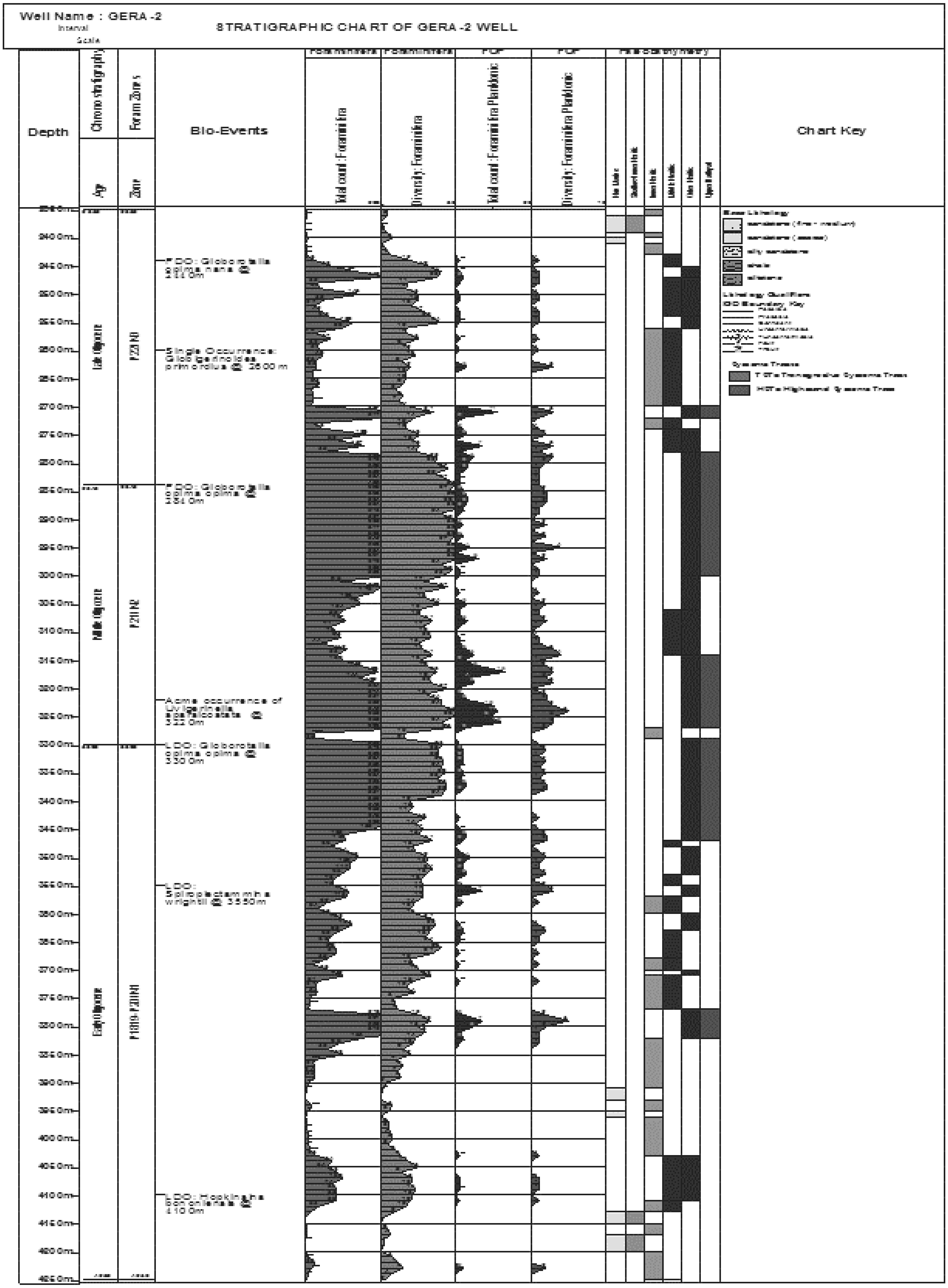
APPENDICES

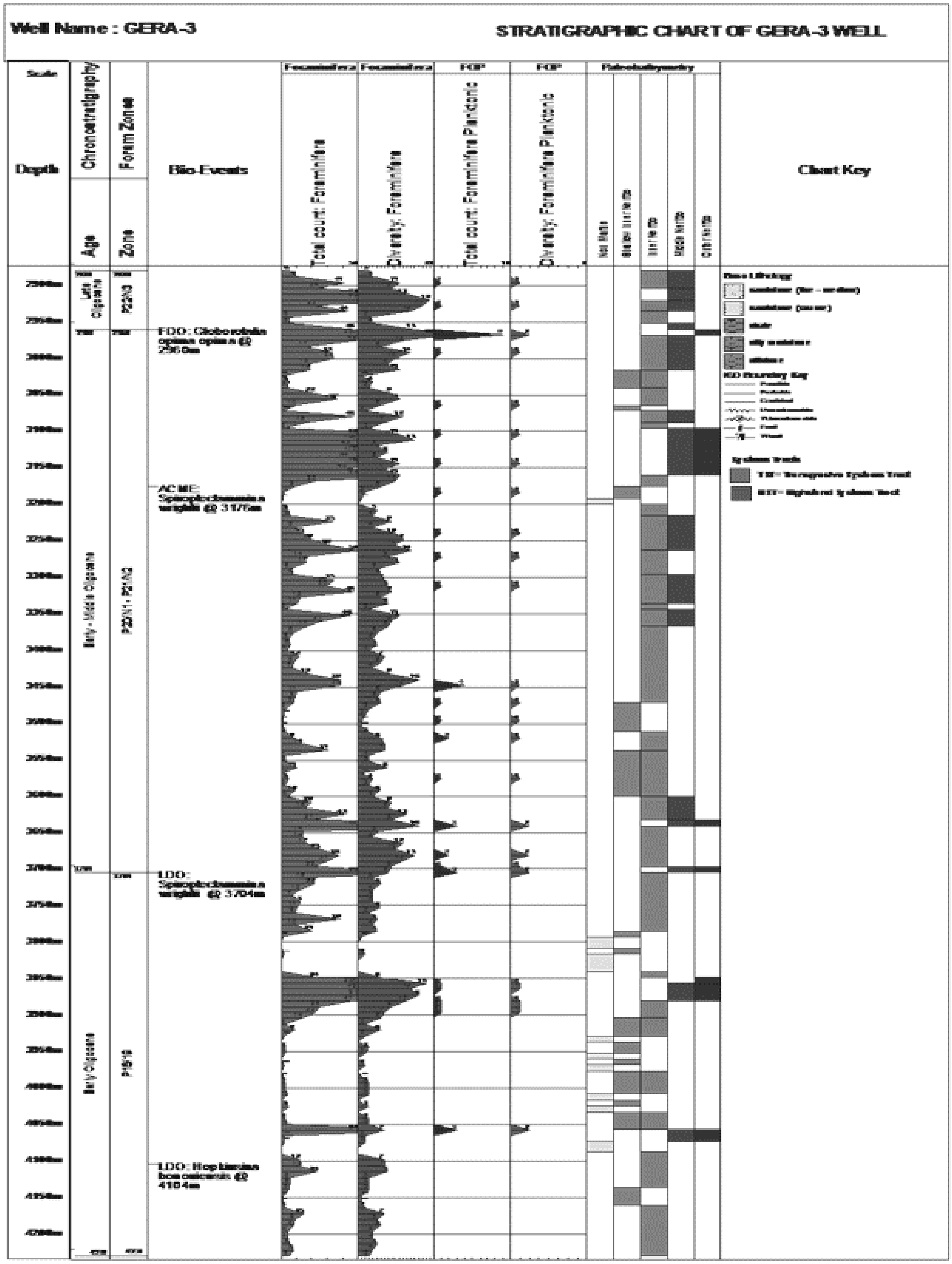
Appendix 1.1: Biostratigraphic chart of Gera -1 well.



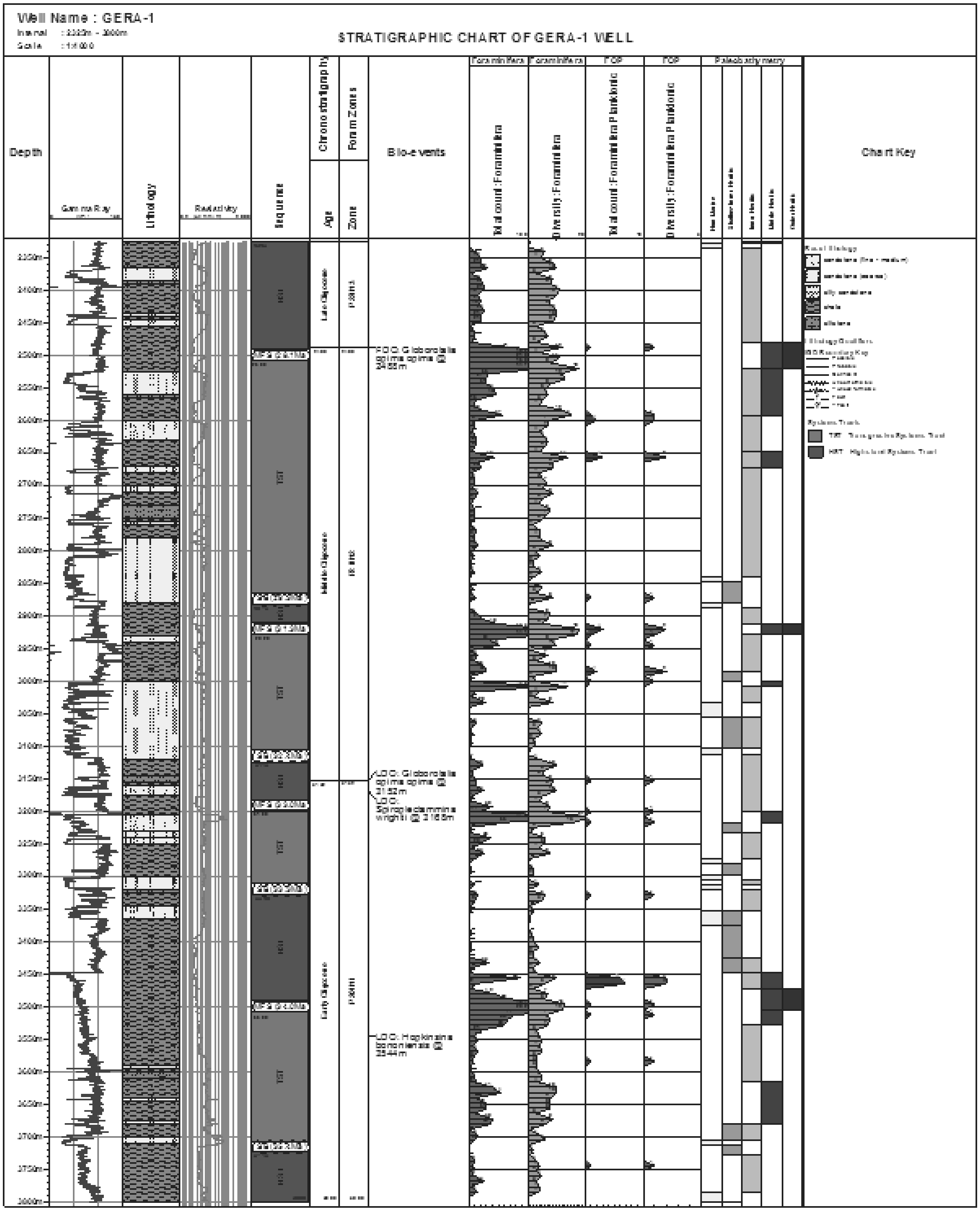
Appendix 1.2: Biostratigraphic chart of Gera -2 well.



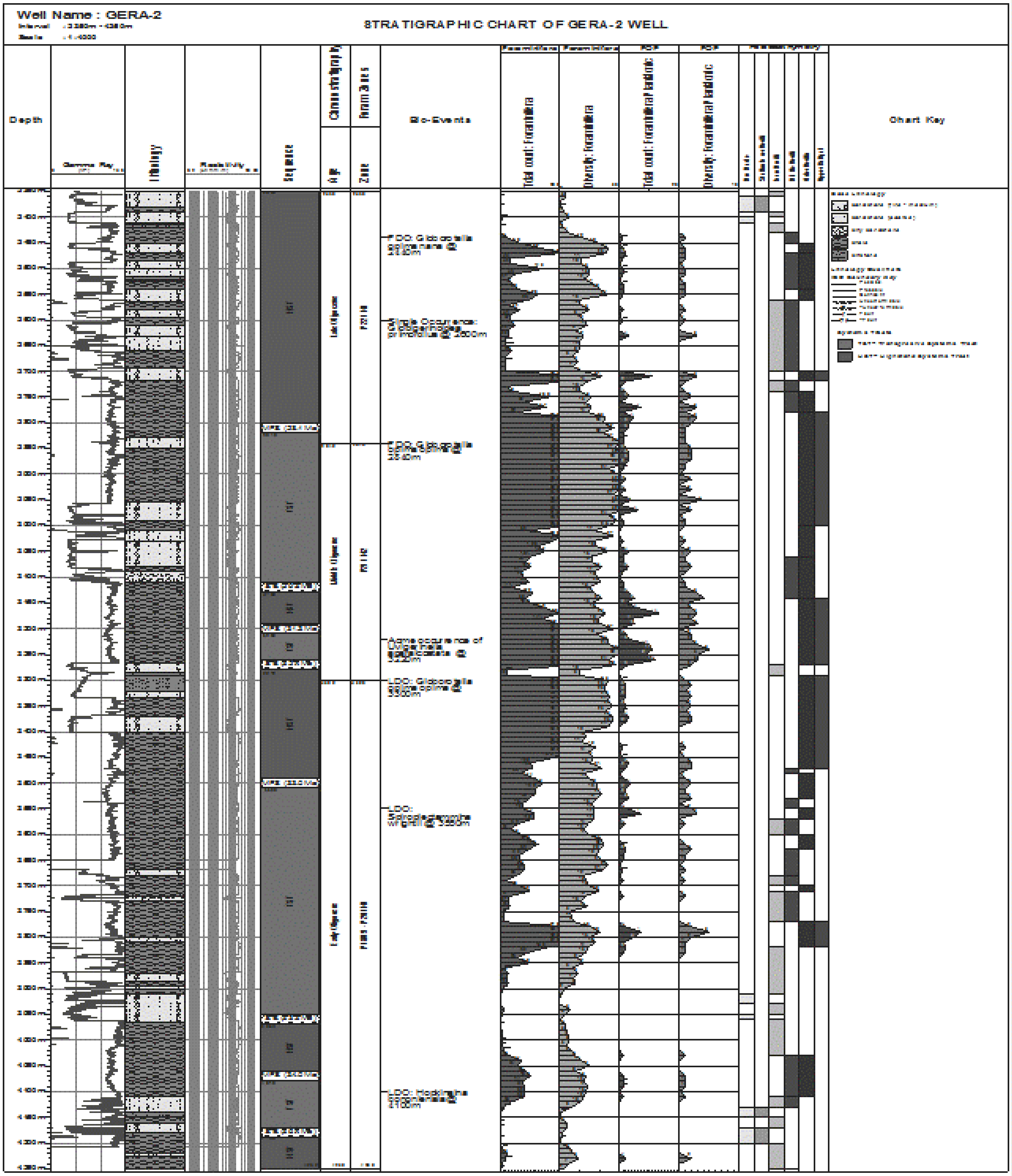
Appendix 1.3: Biostratigraphic chart of Gera -3 well.



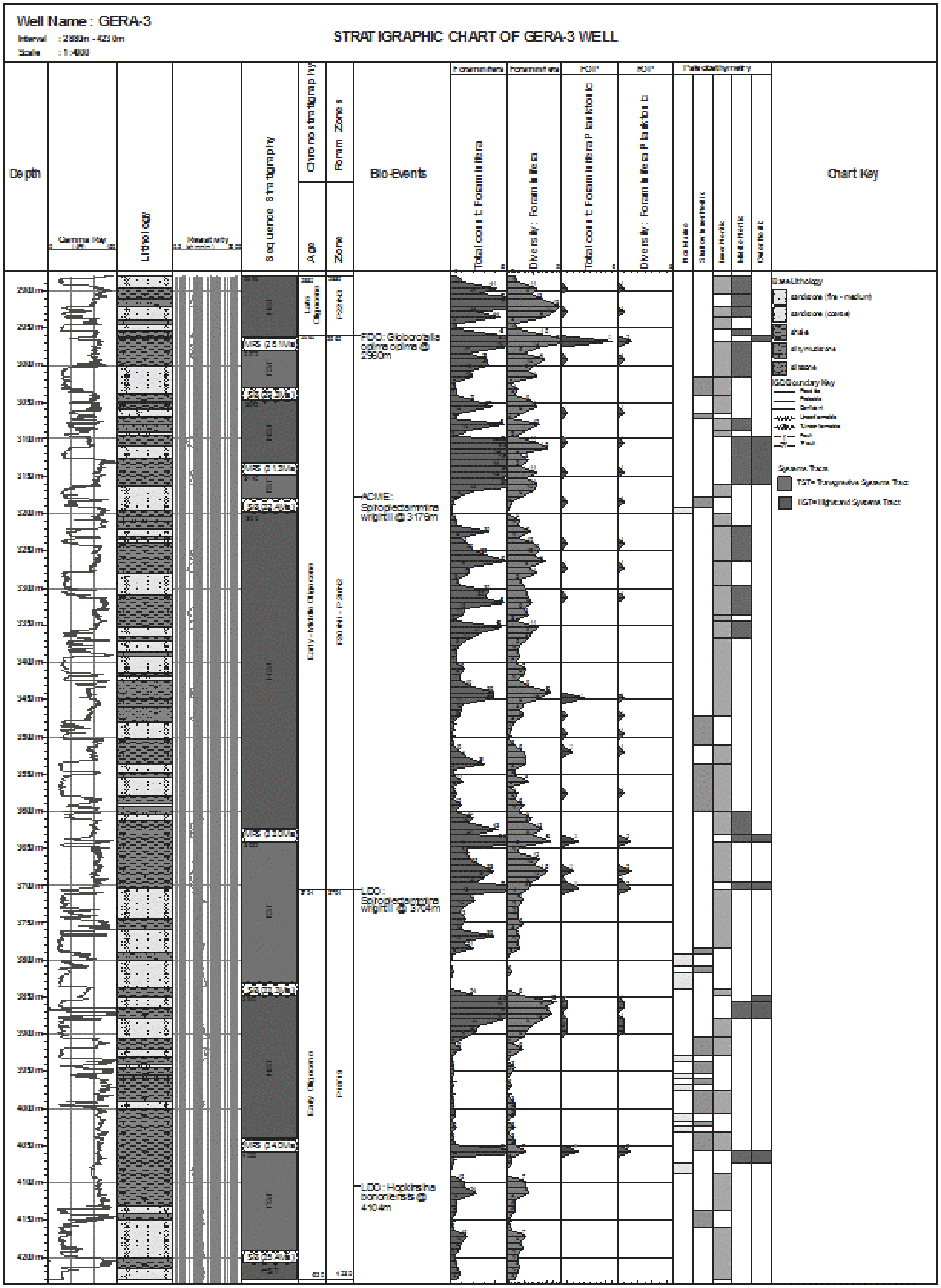
Appendix 2.1: Stratigraphic summary sheet of Gera -1.



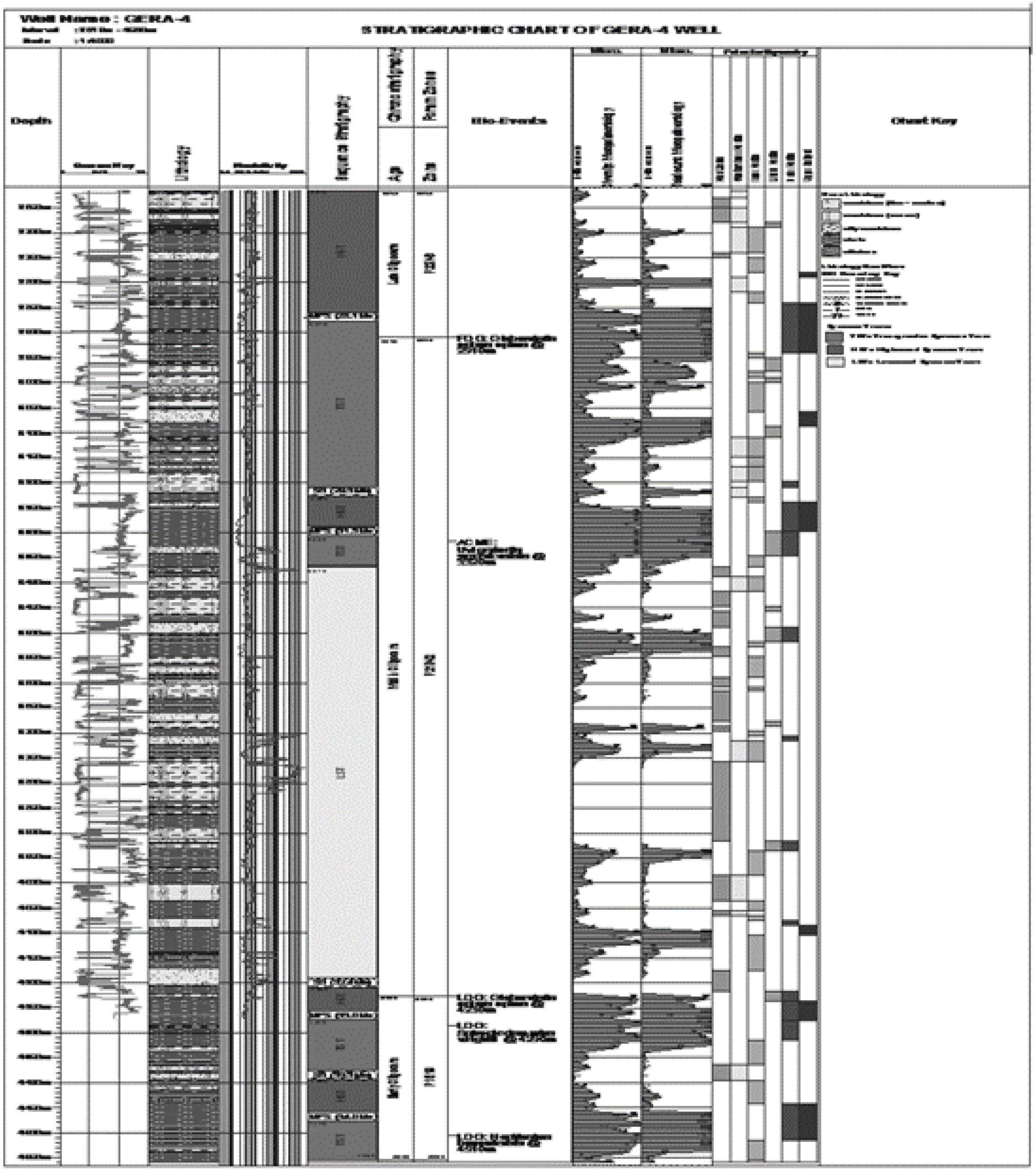
Appendix 2.2: Stratigraphic summary sheet of Gera -2.



Appendix 2.3: Stratigraphic Chart of Gera -3.



Appendix 2.4: Stratigraphic summary sheet of Gera -4.



Appendix 3.0: Cross Section of four (4) wells in Gera field showing the Correlated surfaces