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International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Biofacies and Sequence Stratigraphic Study of Well C and D in the Offshore Niger Delta

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DOI : https://doi.org/10.55248/gengpi.6.0825.3065

ABSTRACT

This study investigates the biofacies and sequence stratigraphy of Wells C and D in the offshore Niger Delta to improve understanding of depositional environments and hydrocarbon potential. Foraminiferal analysis was conducted to establish biozones, identify key stratigraphic surfaces, age and correlate depositional sequences. Results indicate that the wells penetrate the Agbada Formation, with sediments dating to the Miocene epoch. Three depositional sequences were identified, marked by Maximum Flooding Surfaces (MFS) and Sequence Boundaries (SB). The biofacies distribution suggests a shallow marine to neritic environment, influenced by sea-level fluctuations and sediment supply variations. These findings enhance biostratigraphic frameworks and provide insights for hydrocarbon exploration in the Niger Delta.

Keywords : Biofacies, sequence stratigraphy, age, depositional environment.

1. Introduction

The Niger Delta is an oil province of Nigeria located on the West African Continental margin popularly called the Gulf of Guinea. The Niger Delta basin lies between latitude 4°00'00"N and 6°00'00"N and longitude 5°00'00"E and 8°00'00"E. It is bounded to the west and northwest by the Western African shield, which terminates at the Benin hinge line and to the east, by the Calabar hinge line. The Anambra basin and Abakaliki anticlinorium mark its northern limit. To the south, it is bounded by the Gulf of Guinea. The Niger Delta is ranked among the major hydrocarbon provinces in the world, Nigeria has been rated as the sixth largest oil producer and the twelfth giant hydrocarbon province (Okosun et al., 2012). Thousands of wells have been drilled across the delta, penetrating sediments in which petroleum generation, migration and accumulation have occurred (Reijers et al., 1997; Okosun et al., 2012). It is the most important hydrocarbon province in the West African continental margin. The sediments of the Niger Delta show an upward transition from marine pro-delta shales (Akata Formation) through a paralic interval (Agbada Formation) to a continental sequence (Benin Formation). These three formations, extend across the whole of Niger Delta and ranges in age from early Tertiary to Recent (Short and Stauble, 1967; Avbovbo, 1978, Yikarebogha et al., 2013). The use of biofacies biostratigraphy within a sequence stratigraphic context is rapidly emerging as a valuable tool for the recognition of ancient cycles and sequences in the Niger Delta. The application of biostratigraphy to sequence stratigraphy is not a new concept, as both biostratigraphy and sequence stratigraphy have been combined in the study and understanding of depositional environments (e.g. Okosun et al., 2012; Yikarebogha et al., 2013; Ozumba, 1995; Armentrout et al., 1999). The use of microfossils to correlate stratigraphic sections, the paleoenvironmental preferences of these microfossils also provide valuable information on the prevailing depositional settings (Emery and Myers, 1997).

AIM AND OBJECTIVE OF THE STUDY.

The purpose of this study is to carry out a stratigraphic study of the two wells in order to contribute to the data collection of the stratigraphic committee of the Niger Delta (STRATCOM).The main objectives of this work are to:develop biostratigraphic zonation schemes for the two wells based on data generated from the studied wells; investigate the percentages of the palynomorphs and foraminiferal assemblage and ascertain their ecological group associations in the different wells; improve on the zonation schemes of earlier workers in the area from recovered species; apply foraminiferal biostratigraphy in the interpretation of sequence stratigraphy of well-C and D and interpret the environment of deposition.

Location Of Study Area ;The study well pseudo named "Well C and D (Figure 1) is situated in the Greater Ughelli Depo-belt of the Niger Delta on latitudes 5°31'34"N and longitudes 5°42'30"E. It was drilled by Shell Petroleum Development Company (SPDC) in 1962.

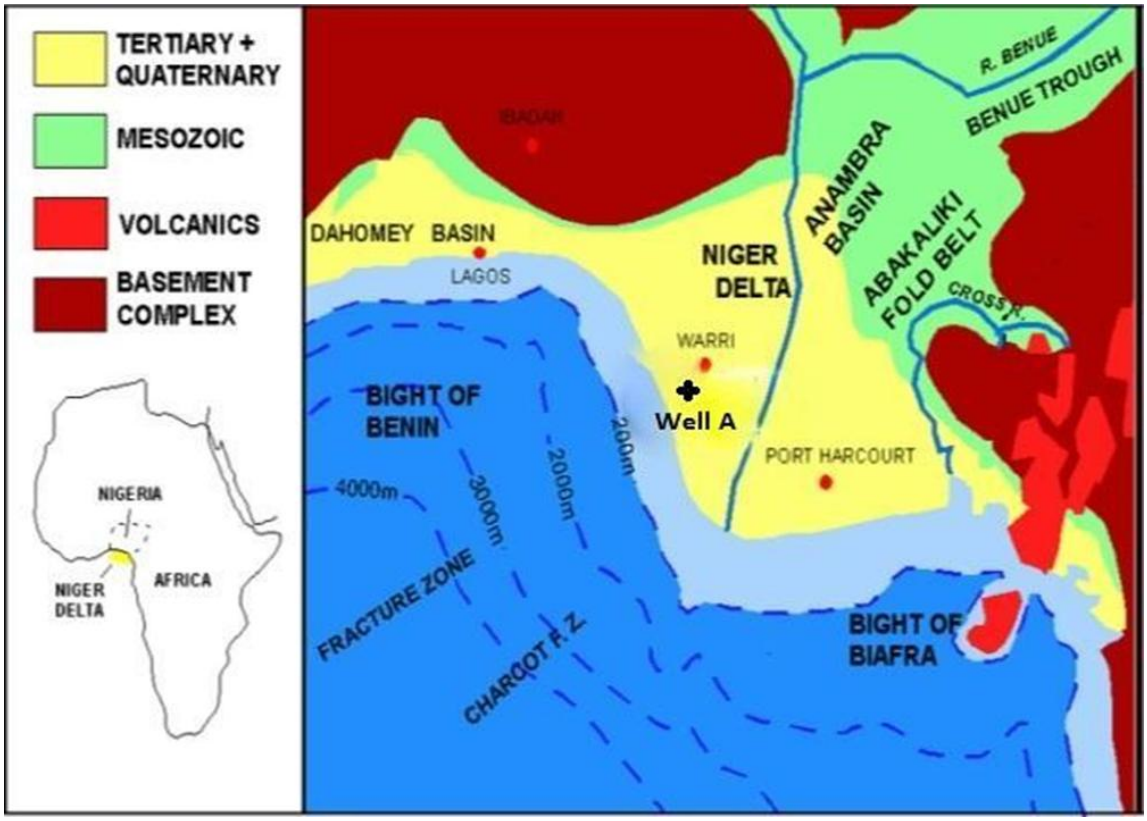


Figure 1: Part of West Africa showing the Niger Delta region and the Location Area of Well C and D. In set is a map of Africa showing location of Nigeria and Niger Delta (modified after Doust and Omatsola, 1990)

Geology and Stratigraphic Evolution of the Niger Delta

The Niger Delta Geology has been studied in recent times by academician and oil companies because of its hydrocarbon potential and economic importance. Many writers have inquired and summarized the basic geology, lithology, palynological and micropaleontological characteristics, depositional environment, structural setting, geophysical characteristics and among others.

Short and Stauble (1969) outline the Niger Delta general geology. They gave a detailed write up on the origin of the Niger Delta. They established that the Tertiary deltaic sediments comprises of an upward-coarsening regressive association of deposits that are strongly diachronous (Eocene to Recent). The sediments in the Niger Delta are divided into Marine Akata, Paralic Agbada and Continental Benin Formations. Stratigraphic Evolution of the Niger Delta

The evolution of Niger Delta started during the Cretaceous times, the region presently occupied by the Niger Delta was the failed armed of the R-R-R (ridge- ridge-ridge) triple junction. According to Short and Stauble (1967), South America and African continent separation occurred as a result of the development of the R-R-R triple junction which started the evolution of the Delta.

The Niger Delta developed over the collapsed continental margin at the site of the triple junction during the middle Cretaceous times. Extensive drainage system has been the main sediment supply Burke et al. (1972). Since the late Cretaceous, sediment input has generally been continuous. Episodic transgression affected the regressive records.According to Evamy et al. (1978) the growth of the Niger Delta can be seen as a function of rate of sedimentation (Rd) and rate of subsidence (RS). The variations in relation to rate of sedimentation and subsidence rate gave rise to the development of distinct sedimentary mega-units of different shapes, sizes and thicknesses.

Niger Delta Stratigraphic Framework

The stratigraphic sequence of the Niger Delta comprises of an upward-coarsening regressive association of Tertiary sediments that are strongly diachronous (Weber and Daukoru 1975; Evamy et al. 1978). The Cenozoic Niger Delta Stratigraphy is a direct product of the various depositional environments. Frankyl and Cordry (1967), Short and Stauble (1967) and Avbovbo (1978), provided the first information on the subsurface distribution units in the Niger Delta, Subsequent studies include those of Evamy et al. (1978), Ejedawe et al. (1984), Nwachukwu and Chukwura (1986), Haack et al. (2000), (Reijers, 2011) among others. The Niger Delta is divided into major three stratigraphic units, which are the Akata, Agbada and Benin Formations (Reijers, 2011). **Akata Formation;** The Akata Formation is situated at the base of the Delta, is of marine origin. The formation is estimated to be 21,000 ft. (6405m) thick in the central part of the clastic sedimentary wedge (Doust and Omatsola, 1989). The lithologies are mainly dark gray shale and silts. There is abundance of both benthonic and planktonic foraminifera in the Akata Shale. The formation ranges in age from Paleocene to

Recent (Doust and Omastola, 1989). **Agbada Formation**; The formation has a maximum thickness of about 11,000 ft. (3355m). The lithologies consist of an alternation of shale, silt and sandstone arranged within tens to hundreds feet succession delineated by progressive upward changes in grain size and bed thickness. The sandstones are the reservoir rocks, they account for the oil and gas production in the Niger Delta. They are believed to have been deposited in a fluvial – deltaic environments made up of distributary channel, delta front and delta plain origin. The sandstone and shale alternation of the formation are cyclic sedimentary sequences of marine and fluvial deposits (Weber, 1971). Hydrocarbon occurs throughout the Agbada Formation of the Niger Delta (Tuttle et al., 1999). The formation ranges in age from Eocene to Pleistocene. **Benin Formation;** The Benin Formation type is defined in Elele-1 well, drilled to about thirty eight kilometer north – northwest of Port Harcourt City (Short and Stauble, 1967). It comprises the top of the Niger Delta clastic wedge. The formation consists mainly of sand to boulder size fraction, subangular to well-rounded, with moderately to well sorted grains. Clay, rootlets, wood fragments, coal are present. It was deposited in a continental environment. It ranges in age from Miocene to Recent with sand thickness of about six thousand (6000) feet. However, the absence of fauna in the formation makes it difficult to date though an Oligocene – Recent age is generally accepted (figure 2).

METHOD OF STUDY.

This study was carried out with secondary data gotten from Shell Petroleum Development Company (SPDC) in Niger Delta. Standard biostratigraphic preparation and analysis procedures was used to get the results given to me. Other materials used include: charts, and computer software (Stratabug, Corel draw, Surfer and Microsoft Excel) for further analysis and interpretation.

RESULTS:

The results of the study are presented under Lithostratigraphy and Biostratigraphy ;

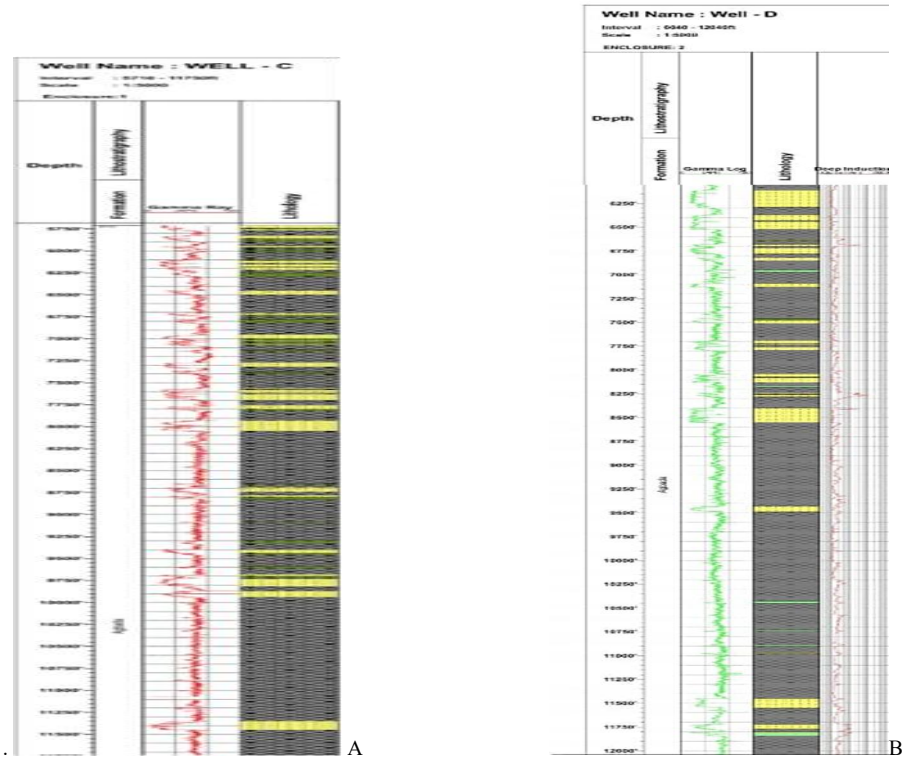
Lithostratigraphy. The lithostratigraphic section of the wells is based on ditch cutting samples described and information gathered from gamma ray log.

The lithologies are mainly sandstone, shale and siltstone. (Figure 3)

a. Sandstone: Smokey white to orange colour, fine to coarse grained, sub-angular to sub-rounded, well sorted, occasionally ferruginized, sometimes containing woody materials, muscovite flakes and some carbonaceous fragments.

b. Shale: Brown to grey, sometimes black, fissile, moderately hard and occasionally carbonaceous.

c. Siltstone: White, fine grained, micromicaceous and carbonaceous, and traces of woody materials



A B

Figure 3; lithologic description of well C and D respectively

DISCUSSION

From the graphic log seen in Figure 3, the lithology show siltstone layers with the alternation of sandstone and shale, the shale is brown to grey in colour (occasionally black to brown,), fissile, moderately hard. The sand is smokey white to orange, fine-grained (occasionally coarse-grained), sub-angular to sub-rounded, well sorted and occasionally ferruginized. According to Short and Stauble (1967), the Agbada Formation is characterized by the alternation of sandstone and sand bodies with shale layers. The sandstone is fine to coarse grained, predominantly unconsolidated. The alternations of the sandstone, and shale in the studied well C interval (5710 – 11750ft) reveals that it penetrated the Agbada Formation of the Niger Delta. In general, the upper part of the formation has a higher sandstone percentage than the lower part, this demonstrates the progressive, seaward advancement of the Niger Delta through geological time despite the numerous transgressive sequences found in the Agbada Formation where as the lithostratigraphic description of well D shows the study interval has percentage composition of sands and shales. The most dominant lithofacies unit was shales, alternated by few units of sands (Figure 3B). The well may have penetrated the Akata formation of the Niger delta that showed thicker units of shale/mudstone

Biostratigraphy Of WELL C.

Foraminiferal analysis was carried out on ninety six (96) samples obtained from the well (interval 5750ft- 11500ft). The foraminifera recovered was fair, the diversity, however, was high. The forms encountered include planktonic foraminifera, benthonic calcareous foraminifera and also benthonic arenaceous foraminifera. Some forms are long ranging in terms of stratigraphic distributions while others had restricted distributions. The benthonic foraminiferal species in the well C are made up of diverse and rich to occasionally abundant species. Preservation is fairly good all through the section. A total of one hundred and nineteen diferent species were recovered from the studied interval, accounting for about ninty nine percent (99%) of foraminiferal count (Figure 5), twenty six percent of which make up the benthonic arenaceous species, and fourty five percent calcareous species (figure 3). The benthonic foraminifera makeup eighty one percent (81%) of the specie distribution, and eighty two percent of specie abundance of well C. are dominated by the following species: *Uvigerina isidroensis, Brizalina mandoroveensis, Lenticulina grandis, Hopkinsina bononiensis, Hanzawaia stratonii, Ammonia beccarii, Heterolepafloridana, Cibicorbis inflata, Uvigerina sp. Valvulineria gasparensis, Haplophragmoides s*p. and *Spiroplectammina sp*. Some of the other species have poor occurrences to single occurrences as in the case of *Textularia laminata, Ammobaculites sp., Bolivina spinata*. Fourteen planktonic foraminifera species which constitutes about twenty eight percent (28%) of foraminiferal count (Figure 4). Poor to fairly rich occurrences were recovered in the well interval. The planktonic foraminifera are dominated by the following species: *Globigerina sp. Orbulina suturalis, Praeorbulina glomerosa, Globorotalia continuosa, and Planktic indet sp. Other important planktonic foraminifera species recovered include Catapsydrax dissimilis, and Praeorbulina sican*

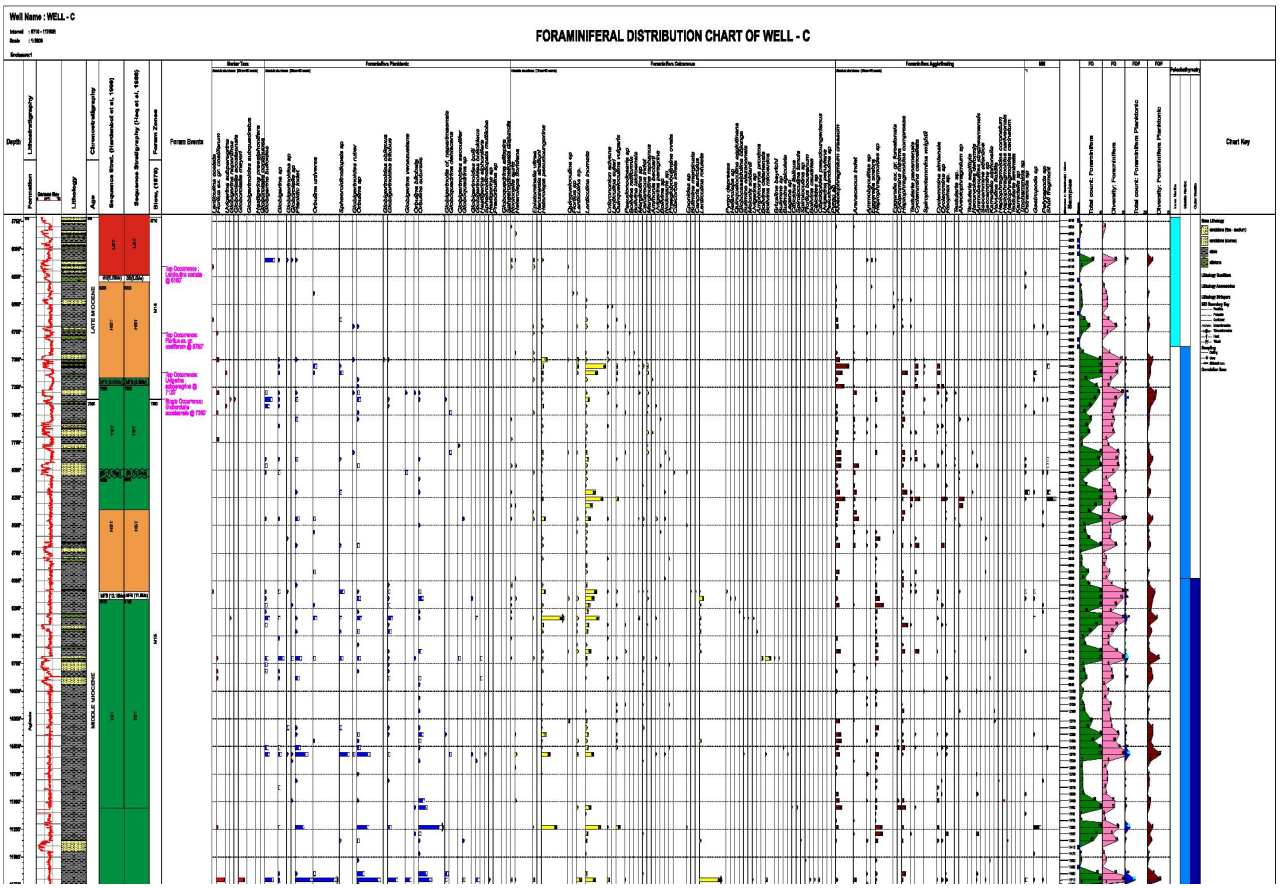


Figure 4 : Faunal distribution of well C

Table 1: Sequence stratigraphy table of Well C

Depth Interval (ft)	Systems Tract	Stratigraphic surfaces
5750- 6250	LST	SB: 8.5Ma @ 6300ft
6300 – 7200	HST	MFS: 9.5Ma@ 7200ft
7200 – 8400	TST	SB: 10.5Ma @ 8050ft
8400 – 9100	HST	MFS: 11.6Ma @ 9100ft
9100 – 11,750	TST	

Sequences of the study well C

Transgressive systems tract (TST)

The TST in the well C at an interval of 9100ft - 7200ft is defined based on its fining upward sequence, and marked at the top by MFS at 8050ft with increased number of faunal assemblage .The lower section of this interval is predominantly shale, the mid-section shows sandstone and shale intercalation, while a predominance of shale caps the top section of the interval (Figure 3)(Table 1). At an interval of 9100ft – 7200ft, the renewed TST in this interval is characterized by intercalation of shale and siltstone in the lower section, and siltstone, shale and sandstone in the upper section, with the shale percentage increasing towards the top of the section reflecting an overall fining upward sequence. Also reflected here is the increasing faunal diversity that culminates at the MFS at 6300ft .

Highstand systems tract (HST)

During this stage, the sea-level rise decreases and they are characterized by initially aggradational deep sea shale that grade into intervals of shallowing upwards. This system tract is first defined at an interval of 6300ft - 9100ft, (Figure 3) based on the presence of the MFS (at 11,750ft)(Table 1) below the HST and the SB (at 6300ft) marking the top of the interval. This progradational sequence is characterized by shale, silt and sand lithofacies, with gradual decrease in the percentage occurrence of shale. This suggest an overall coarsening (shallowing upward) sequence. The biostratigraphic data reveal the relative appearance and diversity of slope benthonic forms (shallow inner neritic forms e.g. *Ammobaculites sp., Valvullineria gasparensis and Globigerina sp*.).

Also at an interval of 8050ft – 9100ft, (Figure. 3) this short lived regression is characterized by shale deposited in the shallow inner neritics at its base on the MFS at 7200ft and marked at the top by the SB at 6300ft.

Lowstand system tract (LST)

The LST in well C is defined at an interval of 5710ft – 6300ft (Figure. 3)(Table 3), This interval shows interbedding of shale and sandstone at the lower section, and siltstone, shale and sandstone interbedded at the top, though the siltstone and shale beds thin upwards while the sandstone becomes relatively thick. The upper part of the LST is no longer erosional as the sea-level starts to rise (5710ft – 6300ft), the geometry starts becoming aggradational and moving seawards, then it becomes stationary, this shows reworked foraminifera assemblages when compared to adjacent shale, it also exhibits a coarsening upward sequence, suggesting incised valley fill deposits. There is decrease in foraminiferal abundance from about eight to zero (barren) at 5710ft – 6300ft interval suggesting a Lowstand Prograding Wedge (LPW). The biofacies associated with the lowstand wedge usually show a shallowing from inner neritic to non- marine environments, each prograding complex is characterized by a regular alternation of thin sandstone and shale bands (incised valley fills deposits) in which the sandstone become relatively thicker and respectively more prominent up section (Emery and Myers, 1997).

Age Determination: The following planktonic index forms were identified from the studied well C interval: Uvigerina subperegrina Globorotalia acostaensis, Orbulina suturalis and Catapsydrax dissimilis. Based on the presence of these index forms, as defined by Bolli and Saunders (1985) and Petters (1983), the age of the studied well C is proposed to belong to Late Miocene to Middle Miocene (Table 5).

Biozonation

Two zones have been proposed in this study (based on the International stratigraphic guide of Hedberg (1976) and the observation of the ranges of planktonic foraminifera in Figure 6 as follows: Catapsydrax dissimilis partial-range zone, Praeorbulina glomerosa interval zone and Orbulina universa taxon-range zone.

Uvigerina subperegrina partial-range zone : Stratigraphic interval: 5710ft – 6700ft

The zone is defined by the First Down Hole Occurrence (FDO) of Uvigerina subperegrina @ 7120ft and the Last Down Hole Occurrence (LDO) of Globorotalia acostaensis @ 7360ft (LDO) . Other planktonic forms occurring within the zone are *Globigerinoides sp., Globigerinoides trilobus immaturis, Planktic idet sp., and Globorotalia humerosa* . This zone is equivalent to N16 – N15 zone of Blow (1969). The extinction of Catapsydrax

dissimilis marks the N6/N7 boundary of Blow (1969). Uvigerina subperegrina is continuously present in the Early Miocene. The age of this zone is late Miocene based on the presence of planktonic index forms .

Globorotalia menardii **taxon – range zone.** Stratigraphic interval: 9160ft – 11530ft

This zone is defined by the entire occurrence of Orbulina universa. The base of the zone is marked by the FDO of *Globorotalia menardii*. Also occurring is *Orbulina universa, and Sphaeroidinellopsis semunulina*, while the top is marked by the FDO of *Orbulina universa, Globigerina gortanii* and Planktic indet sp. Other planktonic forms occurring in the zone are *Globigerina sp., Globigerina ciproensis* , *Globorotalia continuosa, Orbulina saturis and Hastergerina siphonifera*. The zone is equivalent to the N15 zone of Blow (1969). The age of the zone is Middle Miocene based on the presence of planktonic index forms (Figure 4).

Table 2: Showing Identified Datum Markers for Well-C Foraminifera

Depth Interval(ft)	Foram Zones	Age	Foram Events
5710 – 7360	N16	Late Miocene	FDO: Uvigerina subperegrina @ 7120ft LDO: Globorotalia acostaensis @ 7360ft
7360 – 11,750	N15	Middle Miocene	FDO: Globorotalia menardii

Associated key surfaces

The Maximum Flooding Surfaces and sequence boundaries derived from foraminiferal peaks, abundance and diversities is identified basically on the inflection from overall progradation to overall retrogradation of parasequences. **Maximum flooding surface (MFS)**, Stratigraphic interval: at 7200ft (9.5Ma) and 9100ft (11.6Ma). These are the periods between maximum relative sea level rise characterized by abundant and diverse fauna (especially benthonic foraminiferal assemblages).The ages are dated because of their stratigraphic positions above the positively identified TSTs.

Sequence boundaries, Stratigraphic interval: at 6300ft (8.5Ma) and 8050ft (10.5Ma), Identified basically on the inflection from overall progradation to overall retrogradation of parasequences in the shallowing sand units. The relative thickness of the systems tracts suggest changes in sediment accumulation rate as a result of varying local conditions which may include the effect of gravity, tectonics, availability of accommodation space, and eustatic sea level changes. This period is characterized by biostratigraphic gaps suggesting periods of non-preservation of fossils, as seen in SB of 8.5Ma (Table 1). The dates of the SB have been correlated to Haq et al. (1988) chronostratigraphic chart (Table 1). The ages have been dated based on their stratigraphic positions above the positively identified HSTs.

Paleobathymetry

Foraminifera data was most useful in the estimation of paleobathymetry, it involved the use of relative abundance and diversity of the foraminifera encountered as well as the occurrence of environmentally significant taxa. It is on these bases that the sediments of the well were interpreted to have fluctuated from inner to middle neritic as follows

Table 3: Planktonic Foraminiferal Total Count. Paleobathymetry of Well C

Depth Interval (ft)	**Paleobathymetry**
5710 - 5800	NM
5800 - 5920	SH.IN
5920 - 6100	NM
6100 - 6220	SH.IN - IN
6220 - 6400	NM – SH.IN
6400 - 6580	IN
6580 - 6640	NM
6640 - 6820	IN
6820 - 6940	NM
6940 - 7000	IN

		7000 - 7180	MN - ON	
		7180 - 7720	IN - MN	
		7720 - 7840	IN	
		7840 - 8020	MN	
		8020 - 8200	IN	
		8200 - 8320	MN - ON	
		8320 - 8440	IN	
		8440 - 8740	IN - MN	
		8740 - 8920	SH.IN - IN	
		8920 - 9100	IN	
		9100 - 9460	MN - ON	
		9460 - 9640	IN	
		9640 - 9760	MN - ON	
		9760 - 9940	IN	
		9940 – 10,180	SH.IN - IN	
		10,180 – 10,390	IN	
		10,390 – 10,630	MN - ON	
		10,630 – 10,990	IN	
		10,990 – 11,110	MN	
		11, 110 – 11,230	SH.IN	
		11,230 – 11,410	MN – ON	
		11,410 – 11,650	NM – SH.IN	
		11,650 – 11,710	MN – ON	
a.	Middle	11,710 – 11,750	IN	Neritic Environment
b.	Inner			Neritic Environment

c. Shallow Inner Neritic Environment

The well interval possessed characteristics that are exhibited by the above environments Non marine environment ; The intervals ranges from 5710ft – 5800ft, 5920ft – 6100ft, 6580ft – 6640ft, 6820ft – 6940ft, (Table 3). This inference is based on the following reasons: The intervals are characterized by fine to medium through coarse grained sandstone (smoky white to orange, sub-angular to sub-rounded, well-sorted and occasionally ferruginized), siltstone (white, fine-grained, micromicaceous and carbonaceous plus traces of woody materials) and shale (brown to grey, fissile, moderately hard, micromicaceous and occasionally carbonaceous). The presence of coarse sandstone, ferruginous materials and carbonaceous detritus in these intervals suggests deposition in high energy, occasional oxidized conditions, probably near-shore settings, The presence of woody fragments suggest a landlocked body of water system typical of non-marine swamp environments. The intervals are completely barren of foraminifera. The complete absence of fauna in this interval suggest a littoral (shore or coastal) settings.

Shallow inner neritic environment

The intervals inferred to be shallow inner neritic environment ranges from 5800ft – 5920ft, 6100ft – 6220ft, 8740ft – 8920ft, 11, 9940ft – 10,180ft, 110ft – 11,230ft, (Table 3).

This inference is based on the following reasons: The intervals are predominantly characterized by fine to medium grained sand (smoky white to orange, sub-angular to sub-rounded, well-sorted and occasionally ferruginized), suggesting deposition during progradational phase, and thin shale beds (brown to grey, fissile, moderately hard, micromicaceous and occasionally carbonaceous). The intervals contain very few benthonic and planktonic foraminifera eg. Ammobaculites sp., Valvullineria gasparensis and Globigerina sp. Species dominance is low and the number of species (diversity) is high.

Inner neritic environment:

The intervals inferred to be inner neritic environment ranges from 6400ft – 6580ft, 36640ft – 6820ft, 6940ft – 7000ft, 7720ft – 7840ft, 8020ft – 8200ft, 8320ft – 8440ft, 8920ft – 9100ft, 9460ft – 9640ft, 9760ft – 9940ft, 10,180ft – 10,390ft, 10,630ft – 10,990ft and 11,710ft – 11,750ft (Table 3).This inference is based on the following criteria: The micro fauna found here suggest inner neritic environmental settings with middle neritic influence, these include: Quinqueloculina sp. Lenticulina grandis, Uvigerina sp. Miogypsinoides sp. Cubicubis inflata, Briziana mandoreveensis, Spiroplectammina wrightii, Uvigerina isidroensis and Uvigerina sparsicostata. The lithology of the intervals is composed of medium to coarse grained sand (smoky white to orange, sub-angular to sub-rounded, well-sorted and occasionally ferruginized), siltstone (white, fine-grained, micromicaceous and carbonaceous plus traces of woody materials) and shale (brown to grey, fissile, moderately hard, micromicaceous and occasionally carbonaceous).

Inner to middle neritic environment

Depth intervals of the studied well that are inferred to this environment are from 7180ft – 7720ft, and 8440ft – 8740ft (Table 3). The criteria for this inference are based on the following: The occurrence of the typical forms from inner and middle neritic environments, including: Uvigerina sp. Heterolepa floridana, Valvulineria gasparensis, Cibicorbis inflata, Orbulina suturalis, Hanzawaia stratonii, Globigerinoides immaturus, Globigerinoides sacculifer, Globigerinoides trilobus, Hanzawaia concentrica, Hopkinsina bononiensis and *Spiroplectammina wrightii*.There is an increase in the population of the planktonics and increase in species diversity.

Middle neritic environment

This environment is marked at the following intervals 7840ft – 8020ft, and 10,990ft – 11,110ft (Table 3), based on the following characteristics: The presence of indicator fauna like: Lenticulina inornata, Heterolepa pseudoungeriana, Lenticulina grandis, Uvigerina isidroensis, Brizalina mandoroveensis, Valvullineria gasparensis, Globigerina sp., Globigerina venezuelana, Orbulina universa, Globorotalia continuosa, Panktic indet sp. and Praeorbulina glomerosa.Increase in the number of planktonic specimens. The average planktonic/benthonic ratio is high, the simple species diversity also increased, ranging from 0-23 species

Well D

Foraminiferal Biostratigraphy, fairly rich abundant and diverse foraminiferal assemblages were recorded. The upper interval (5040-8550ft) recorded sparse to barren foraminiferal species, Interval 8550-9500ft dominated by calcareous benthic and planktic species. The lower interval (9500 – 11,750ft) showed moderate recovery, dominated by arenaceous benthic foraminiferal species Some of the age-diagnostic species recorded include Gligerinoides subquaratus, Globorotalia continuosa, Globorotalia mayeri, Uvigerina subperegrina, Globorotalia acostaensis, and Florilus ex. gr. costiferum.

Associated benthic marker species recovered include Uvigerina subperegrina, and Florilus ex. gr constiferum (Nonion sp). A foraminiferal distribution, abundance and diversity chart of the recovered forms together with the foraminiferal zones recognized are presented in Figure 5. The foraminiferal zonation of well D was guided by the works of Blow (1969, 1979) while the numerical ages (Ma) were based on the works of Berggren (1995).

The results of the analysis indicate that the studied interval (5040-12040ft) was deposited during the middle Miocene epoch, of estimated numerical age of 12.18Ma to 7.40Ma and straddling the *Florilus ex. gr. costiferum, Uvigerina subperegrina* (N16) and Globorotalia acostaensis (N15) planktic zone of Bolli and Suanders (1985) and Blow 1969,1979 (Figure 5)

Index species among the recovered foraminiferal assemblages have been used in dating and zoning the intervals. Details are given below:

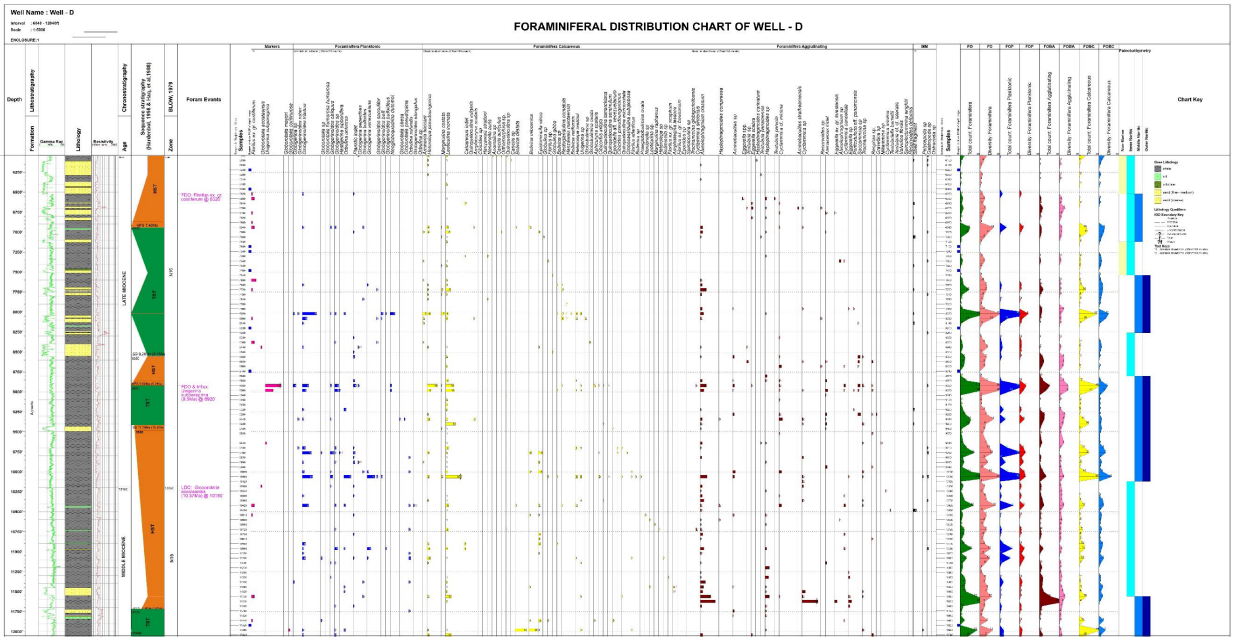


Figure 5; Paleontological distribution chart of Well D

Sequence Stratigraphic Units

Sequence stratigraphic analysis of the well is based on lithostratigraphic data and biostratigraphy of the well. From the analysis, five systems tracts as well as associated key surfaces were delineated. The delineated data were correlated to Haq *et al.* (1988) chart. Delineated systems tracts include:

Highstands systems tract	HST	5040ft – 6940ft
Transgressive systems tract	TST	6940ft – 8550ft
Highstands systems tract	HST	8550ft – 8920ft
Transgressive systems tract	TST	8920ft – 9500ft
Highstands systems tract	HST	9500ft – 11620ft
Transgressive systems tract	TST	11620 – 12040ft

Age Determination

Planktonic foraminifera represent a major calcareous microfossil group widely used for biostratigraphic subdivisions and correlation of deep sea cores (Bolli and Saunders, 1985). The value of the planktonic foraminifera as index fossils has become increasingly recognized, their abundance in marine sediments combined with the short life span of many species makes the planktonic foraminifera in this respect often superior to benthonic foraminifera and other micro and macro organisms for stratigraphic correlations. It is their wide geographical distribution combined with additional dispersal by ocean currents that make the planktonic Foraminifera such valuable index fossils for world-wide stratigraphic correlation (Bolli and Saunders, 1985).

The following planktonic index forms were identified from the studied well interval: *Orbulina universa, Globorotalia humerosa humerosa, Orbulina suturalis* and *Neogloboquadrina dutertrei.* Based on the presence of these index forms, as defined by Bolli and Saunders (1985) and Petters (1983), the age of the studied well is proposed to belong to Early Miocene to Middle Miocene (Figure. 5)

Table 4 Showing Identified Datum Markers for Well-D Foraminifera Data

Depth Interval(ft)	Foram Zones	Age	Foram Events
6040 – 10,180	N16	Late Miocene	FDOs: *Florilus ex gr costiferum* @ 6520ft *Uvigerina subperegrina* @ *892*0ft LDO: *Globorotalia acostaensis* @ 10,180ft
7360 – 11,750	N15	Middle Miocene	

Late Miocene

The upper limit of the late Miocene in the studied well interval is marked at 10180ft, based on the Last down hole occurrence (LDO) of *Globorotalia acostaensis* at 10180ft and the lower limit is marked at 5040ft based on the first down hole (FDO) occurrence of *Florilus ex gr costiferum at* 6520ft (Figure. 5). This interval is characterized by the influx and presence of other typical late Miocene planktonics, such as *Uvigerina subperegrina* and *Globigerinoides trilobus.*

Middle Miocene

The upper limit is marked at 10180ft based on the last down hole occurrence (LDO) of *Globorotalia acostaensis* and the lower limit is marked at 12040ft (Figure. 5). Other planktonic forms present include *Globigerinoides trilobus, Orbulina universa* and *Hastigerina siphonifer*

Biozonation

Three zone have been proposed in this study (based on the International stratigraphic guide of Hedberg (1976) and the observation of the ranges of planktonic foraminifera in Figure 5 as follows: *Florilus ex gr.* partial-range zone, *Uvigerina subperegrina* interval zone.

***Florilus ex. gr* partial range zone**

Stratigraphic interval: 6520ft – 8380ft

The zone is defined by the First Down Hole Occurrence (FDO) of *Florilus ex gr costiferum at 6520ft* (Figure. 4.7). Other planktonic forms occurring within the zone are *Globigerinoides* sp., *Globigerinoides trilobus, Planktic idet* sp., *Globorotalia acostaensis* and *Globorotatalia humerosa.* This zone is equivalent to N16 zone of Blow (1969). The age of this zone is Late Miocene based.

***Uvigerina subperegrina* interval zone**

Stratigraphic interval: 8920ft – 9640ft

The zone is defined by the FDO of Uvigerihna subperegrina at 8920ft at the top.

Other planktonic forms occurring in this zone are *Globigerina venezuelana, Globigerinoides sacculifer,Globigerinoides trilobus* and *Orbulina universa.*

This zone is equivalent to the N16 zone of Blow (1969). The age of the zone is Late to Middle Miocene, based on the presence of planktonic index forms.

The planktonic foraminiferal preservation in the upper intervals of the well is poor. Stratigraphically important taxa (planktonic index forms) were not identifiable, therefore the undiagnosed stratigraphic interval above the *Uvigerina subperegrina* taxon – range zone is assumed to be N15 zone of Blow (1969), because of the stratigraphic position above the positively analyzed zone (*Uvigerina subperegrina* taxon – range zone). The age is also assumed to be Middle Miocene for the same reason (Table. 4.).

Sequence Stratigraphy

Sequence stratigraphy is the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non- deposition, or their correlative conformities (Van Wagoner *et al.,*1988). Sequences can be divided into system tracts which are a linkage of contemporaneous depositional systems. The term system tracts is used to designate three subdivisions within each sequence:Lowstand Systems Tract (LST), Transgressive Systems Tract (TST), and Highstand Systems Tract (LST), exhibiting periods of transgression and regression (Brown and Fishers, 1980).

Sequence stratigraphic analysis of the studied well-D based on foraminiferal biofacies and lithologic descriptions revealed five systems tracts (three TSTs, three HST), three MFS (proposed at 6940ft and 8920ft, dated 7.4Ma, 9.5Ma and 12.18Ma respectively) and two sequence boundaries proposed at 8550ft (9.26Ma) and 9500ft (11.70Ma), as a result, three depositional sequences were established from the well intervals.

Table 4: Planktonic foraminiferal Total count for Sequence stratigraphy

Depth Interval (ft)	**Systems Tract**	**Stratigraphic surfaces**
6040 - 6940	HST	MFS: 7.4Ma@ 6940ft
6940 - 8550	TST	SB: 9.26Ma @ 8550ft
8550 – 8920	HST	MFS: 9.5Ma @ 8920ft
8920 – 9500	TST	SB: 11.70Ma @ 9500ft
9500 – 11,620	HST	MFS: 12.18Ma @ 11,620ft
11,620 – 12,040	TST	

Sequences of the study well D

Transgressive systems tract (TST)

This system tract develops as a result of an increase in the rate of sea-level rise which has an overall deepening upward bathymetric signature (Posamentier and Vail, 1988). It is a period of increasing rate of relative sea level that is characterized by an overall fining upward sequence, the TST is composed of retrogradational parasequence sets, in a vertical succession, the biofacies pass upward from terrestrial through brackish to shallow marine and finally deep marine assemblages (Armentrout, 1987).

The TST in the well D at an interval of 6940ft – 8550ft is defined based on its fining upward sequence, and marked at the top by MFS at 6940ft with increased number of faunal assemblage. The lower section of this interval is predominantly shale, the mid-section shows sandstone and shale intercalation, while a predominance of shale caps the top section of the interval (Figure 5).

At an interval of 6940ft – 8550ft, the renewed TST in this interval is characterized by intercalation of shale and siltstone in the lower section, and siltstone, shale and sandstone in the upper section, with the shale percentage increasing towards the top of the section reflecting an overall fining upward sequence. Also reflected here is the increasing faunal diversity that culminates at the MFS at 6940ft.

Highstand systems tract (HST)

During this stage, the sea-level rise decreases and they are characterized by initially aggradational deep sea shale that grade into intervals of shallowing upwards. This system tract is first defined at an interval of 5040ft – 6940ft, (Table 4.) based on the presence of the MFS (at 6940ft) below the HST and the SB (at 8550ft) marking the top of the interval. This progradational sequence is characterized by shale, silt and sand lithofacies, with gradual decrease in the percentage occurrence of shale. This suggest an overall coarsening (shallowing upward) sequence. The biostratigraphic data reveal the relative appearance and diversity of slope benthonic forms (shallow inner neritic formse.g. *Ammobaculites stratheamensis.*, *Valvullineria flexilis and*

Globigerina sp.). This is consistent with the views of Armentrout (1987). Also at an interval of 8550ft – 8920ft, (Table 4.) this short lived regression is characterized by shale deposited in the shallow inner neritics at its base on the MFS at8920ft and marked at the top by the SB at 8550ft.

Associated key surfaces

The Maximum Flooding Surfaces and sequence boundaries derived from foraminiferal peaks, abundance and diversities is identified basically on the inflection from overall progradation to overall retrogradation of parasequences. The relative thickness of the systems tracts reveal changes in sediment accumulation rate as a result of varying local conditions which may include the effect of gravity, tectonics, availability of accommodation space, and eustatic sea level changes.

Maximum flooding surface (MFS)

Stratigraphic interval: at 6940ft (7.4Ma) and 8920ft (9.5Ma)

These are the periods between maximum relative sea level rise and maximum relative sea level characterized by abundant and diverse fauna (especially benthonic foraminiferal assemblages). The dates of the MFS have been correlated to the Haq *et al.* (1988) chronostratigraphic chart.The ages are dated because of their stratigraphic positions above the positively identified TSTs.

Sequence boundaries

Stratigraphic interval: at 8550ft (8.5Ma) and 9500ft (10.5Ma)

Identified basically on the inflection from overall progradation to overall retrogradation of parasequences in the shallowing sand units. The relative thickness of the systems tracts suggest changes in sediment accumulation rate as a result of varying local conditions which may include the effect of gravity, tectonics, availability of accommodation space, and eustatic sea level changes. This period is characterized by biostratigraphic gaps suggesting periods of non-preservation of fossils, as seen in SB of 8.5.7Ma (Table 4.). The dates of the SB have been correlated to Haq *et al.* (1988) chronostratigraphic chart (Table 4.). The ages have been dated based on their stratigraphic positions above the positively identified HSTs.

Paleoenvironment

The paleodepositional environments of the studied well was interpreted based on the biofacies information obtained from the evaluation of the benthonic foraminiferal assemblages. This has been integrated with the lithologic description of the well and the planktonic/benthonic foraminifera ratio. It is on these bases, that the sequences of the wells are interpreted to have fluctuated from non-marine to coastal deltaic to marine (i.e. non-marine to shallow inner neritic, to inner neritic to middle neritic).

Foraminiferal data (benthonic foraminifera) was most useful in paleobathymetric estimation, this involved utilizing relative abundance and diversity of encountered benthonic foraminifera (Boersma, 1978). There is therefore a general relationship between benthonic organisms and water depth. Furthermore, the percentage ratio of calcareous benthonic to arenaceous benthonic foraminifera (FOBC/FOBA ratio) provides useful paleoenvironmental guide, the higher the percentage FOBC ratio, the shallower the paleodepths, conversely, the higher the percentage FOBA, the deeper the paleodepths (Boersma, 1978).

Paleobathymetry

Foraminifera data was most useful in the estimation of paleobathymetry, it involved the use of relative abundance and diversity of the foraminifera encountered as well as the occurrence of environmentally significant taxa. It is on these bases that the sediments of the well were interpreted to have fluctuated from non-marine to middle neritic as follows:

6040-6160ft, Proximal to Distal Inner Neritic

The presence of few foraminiferal species consisting of rare calcareous benthic and rare to absence of planktics indicate deposition in a shallow water. Foraminiferal assemblage is characterized by *Saccammina sp, Bolivina dilatata*, and *Bolivina sp* suggesting sediments deposition fluctuating between proximal to distal Inner Neritic

8020-8140ft, Middle to Outer Neritic

This interval is characterized by a gradual increase in the abundance and diversity of planktic and benthic foraminiferal species and a corresponding increase in recovery of calcareous nannofossil. The co-occurrences of planktic foraminiferal species and calcareous nannofossils within this interval suggest deposition in open marine settings. The paleowater depth gradually increased to deeper water fluctuating between Middle Neritic to Outer Neritic. Foraminiferal assemblage consists of *Cancris auriculus, Uvigerina subperegrina, Hanzawaia mantaensis, Heterolepa pseudoungeriana, Ammobaculites stratheanmensis,, Haplophragmoides compressa , Heterolepa crebbsi, Marginulina costata, , Bulimina costata and Eggerella sp.*

This foraminiferal biofacies suggests sediment deposition in Middle to Outer Neritic setting.

Table 5: Planktonic Foraminiferal Total Count. Paleobathymetry of Well D

Depth Interval (ft)	**Paleobathymetry**
6040 - 6160	IN

6160 - 6520	NM –SH.IN
6520 - 6820	IN
6820 - 6940	SH.IN
6940 - 7120	IN –MN
7120 - 7360	NM –SH.IN
7360 - 7480	SH.IN – IN
7480 - 7600	NM – SH.IN
7600 - 7840	IN
7840 - 7960	SH.IN
7960 - 8020	IN
8020 - 8140	MN – ON
8140 - 8380	NM – SH.IN
8380 - 8500	IN
8500 - 8560	SH.IN
8560 - 8740	IN
8740 - 8860	NM – SH.IN
8860 - 9040	MN – ON
9040 - 9220	SH.IN – IN
9220 - 9460	IN – MN
9460 - 9640	IN
9640 – 9820	IN – MN
9820 – 10,000	IN
10,000 – 10,120	MN – ON
10,120 – 10,180	SH.IN
10,180 – 10,600	IN – MN
10,600 – 10,960	IN
10,960 – 11,200	IN – MN
11,200 – 11,320	SH.IN
11,320 – 11,560	IN
11,560 – 11,680	MN – ON
11, 680 – 11,920	IN
11,920 – 11,980	NM
11,980 – 12,040	IN – MN

8740- 8740ft, Inner Neritic

Inner Neritic foraminiferal species thrieved within this depositional unit. The foraminiferal species recorded include *Spirosigmoilina oligocaenica, Cassidulina neocarinata, Bolivina sp, Ammonia becarri, Alveolophragmium crissum, Trochammina sp, Florilus atlanticus and Nonoionella auris*. The rare to sparse planktic foraminiferal species recorded within this interval suggest deposition within a photic realm of Open marine condition

10000– 10120ft, Middle to Outer Neritic

A gradual increase in abundance and diversity of foraminiferal fauna with a corresponding increase in paleobathymetry dominated by Middle to Outer Neritic biofacies characterized this interval. The interval is also dominated by deep water arenaceous species. Calcareous benthic foraminiferal species consists of *Heterolepa pseudoungeriana, Globocassidulina subglobosa, and Uvigerina subperegrina. Arenaceous assemblage recorded include Valvulina flexilis, Cyclammina cf. minima, Alveolophragmium crissum, , Haplophragmoides compressa, Trochammina sp, Ammobaculites agglutinans, and Haplophragmoides narivaensis.* The occurrence of planktic foraminiferal species within this interval also suggests deposition in the open marine setting. The above foraminiferal assemblage suggests deposition in the Middle to Outer Neritic

This inference is based on the following reasons:

The intervals are predominantly characterized by fine to medium grained sand (smoky white to orange, sub-angular to sub-rounded, well-sorted and occasionally ferruginized), suggesting deposition during progradational phase, and thin shale beds (brown to grey, fissile, moderately hard, micromicaceous and occasionally carbonaceous). The presence of coarse sandstone, ferruginous materials and carbonaceous detritus in these intervals indicates deposition in high energy, probably near-shore settings

The intervals contain very few benthonic and planktonic foraminifera eg. *Ammobaculites* sp., *Valvullineria gasparensis and Globigerina* sp. Species dominance is low and the number of species (diversity) is high. The planktonic types constitute from 15-30% of the total fauna, (Boersma, 1978).

Conclusion

Based on lithologic and foraminiferal analysis, this study has established that the well interval penetrated the Agbada Formation with deposition occurring during the Miocene (Late and Middle Miocene), similar to the findings of Okosun et al (2012) and Chukwu et al. (2012).

Five systems tracts, two Maximum Flooding Surfaces and two Sequence Boundaries were recognized, along with the establishment of three depositional sequences in the well interval. Depositional environments and paleobathymetric interpretations from the well revealed a transitional to deep shelf depositional settings (shallow to inner shelf.).

Recommendation

It is hoped that the three biozones proposed in this study will contribute to the findings of the stratigraphic committee of the Niger Delta (STRATCOM), to produce a generally acceptable delta-wide biostratigraphic frame work.

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