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Sequence Stratigraphic Study of "B-24 Well" Northern Depobelt, Niger Delta, Southeastern Nigeria

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Abstract: *Sequence Stratigraphic Study of B-24 well (interval 3396m -2008m) in the Northern Depobelt of the Niger Delta basin, southeastern Nigeria was carried out using biostratigraphic data and well logs. Standard methods for foraminiferal sample preparation which involved sample disaggregation and washing through a 63 micron mesh sieve, drying and picking of the foraminifera and other biota were used for biostratigraphic analysis. This was integrated with well logs data and used to subdivide the well section into sediment packages bounded by significant chronostratigraphic surfaces. The results revealed three (3) Maximum Flooding Surfaces (MFSs) identified at 2,900m, 2,768m, and 2,528m and dated 38.0Ma, 36.8Ma and 35.9Ma respectively and three (3) Sequence Boundaries (SBs) identified at 2840m, 2728m and 2408m and dated 37.3Ma, 36.3Ma and 35.4Ma respectively. The obtained results enabled the subdivision of the well section into four depositional sequences consisting of Lowstand Systems Tract (LST), Transgressive System Tract (TST) and Highstand System Tract (HST). The section of the well studied was dated late Eocene to Early Oligocene (P16/17-P18/19) based on the presence of age diagnostic foraminiferal markers (Bolivina tenuicostata, Bolivina imperatrix, Bolivina ihuoensis and Globigerina ampliapertura) which further enabled the dating of the delineated Sequence Boundaries (SB) and the Maximum Flooding Surfaces (MFS) and correlation of the same to the Niger Delta chronostratigraphic chart. The sedimentary facies in the well corresponds to the depositions of the Northern depobelt which range from non-marine through coastal deltaic to marine environment of deposition.*

Keywords: *Maximum Flooding Surfaces, Sequence Boundary, Systems Tracts, Eocene, Oligocene, Northern Depobelt, Niger Delta.*

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I. Introduction

The complexity in the stratigraphic framework of the Niger delta basin fill has made genetic correlation of reservoirs a difficult task to achieve; the undercompacted marine shales of the Akata Formation are overlain by the prograding sequences of the deltaic Agbada and the continental Benin Formations. This complications result from the effects of tectonics and eustacy (Short and Stauble, 1967; Frankl and Cordy, 1967; Weber and Daukoru, 1975; Whiteman, 1982). The application of sequence stratigraphic technique has proven to be useful for hydrocarbon exploration in the Niger Delta basin as this technique has enabled the subdivision of sedimentary units into packages of sediments, essentially bounded by time-stratigraphically significant surfaces. Sequence stratigraphy evolved as an aspect of stratigraphy that involves the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities (Posamentier *et al*., 1988; Van Wagoner, 1995). It involves the analysis of repetitive genetically related depositional units bounded in part by surfaces of nondeposition or erosion (Galloway, 1989). The concept is most successfully achieved through integration of well logs, biostratigraphic, core, and seismic data. This approach offers a predictive model for the identification of the key bounding surfaces, systems tracts, and depositional sequences in response to cycle of fall and rise in sea level.

The study well,"B-24 Well", is located in the Northern depobelt, Niger Delta, Southeastern Nigeria (Fig. 1).The Niger Delta is located on the continental margin of the Gulf of Guinea, Central West Africa, at the southern end of the Benue Trough and lies between Latitudes 4^0 and 7^0 N and Longitudes 3^0E and 9^0 E (Whiteman, 1982). The Niger Delta is one of the most prolific hydrocarbon provinces in the world. As exploration proceeds to the deeper waters with more complex stratigraphic settings, more promising reserves are discovered, thus making the region a focus for more hydrocarbon exploration activities. The ease of achievement of giant oil fields can be greatly enhanced by the application of sequence stratigraphy as an indispensable tool in petroleum exploration.

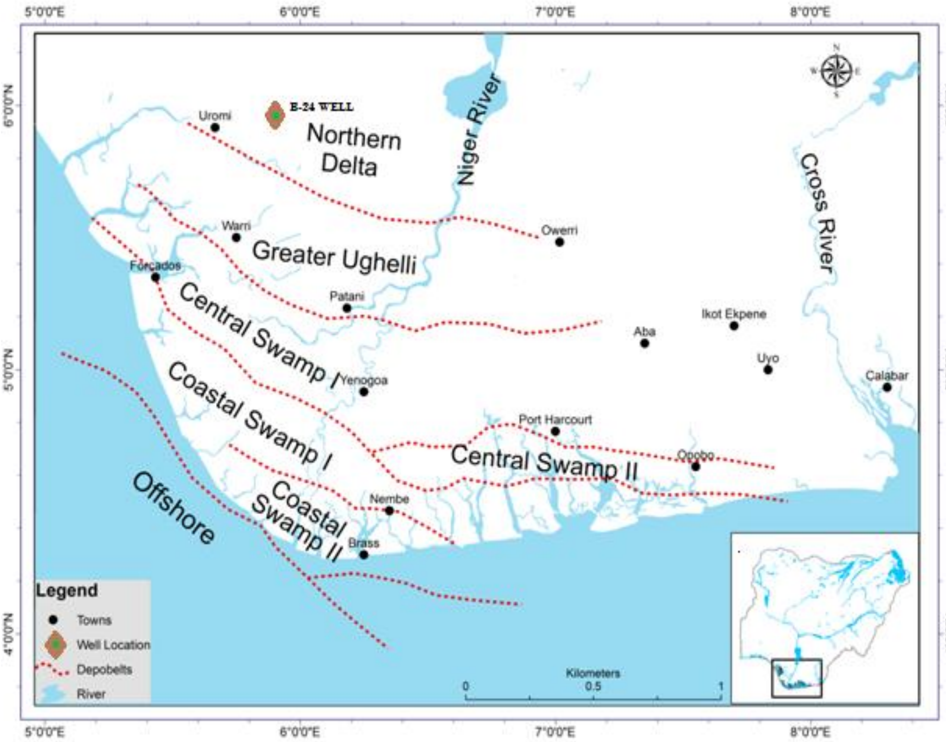

Figure 1: Map of the Niger Delta Depobelts Showing the Location of B-24 Well (modified after Stacher, 1995)

Several studies have been carried out in relation to the sequence stratigraphy of different wells in the Niger Delta basin. These include Armentrout *et al*. (1999) who proposed three sequence stratigraphic models for the Oso Field Niger Delta basin viz: Model based on biostratigraphic data and core sedimentology, model based on core sedimentology and model based on regional seismic reflection profile and well log data. Stacher (1995) developed a delta wide sequence stratigraphic framework for the Niger Delta based on biostratigraphic data obtained from several oil wells. Nton and Ogungbemi (2011) carried out a sequence stratigraphic study of K-Field, within the western Niger Delta based on wireline logs and high resolution biostratigraphic data.

Onyekuru *et al*., (2012) carried out a sequence stratigraphic interpretation of some wells in the "XB Field", Central Swamp Depobelt, Niger Delta using well logs and biostratigraphic data. The study revealed four 3rd order depositional sequences bounded by three Sequence Boundaries and three 3rd order Maximum Flooding Surfaces dated 15.9, 17.4 and 19.4 Ma, respectively as well as Systems Tracts. Similarly, Adegoke (2012) carried out an integrated interpretation of well logs and biostratigraphic data from three wells within the western offshore Niger Delta. Ukpong *et al*. (2017b) employed the concept of sequence stratigraphy in the study of well-X27 in the Greater Ughelli Depobelt of the Niger Delta. Their study was based on well logs and biostratigraphic data extracted from ditch cuttings. Results of the study revealed two (2) 3rd order depositional sequences and three (3) Maximum Flooding Surfaces (MFS 1, 2, and 3) dated 33.0 Ma, 31.3Ma, and 24.3Ma respectively. Okengwu and Amajor (2015) identified three (3) sequences, Sequences Boundaries, Maximum Flooding Surfaces and associated Systems Tracts using well logs and high resolution biostratigraphic data from Biwa Field in the Greater Ughelli depobelt of the Niger delta basin.

A detailed understanding of sequence stratigraphy can provide a chronostratigraphic framework for stratigraphic predictions, correlation and mapping of sedimentary packages. The aim of this study is to carry out a sequence stratigraphic interpretation of B-24 Well in Northern Depobelt of the Niger Delta basin by integrating biostratigraphic data from ditch cutting samples with well logs. This will greatly enhance the prediction of oil reserves, particularly those with stratigraphic bias in the study well.

II. Regional Geologic Setting And Stratigraphy

The Niger Delta is situated in the Gulf of Guinea on the margin of West Africa (Fig. 2). It is one of the largest regressive deltas in the world that has prograded southwestwards forming depobelts that represent the most active portion of the delta at each stage of its development (Doust and Omatsola, 1990).The Niger Delta is bounded by the Cameroon volcanic line to the east, the Dahomey basin to the west, and the 4000-m (13,100-ft) bathymetric contour (Fig. 2) (Corredor *et al.,* 2005). The Delta is a classical shale tectonic province (Wu and Bally, 2000) whose shape and internal structure are controlled by fracture zones along the oceanic crust, denoted as trenches and ridges (Corredor *et al.*, 2005). The Niger Delta sits at a failed arm of a rift triple junction, located at the southern end of the Benue Trough, in which the rifting ended in the Late Cretaceous (Lehner and De Ruiter, 1977). The stratigraphy of the Tertiary Niger Delta is divided into three formations, representing prograding depositional environments (Short and Stauble 1965). These formations were deposited in the continental, transitional and marine environments, respectively; together they form a thick, overall progradational passive-margin wedge (Corredor *et al.*, 2005).The Akata Formation is the basal unit and composed mainly of marine shales believed to be the main source rock within the basin. The Agbada Formation is made up of alternating sandstone, siltstone and shale sequences and represents the actual deltaic portion of the sequence that forms the primary reservoirs in the Niger Delta (Corredor *et al.*, 2005). The Agbada Formation is overlain by the Benin Formation, which is composed of continental deposits, including alluvial and upper coastal-plain deposits (Avbovbo, 1978). A stratigraphic section showing the three formations in the Niger Delta is shown in Figure 3.

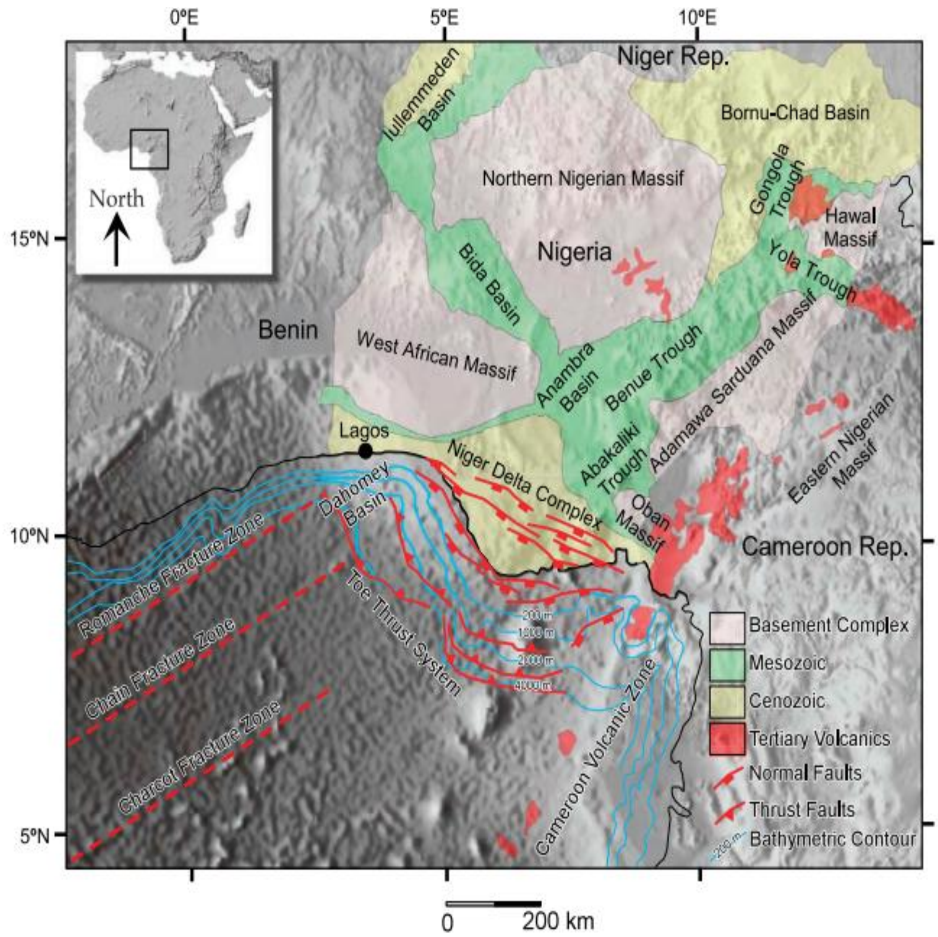

Figure 2: Location map of the Niger Delta region showing the main sedimentary basins and tectonic features (after Corredor *et al.*, 2005).

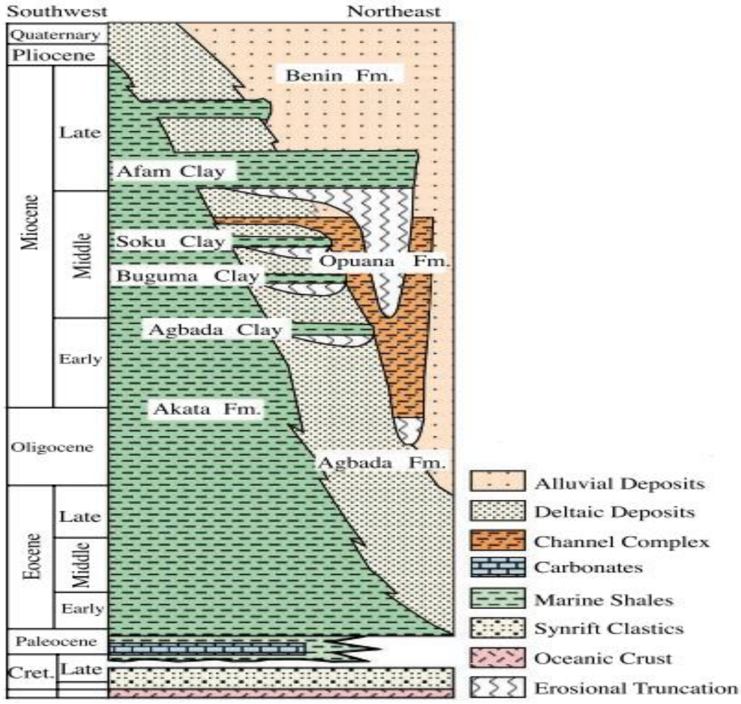

Figure 3: Schematic diagram of the regional stratigraphy of the Niger Delta (after Corredor *et al.*, 2005).

III. Materials And Methods

The datasets provided for this study include geophysical well logs (Gamma Ray (GR) Log and Resistivity Log) and ditch-cutting samples retrieved from interval 3396m -2008m of "B-24 Well". The approximate location of the well is as shown in Figure 1. Standard methods of foraminiferal sample preparation were used (Brasier, 1979; Armstrong and Brasier, 2005; Ukpong *et al*., 2017a). Foraminifera were identified to genus and species levels where possible using the taxonomic scheme of Leoblich and Tappan (1964), Petters (1982) and other published foraminiferal literatures. The residues left after the extraction of foramnifera from the prepared samples were used for lithologic analysis. This was made possible by examining the residues under the binocular microscope. Foraminiferal and lithologic information were inputed into Strata-Bugs (Biostratigraphy Data Management software) to prepare the stratigraphic chart. The First and Last down hole occurrence (FAD and LAD) of chronostratigraphically significant foraminiferal species including foraminiferal species whose stratigraphic ranges are well established in the Niger Delta and worldwide as well as the stratigraphically important foraminifera species which have been extensively utilized and established in the Niger delta (Bolli and Saunders 1985; Petters, 1982; Petters, 1979; Blow, 1979; Fayose, 1970) were the important bio-events used.

Lithology and facies stacking pattern were interpreted from the Gamma ray and resistivity logs. This aided in the identification of the various systems tracts, sequences and key bounding surfaces. The well logs were displayed at consistent scales to enhance log trends in order to identify facies stacking patterns and parasequences. Parasequence stacks (vertical occurrences of repeated cycles of coarsening or fining upwards sequences), resulted in the identification of progradational, retrogradational, or aggradational parasequence sets. Gamma ray log signatures (fining and coarsening upward signatures) also aided in lithostratigraphic interpretation and the determination of paleobathymetry. The Maximum Flooding Surface (MFS) was identified from the well logs and biostratigraphic data as follows: the point of intersection between the retrogradational parasequence sets and progradational parasequence sets; sections with maximum shale peaks as seen on the Gamma ray logs; a surface of maximum foraminiferal abundance and diversity. Sequence Boundaries (SBs) were picked as surfaces with low faunal abundance and diversity or absence of known bioevents, corresponding to low Gamma ray and high Resistivity logs responses at shallowing sections (Onyekuru *et al*., 2012). Sequence Boundary (SB) was also defined at the base of a progradational stacking pattern. Systems Tracts (Lowstand Systems Tract, Transgressive Systems Tract, and Highstand Systems Tract) were mapped and recognized using the methods of Vail *et al*. (1977) and Van Wagoner *et al*. (1988). The Key bounding surface (MFSs and SBs) identified were dated using the corresponding bio-events and by correlation to the Niger Delta Chronostratigraphic Chart (Fig. 4) (Haq *et al*., 1988). An ideal clastic sequence Staking pattern (Kendall, 2004) is shown in figure 5. The Relative age of the well was determined using the characteristic age diagnostic foraminifera recovered from the well (Blow, 1969, 1979; Bolli and Saunders 1985) and by correlation with established works in the Niger delta and worldwide (Petters 1982; Blow, 1979; Bolli and Saunders, 1985; Ukpong *et al*., 2017a).

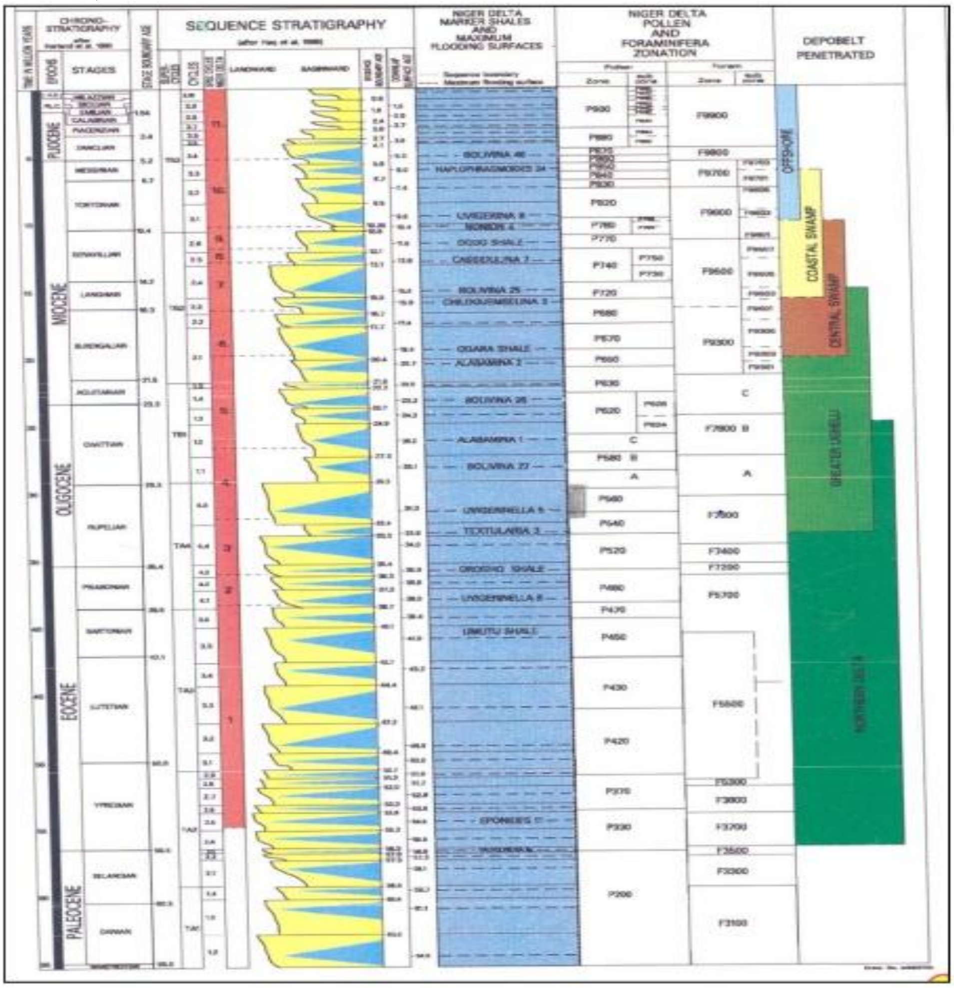

Figure 4: The Niger Delta Chronostratigraphic Chart (Haq *et al.,* 1988).

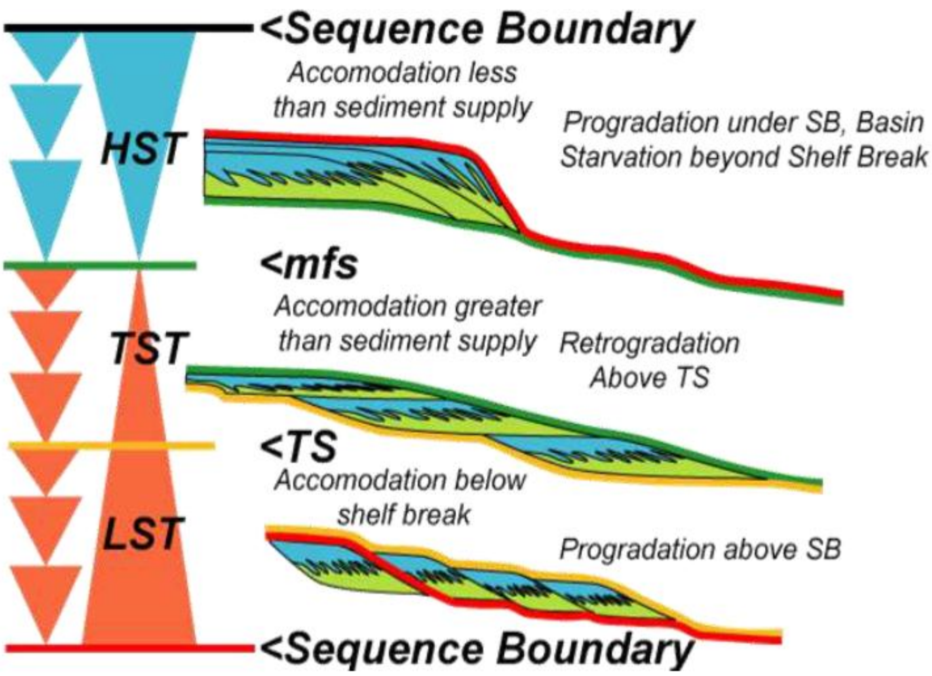

Figure 5: An ideal clastic sequence Staking pattern (Kendall, 2004).

IV. Results And Discussion

4.1 BIOSTRATIGRAPHIC INTERPRETATION

Bio-zonation result of the study well is summarized in (Table 1). The standard foraminiferal zonation scheme of Blow (1969, 1979) was used to erect biozones for the study well. Two foraminiferal biozones (P16/17 and P16/17-P18/19) were identified in the study well. The P16/17 bio-zone was defined on the basis of the LDO of *Globigerina ampliapertura* at 2928m and the FDO of *Bolivina ihuoensis* at 2768m while the P16/17 P18/19 zone was tentatively defined at 2248m on the basis of the co-occurrences of *Bolivina tenuicostata and Bolivina imperatrix* which had its base at 2648m (LDO of *Bolivina imperatrix)*. Low faunal diversity and abundance and absence of known bio-events were used to pick Sequence Boundaries (SB). The presence of some age diagnostic foraminifera assemblages of the Niger Delta such as *Bolivina tenuicostata*, *Bolivina imperatrix, Bolivina ihuoensis and Globigerina ampliapertura* were used to assign a Late Eocene to Early Oligocene age for the study well (Fig. 6).The geologic age of the well section as well as the nature of the stratigraphic sequences within the interpreted well sections were also obtained based on the biostratigraphic information. The geologic ages and the positions of Sequence Boundaries (SBs) and Maximum Flooding Surfaces (MFSs) respectively as correlated to the Niger Delta chronostratigraphic chart (Fig. 4) correspond to the sedimentary facies deposited in the Northern depobelt of the Niger Delta basin (Knox and Omotsola, 1989).

Table 1: Age and Bio-zonation of B-24 Well

Depth (m)	Age	Zones	Bioevents
2008 – 2248	Indeterminate	Undiagnostic	Indeterminate
2248m– 2648	Late Eocene – Early Oligocene	P16/17 – P18/19	- Last Downhole Occurrence (LDO) of *Bolivina imperatrix* @ 2648m
2648 – 3396	Late Eocene	P16/17	-First Downhole Occurrence (FDO) of *Bolivina ihuoensis* (36.8Ma) @ 2768m -Last Downhole Occurrence (LDO) of *Globigerina ampliapertura* @ 2928m

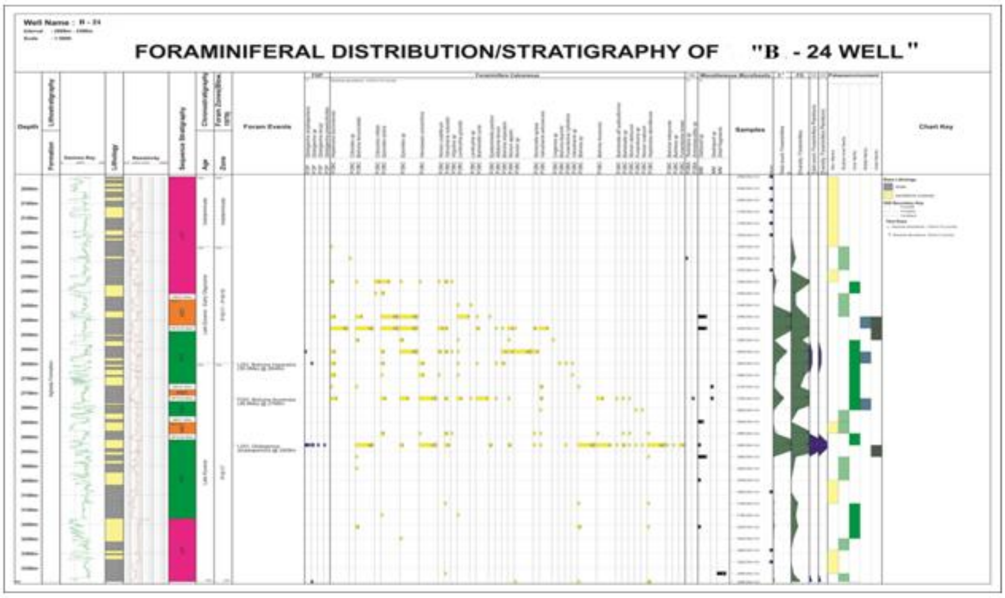

Figure 6: Foraminiferal Distribution and Stratigraphic Chart of "B- 24 Well

4.2 SEQUENCE STRATIGRAPHY

Biostratigraphic information was tied to the well logs; Systems tracts, maximum flooding surfaces and sequence boundaries identified from the biostratigraphic data were redefined so that maximum flooding surfaces corresponded to shaly zones while sequence boundaries corresponded to sandy zones on well logs. The first basal Maximum Flooding Surface (MFS1) identified in the B-24 Well was dated 38.0Ma using the LDO of *Globigerina ampliapertura* at 2928m (Fig. 6). This bio-event occurred within the P16/17 Foram zone of Blow (1979) and was correlated to a regional marker, Uvigerinella-8 which occurred in the late Eocene in the Niger Delta Chronostratigraphic Chart (Fig. 4). The second Maximum Flooding Surface (MFS2) recognized in the study well was dated 36.8Ma using the FDO of *Bolivina ihuoensis* at 2768m which also occurred within the P16/P17 Foram zone of Blow (1979). Correlation was made in the Niger Delta Chronostratigraphic Chart (Fig. 4) to a regional shale marker of Eocene age. The third Maximum Flooding Surface (MFS3) identified in B-24Well, was dated 35.9Ma based on the LDO of *Bolivina imperatrix* at 2648m. This bio-event occurred within the P16/17-P18/19 Foram zone of Blow (1979) which is of late Eocene to Early Oligocene age. This bio-event was correlated to a regional marker, Orogho shale in the Niger Delta Chronostratigraphic Chart (Fig. 4).The oldest Sequence Boundary (SB1) identified at the depth of 2840m in B -24 well was dated 37.3 Ma. This is a substantial erosional surface. The second Sequence Boundary (SB 2) delineated at the depth of 2728m was dated 36.3Ma while the third Sequence Boundary (SB 3) delineated at the depth of 2420m was dated 35.4Ma. These surfaces were also dated using the Niger Delta Chronostratigraphic Chart (Fig. 4).The depositional environment of the well consisted of non-marine to coastal deltaic to marine (non-marine through shallow inner neritic, inner neritic, middle neritic and outer neritic) (Fig. 6).

Sequence I (3396– 2840m)

Sequence 1 consists of a Lowstand System Tract (LST), Transgressive Systems Tract (TST) and a Highstand Systems Tract (HST). The Lowstand Systems Tract (LST) was penetrated in this sequence between 3396-3180m while the Transgressive Systems Tract (TST) was penetrated between 3180 - 2900 m. The TST is characterized by a retrogradational stacking pattern of sandstone and shale alternations. The Transgressive Systems Tract terminated at the MFS dated 38.0Ma which is indicated by the abundance peaks of the LDO of *Globigerina ampliapertura* at 2928m. The Highstand Systems Tract (HST: 2900 - 2840m) is composed of prograding shale and a thick aggradational unit of sandstone which terminated at the top by Sequence Boundary (SB) at 2840 m, defined at the inflection point of the stacking pattern from the maximum point of coarsening upwards to the minimum point of fining upwards. This is an erosional truncation surface as evidenced from the Gamma ray log signature (Fig. 6).The base of this sequence was not penetrated in the study well (incomplete sequence)

Sequence II (2840 - 2728m)

This sequence is made up of Transgressive Systems Tract and Highstand Systems Tract and is marked at the base by Sequence Boundary (SB) at 2840 m. The Transgressive Systems Tract (TST: 2840 - 2768m) is composed of thin sand beds that are capped by thick shale units which displayed a retrogradational stacking pattern with a fining upward units. This is shown in the well log signature that thinned into a condensed section. The occurrence of a major bioevent, FDO of *Bolivina ihuoensis* at 2768Ma and high faunal abundance and diversity which indicated the maximum flooding surface (MFS) dated 36.8Ma also characterized this TST. The Highstand Systems Tract (HST: 2768– 2728 m) showed an agradational stacking pattern comprising of a thick shale unit. The Highstand Systems Tract terminated at the top in a Sequence Boundary (SB) at 2728 m depth which was defined at the point of inflection in the stacking pattern from the minimum fining upwards to the minimum coarsing upwards. The sequence boundary was dated 36.3 Ma.

Sequence III (2728- 2420 m)

This sequence is comprised of the Transgressive Systems Tract and Highstand Systems Tract. The Transgressive Systems Tract (2728 - 2528 m) consists of sandstone units with shale alternations and a thick shale unit, showing a retrogradational stacking pattern with upward fining units as shown on the well log signatures. This system tract thins into the shale units that terminated at a surface of the faunal diversity and abundant peak indicating the maximum flooding surface (MFS: 35.9 Ma) at 2528 m. The MFS is dated based on the FDO of *Bolivina imperatrix*. The Highstand Systems Tract (HST: 2528 – 2420 m) in this sequence is characterized by aggradational stacking pattern of shale and sand units. The Highstand Systems Tract is terminated at the top by a Sequence Boundary (SB) at 2420m depth, defined at the point of inflection in the stacking pattern from net coarsening upwards to net fining upwards and dated 35.4Ma. This surface also depicts an erosional truncation as shown by the sharp change in gamma ray log signature.

Sequence IV (2420- 2008m)

This is an incomplete sequence because the top of the sequence was not encountered in the study well (Fig. 5). This sequence consists of only the Lowstand System Tract (LST: 2420 -2008m).The lowstand system tract in this sequence is characterized by an alternation of sandstone and shale units typical of the Agbada Formation. The near absence of fauna in this sequence especially at the upper units made the age at this interval not to be determined. The upper units of this sequence were probably deposited in a non marine environment (Fig. 5).

V. Summary And Conclusion

Biostratigraphic data generated from ditch cutting samples was integrated with well log signatures (gamma-ray and resistivity logs) to interpret the sequence stratigrtaphy of B-24 Well in the Northern Depobelt of the Niger Delta. Parasequence stacking patterns were used to delineate the system tracts. Maximum Flooding Surfaces were picked at points of high diversity and abundance peak of micro fauna corresponding to highest gamma ray and lowest resistivity readings while the Sequence Boundaries were identified at points of minimum fauna diversity and abundance or absence of known bio-event which corresponds to the points of low Gamma ray and high resistivity log responses. Three (3) Maximum Flooding Surfaces (MFSs) were identified at 2,900m, 2,768m, and 2,528m and dated 38.0Ma, 36.8Ma and 35.9Ma respectively. Three (3) Sequence Boundaries (SBs) were also identified at 2840m, 2728m and 2408m and dated 37.3Ma, 36.3Ma and 35.4Ma respectively. Lowstand Systems Tract (LST), Transgressive System Tract (TST) and Highstand System Tract (HST) were also delineated. B-24 well was dated late Eocene to Early Oligocene (P16/17-P18/19) based on the presence of age diagnostic foraminiferal markers (*Bolivina tenuicostata, Bolivina imperatrix, Bolivina ihuoensis and Globigerina ampliapertura*) as well as the geologic ages of Sequence Boundaries (SB) and the Maximum Flooding Surfaces (MFS) as correlated to the Niger Delta chronostratigraphic chart. The sedimentary facies in the well corresponds to the depositions of the Northern depobelt of the Niger Delta Basin.

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