Sequence Stratigraphic Analysis of Well BB-3, Deep Offshore, Niger Delta Basin, Nigeria: Insight from Palynological Studies

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ABSTRACT

Sequence stratigraphic analysis was carried out on well BB-3, deep offshore, Niger Delta Basin, Nigeria. This is done in order to delineate sequence stratigraphic surfaces using vertical sequence of depositional environment. Palynological analysis was carried out on 82 ditch cutting samples from well BB-3 using the standard acid technique in order to zone the well. Open hole geophysical log data was also provided for the studied interval 10700-15600 ft belonging to the Agbada Formation. Lithologically, the section varies from alternation of sand and shale units with carbonaceous debris, mica flakes, ferruginised materials and glauconite at some interval as accessory minerals. Biozonation included three taxon range biozones in BB-3 well, the proposed palynological biozones are *Belskipollis elegans, Crassoretitriletes vanraadshooveni, Pachydermites diederixi* biozones which are correlatable with the pantropical zones. Samples from the section are dated early Miocene to middle Miocene age based on the independent palynological evidences. The deduced paleoenvironments of the strata penetrated by the well range from outer neritic through bathyal to abyssal. The successions were broken into Highstand Systems Tracts (HST), Lowstand Systems Tracts (LST) and Transgressive Systems Tracts (TST) and chronostratigraphic surfaces such as Maximum Flooding Surface (MFS), Sequence Boundary (SB) and Transgressive Surface (TS). Three HST, three LST, three TST, two MFS and three SB were recognised. The MFS and SB were dated 15.9 Ma, 15.0 Ma and 16.7 Ma, 15.5 Ma, 13.1 Ma respectively by correlation of the established pollen zones with the Niger delta Cenozoic chronostratigraphic chart. The sandstone and shale units of the Systems Tracts are potential hydrocarbon reservoirs and seal rocks respectively.

Keywords: Sequence, palynozonation, Agbada Formation, Miocene, Niger Delta, Nigeria

1. INTRODUCTION

Palynofacies was originally defined by Combaz (1964) to represent the total organic content of a palynological assemblage (tracheids, woody tissue, microplankton, palynomorphs and microforaminiferal linings). The modern palynofacies concept was introduced by Tyson (1995) to represent a body of sediments containing a distinctive assemblage of palynological organic matter thought to reflect a specific set of environmental conditions, or to be associated with a characteristic range of hydrocarbon.

Sequence stratigraphy is the study of rock relationship within a time stratigraphic framework of repetitive genetically related strata bounded by surfaces of erosion or non-deposition or their correlative conformities (Posamentier *et al.,* 1988; Van-Wagoner, 1995).

Sequence stratigraphy is mainly focused on analyzing changes in facies and geometric character of strata and identification of key stratigraphic surfaces to determine the chronological order of

basin filling and erosional events. Stratal stacking patterns respond to the interplay of changes in rate of sedimentation and base level, and reflect combination of depositional trends that include progradation, retrogradation, aggradation and down cutting (Catuneanu *et al.,* 2009). Each stratal stacking pattern defines a particular genetic type of deposit ('transgressive', 'normal regressive', and 'forced regressive') with a distinct geometry and facies presentation style (Hunt and Tucker, 1992; Posamentier and Morris, 2000).

Biostratigraphic and sequence stratigraphic researches in the Niger Delta have not yet been exhausted. The establishment of palynostratigraphic zone in line with the international stratigraphic guide could contribute to the standardisation and harmonisation of biozonation scheme in the Niger Delta Basin. Precise delineation of systems tracts, biozones and correlation could lead to discovering and locating bypassed hydrocarbons. This work seeks to establish biostratigraphic zones in line with the international stratigraphic guide and incorporates palynofacies data into wireline log to achieve stratigraphic sequence characterization.

2. REGIONAL SETTING AND STRATIGRAPHY

The Niger Delta is formed along a failed arm of a triple junction system (aulacogen) that originally developed during breakup of the South American and African plates in the late Jurassic (Burke *et al*., 1972; Whiteman, 1982). The two arm 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.

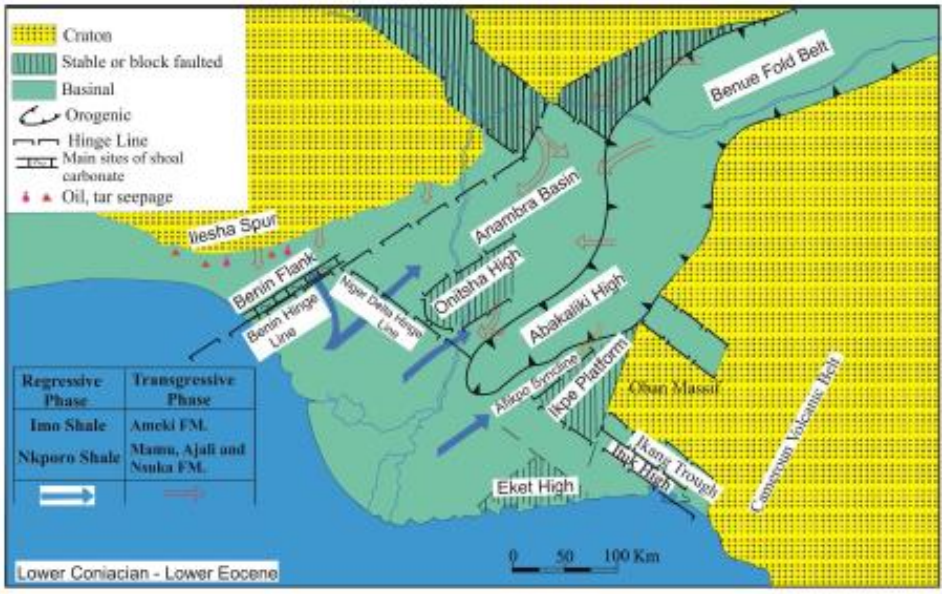

Figure 1: Evolution of the Niger Delta Sedimentary Basin (Bankole, 2010)

The Niger Delta stratigraphic sequence comprises an upward-coarsening regressive association of Tertiary clastics up to 12 km thick (Weber and Daukoru, 1975; Evamy *et al.,* 1978) (Figure 1.4). Three lithostratigraphic units have been recognised in the subsurface (Short and Stauble, 1967)

which are the basal and oldest Akata Formation that compose primarily of marine dark shale of unknown thickness at the base with occasional sand and considered the hydrocarbon producing unit. The middle Agbada Formation considered the main petroleum bearing unit and composed of interbedded sandstone, siltstone, claystone and shale in which the sand percentage increases upwards. Lastly, is the topmost Benin Formation which is composed majorly of continental sand (Short and Stauble, 1967). These formations were deposited in environments which are marine, transitional and continental respectively; forming a thick, progradational passive-margin wedge (Esan, 2002).

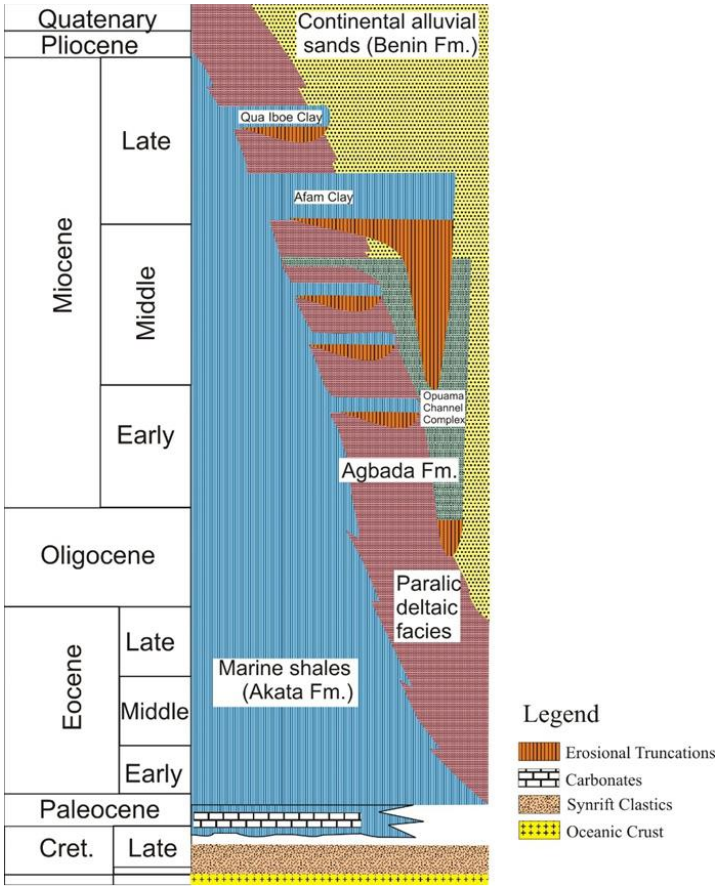

Figure 2: Lithostratigraphic column of the Niger Delta (After Lawrence *et al*., 2002).

3. THE STUDY AREA

The study area is part of the Niger Delta Basin's offshore depobelt. The Niger Delta lies within latitudes 04º and 06º N and longitudes 03º and 09º E (Figure 1.1). BB-3 oil well is situated in BB field western part of the Niger Delta within latitude 5º 08′ 09″ N and longitude 4º 19′ 10″ E

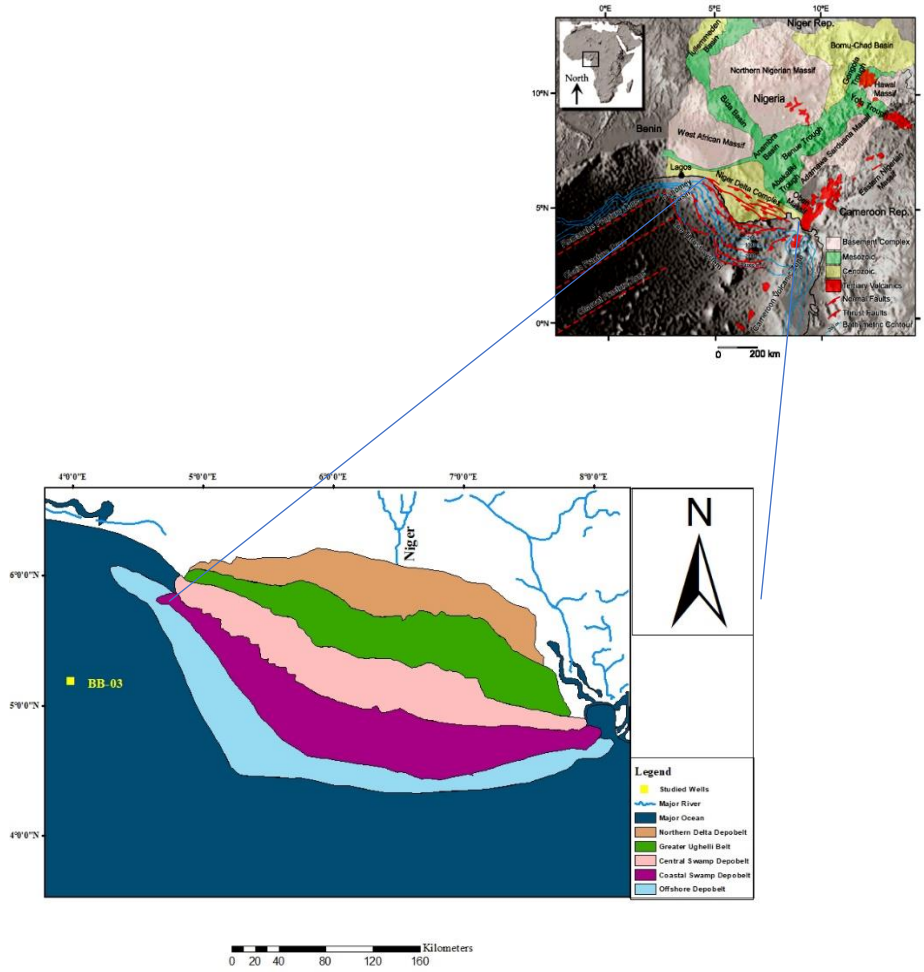

Figure3: Location of BB-3 oil wells in the deep offshore depobelt Niger Delta Basin, Nigeria (Redrawn after Okosun and Chukwuma-Orji,2017)

4. METHODOLOGY

A total of eighty-two (82) ditch cutting samples from BB-3 composited at 60 ft interval provided by SNEPCO were utilized for this study. The interval studied is 10700-15600 ft from BB-3, open hole geophysical log data was also provided for the studied interval. Palynological processing follows the standard acid preparatory method Ridings (2007) where twenty grammes (20g) of sample was treated with 10% HCl under a fume cupboard for the complete removal of carbonates that may be present in the samples. This was followed by complete neutralisation with distilled water before the next procedure. Then 40% HF was added to the sample which was placed on a shaker for 24 hours to speed up the reaction rate, to ensure a complete dissolution of the silicates that may be present in the samples and for the particles to settle down. Thereafter, the HF was carefully decanted, then followed by complete neutralisation with distilled water in order to remove fluoro-silicate compounds usually formed from the reaction with HF.

Sieving and separation was performed using Brason Sonifier 250. Brason Sonifier is an electric device used with the aid of 5 micron sieve to filter away the remaining inorganic matter (silicates,

clay, and mud) and heavy minerals to recover organic matters. It operates in a sonic vibration to filter out inorganic matter and heavy minerals. The treatment of samples with HCl and HF is referred to as demineralisation. The sieved residue was given controlled oxidation using concentrated nitric acid (HNO_3) for palynomorph slides. However, the oxidation process is omitted for palynodebris slide in order not to bleach the palynodebris. The level of oxidation required by each sample was closely monitored under a palynological microscope. This oxidation process is known as maceration. Staining with safranin O is done for palynodebris slides in order to enhance the clarity of dinoflagellate cyst.The prepared slides were studied under transmitted binocular microscope. Identification and analysis were attempted for as many forms as possible with the help of publication from different authors.

5. RESULTS AND DISCUSSION

5.1 Palynological Biostratigraphy of Well BB-3

Moderately rich, well preserved and fairly diverse palynomorph assemblage were recorded within the analyzed interval. *Zonocostites ramonae*, *Monosporites annulatus*, fungal spores/hyphae, species of *Sapotaceoidaepollenites* and *Laevigatosporites* dominated the microfloral assemblage of the analyzed section. Few specimens of marine indicator palynomorphs recorded include *Operculodinium centrocarpum, Lingulodinium machaerophorum, Achomosphaera ramulifera, Spiniferites ramosus* and indeterminate dinoflagellate cysts. Some of these forms recovered from the studied wells are illustrated in photomicrographs plates 6,7 and 8, while palynomorph and palynofacies distributions chart of well BB-3 is shown in Figure 4.

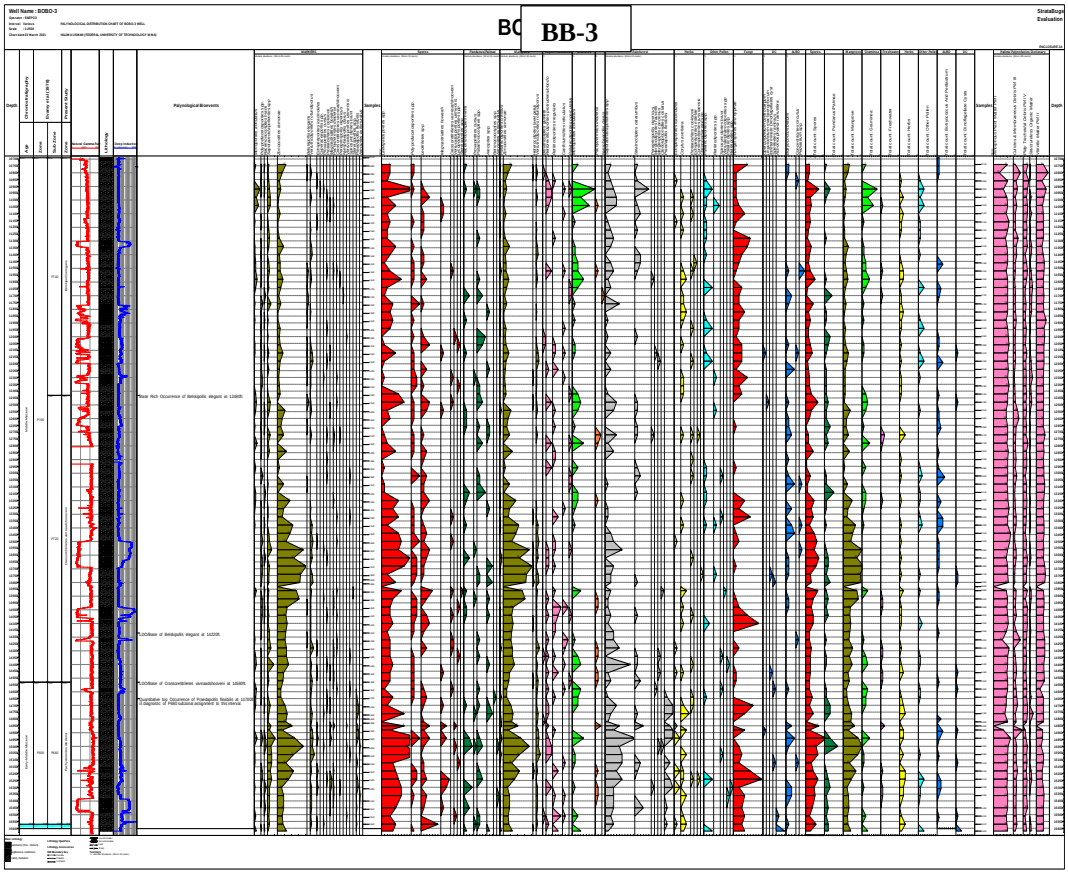

Figure 4: Palynomorph and palynofacies distribution chart of well BB-3

5.2 Palynological Biozonation of Well BB-3

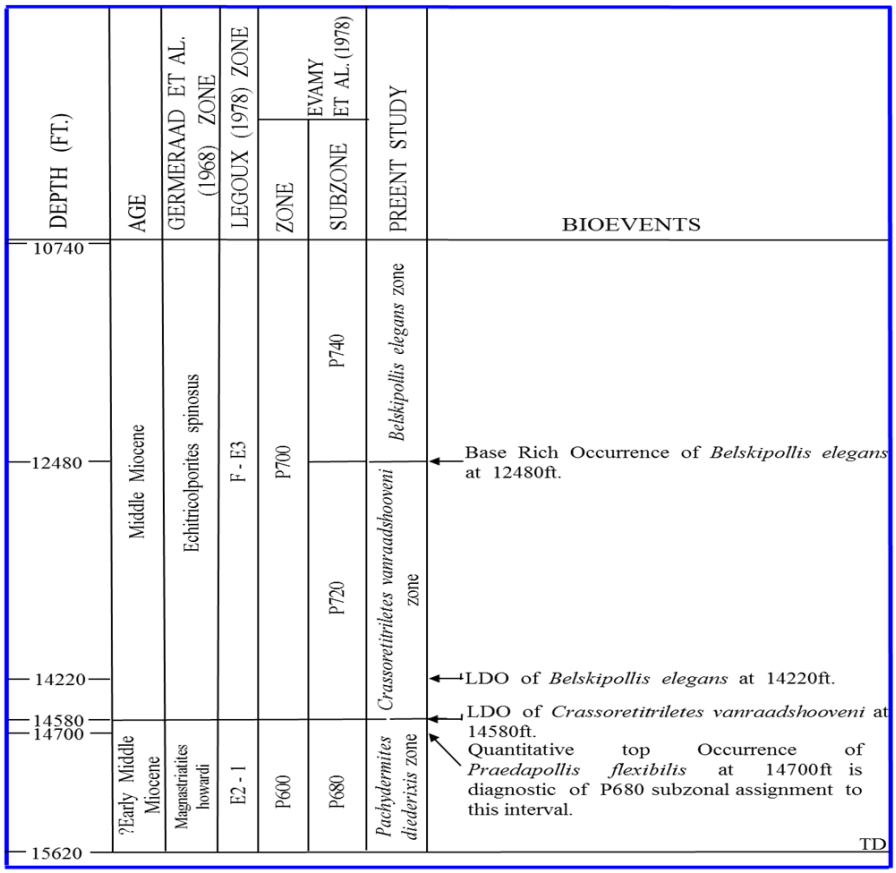

Figure 5: Palynological biozonation of well BB-3

***Belskipollis elegans* zone – taxon range zone**
Stratigraphic Interval: 10740–12480 ft

Description: Subzonal top is tentatively placed at 10740ft, top of the analyzed section while base rich occurrence of *Belskipollis elegans* at 12480ft defines the subzonal lower boundary.

Diagnosis: Moderately rich abundance and fairly diverse of miospores characterize this interval. *Zonocostites ramonae*, *Monoporites annulatus*, fungal spore/hyphae, species of *Psilamonocolpites, Sapotaceoidaepollenites*, *Laevigatosporites*, *Polypodiaceiospori tes* and *Leoitriletes* dominated the microfloral assemblage of this interval. Sparse to common recoveries of *Racemonocolpites hians*, *Verrutricolporites rotundiporus* and *Belskipollis elegans* are other diagnostic feature of this zone.

Age: The zone is dated Middle Miocene because taxa such as *Verrutricolporites rotundiporus* and *Racemonocolpites hians* are diagnostic of Middle Miocene (Morley, 1997).

Remark: This is equivalent to P700 zone and P740 subzone of Evamy *et al*. (1978)

***Crassoretitriletes vanraadshooveni* zone – taxon range zone**
Stratigraphic Interval: 12480-14580 ft

Description: Base rich occurrence of *Belskipollis elegans* at 12480ft defines subzonal top while Last Downhole Occurrence (LDO)/base occurrence of *Crassoretitriletes vanraadshooveni* at 14580ft marks the subzonal lower boundary.

Diagnosis: *Zonocostites ramonae* and *Laevigatosporites* spp were abundant while *Monoporites annulatus*, fungal spore/hyphae, species of *Sapotaceoidaepollenites*, *Psilamonocolpites, Polypodiaceiosporites* and *Leoitriletes* were appreciable or fair within the interval.

Age: First Downhole/Top Occurrence of *Spirosyncolpites bruni* at 13020ft and Last Downhole/Base Occurrence of *Belskipollis elegans* at 14220ft confirm penetration of Middle Miocene.

Remark: This is equivalent to P700 zone and P720 subzone of Evamy *et al*. (1978)

***Pachydermites diederixi* zone- taxon range zone**

Stratigraphic Interval: 14580–15620ft

Description: Base occurrence of *Crassiretitriletes vanraadshoveni* defines the subzonal upper boundary at 14580ft while the subzonal lower boundary is tentatively placed at 15620ft, depth of last analyzed sample.

Diagnosis: Appreciable recoveries of miospore were recorded within this interval. The earlier mentioned miospores in the overlying subzone still dominated the microfloral assemblage. *Zonocostites ramonae*, fungal spore/hyphae, species of *Sapotaceoidaepollenites* and *Laevigatosporites* dominated the microfloral assemblage of this interval. Slight improvement in the recoveries of *Racemonocolpites hians*, *Magnastriatites howardi* and *Echiperiporites icacinoides* are diagnostic of the interval.

Age: Quantitative top occurrence of *Praedapollis flexibilis* at 14700ft confirms the penetration of this zone and dated Early-Middle Miocene.

Remark: This is equivalent to P600 zone and P680 subzone of Evamy *et al*. (1978)

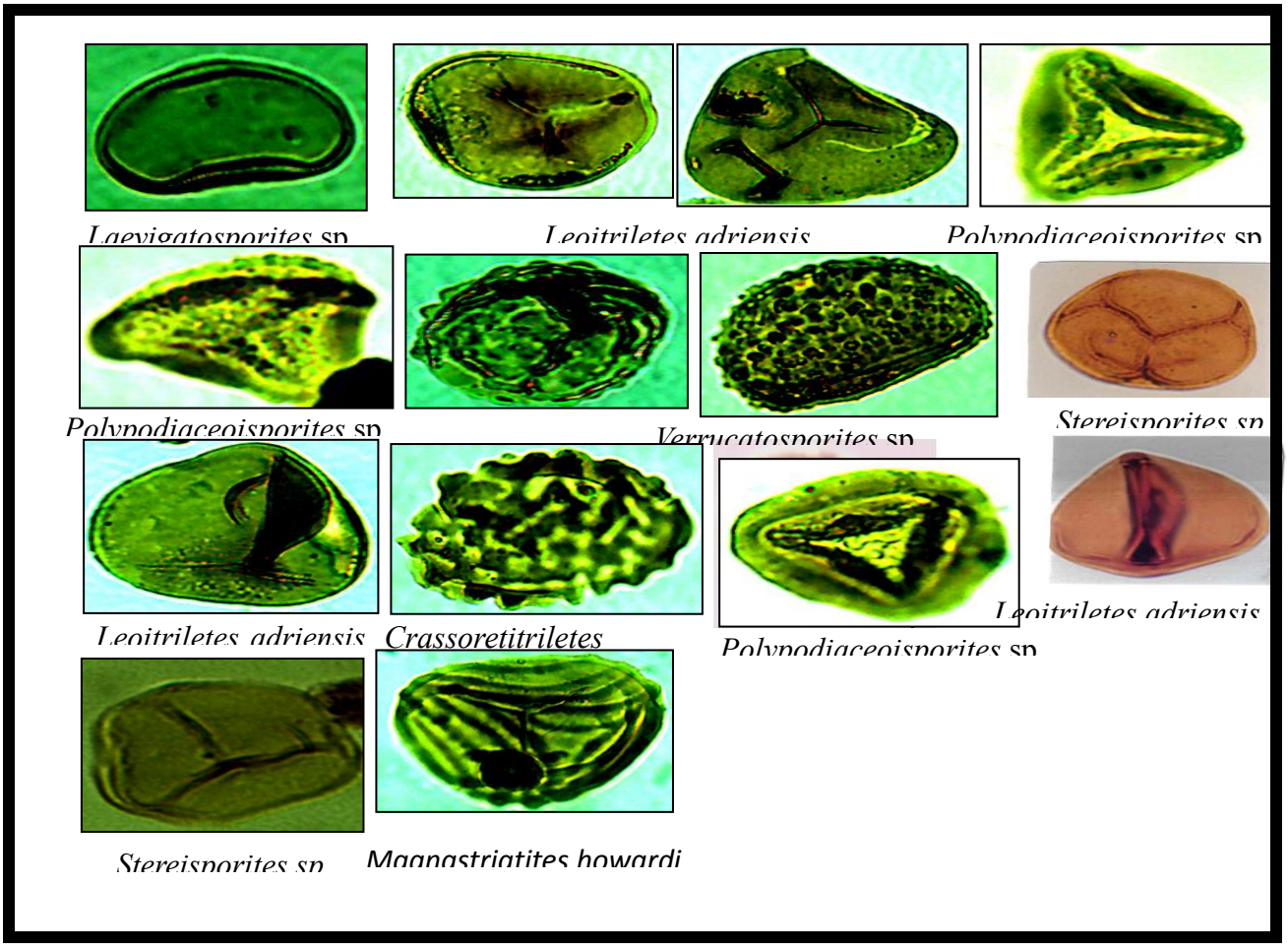

Figure 6: Palynomorphs recovered from well BB-3

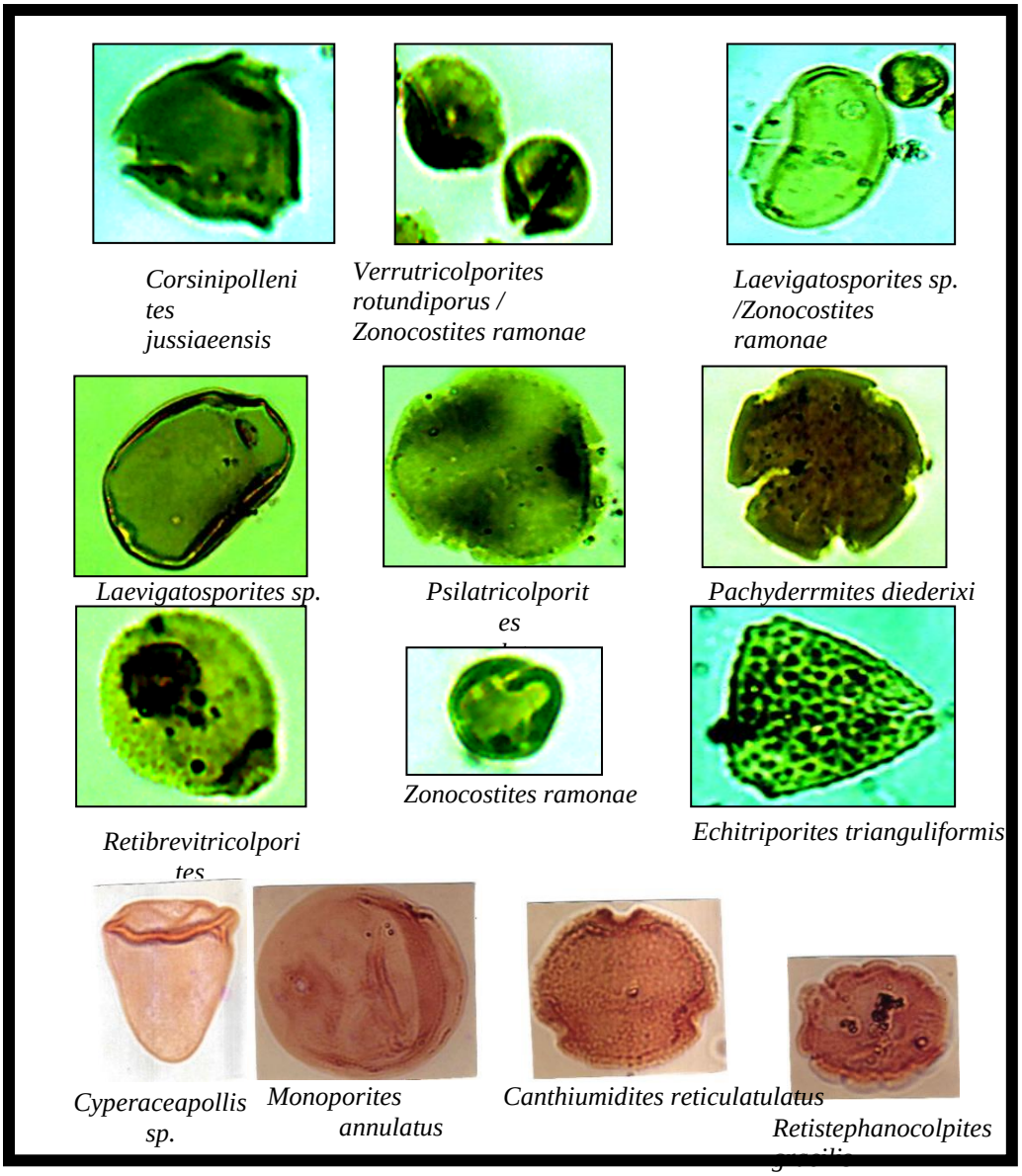

Figure 7: Palynomorphs recovered from well BB-3

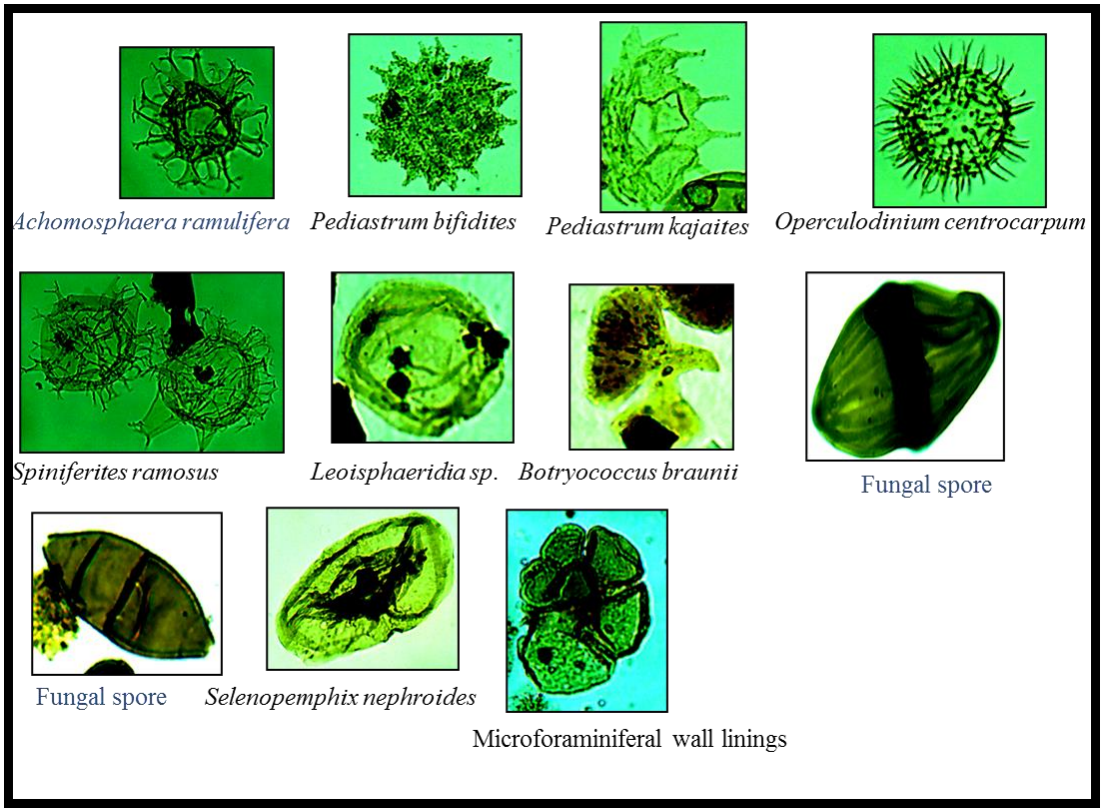

Figure 8: Palynomorphs recovered from well BB-3

5.3 Sequence Stratigraphy

Sequence stratigraphic analysis of well BB-3 is presented in Figure 9. Sequence stratigraphic analysis and interpretation of well BB-3 was carried out by the integration of biostratigraphic, lithologic and wireline (Gamma Ray and Resistivity) log data. Well log sequence stratigraphic technique proposed by Vail and Wornardt (1991) was used for this study bearing in mind the possible pitfalls commonly associated with log facies analysis, ie downhole cave-ins and broad sampling intervals.

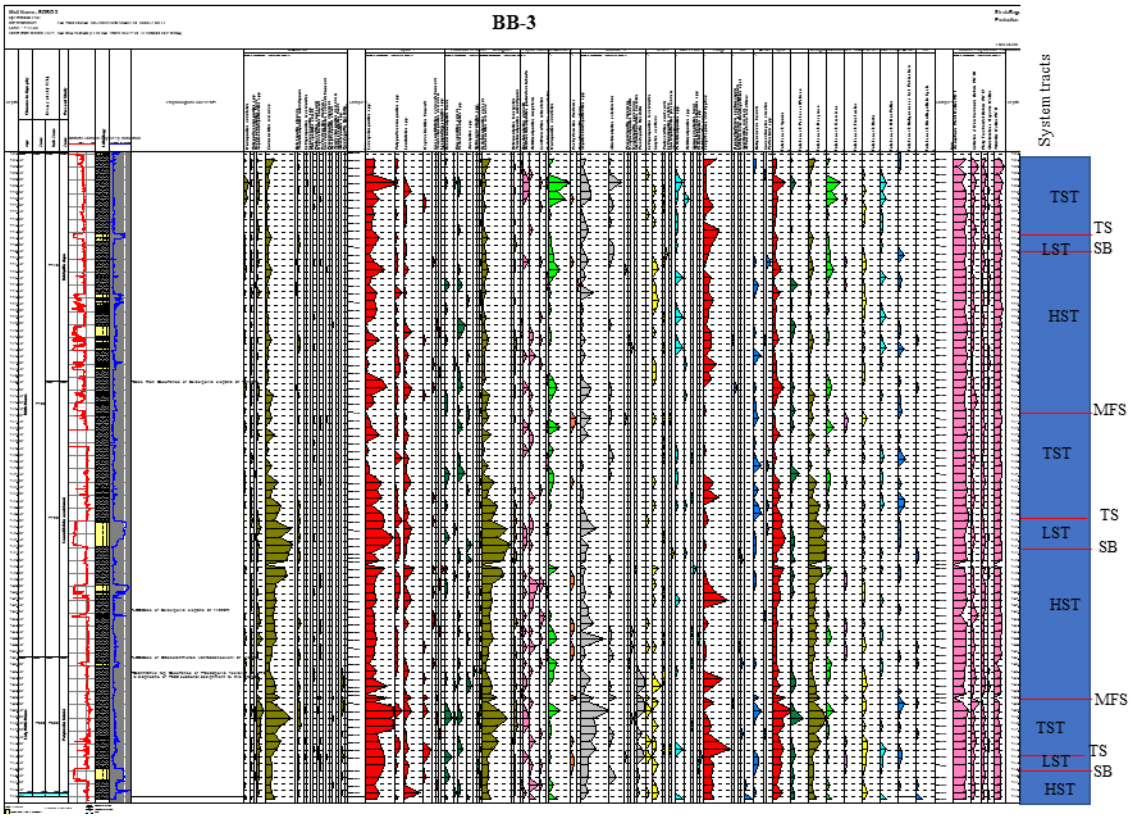

Figure 9: Palynological distribution and System tracts chart of well BB-3

Sequence stratigraphic interpretations of the well relied on the fair to good recoveries of palynomorphs and occurrences of key marker species. The sequence stratigraphic summary is presented in Figure 10. Details of the interpreted systems tracts are presented below for the wells. In this study four depositional sequences were recognized in BB-3, comprising transgressive system tracts (TST), highstand systems tracts (HST), low stand system tracts (LST), Maximum flooding surface (MFS) with their corresponding Sequence Boundaries (SBs).

Highstand Systems Tract (HST)

The Highstand Systems Tract is characterised by stratigraphic interval deposited during a relative decrease in sea level between the MFS and the overlying SB (Boggs, 2006), a set of prograding coarsening upward and shallowing upward parasequence that terminates at SB (Reijers *et al*., 1996), a shift in palynomorph associations from dinoflagellate and marine organic matter dominant assemblages (TST) to spore-pollen and terrestrial organic matter dominated assemblages owing to increased freshwater influx and the progradation of the coastline (Sancay, 2005). Phytoclasts in HST are not degraded (Tyson, 1995). Three HST were encountered within TD-15460 ft, 14950-13690 ft, and 12750-11330 ft in the studied well.

Transgressive Systems Tract (TST)

TST is deposited during the relative rise of sea level and persists until the maximum relative rise of sea level is released at the MFS. TST is characterized by parasequences backstep in a retrogradational parasequence set, progressively deepen upwards as successively younger parasequence step further landward (Reijers *et al*., 1996). The palynofacies association is more of

marine taxa, progressive decrease in the abundance of phytoclasts with paticles becoming more rounded. TST is usually composed of basal shore-face sands overlain by fossiliferous pelagic shales which displays a fining upwards sequence and it is bounded below and above by Transgressive Surface (TS) and the downlap surface of the MFS respectively (Reijers *et al*., 1996). The shales and mudstones of TST form an excellent seal for hydrocarbon reservoirs. TST in the Niger Delta is commonly made up of thick shales occasionally punctuated by relatively thin and poorly developed reservoirs sand bodies. TST were encountered within 15370-14920 ft, 13500-12800 ft and 11240 ft in the studied well.

Lowstand Systems Tract (LST)

LST is deposited as lowstand prograding complexes during the slow relative rise of sea level at or near shelf margin (Vail and Wornardt, 1991). LST is characterised by is overall coarsening upward parasequences sets which show sedimentation rate in excess of the accommodation space. The Transgressive Surface (TS) separates the Lowstand System Tract and the Transgressive System Tract. Palynofacies association within LST contains abundant large phytoclasts (black, charcoalified woody detritus) and poorly preserved pollen and spores indicative of partial oxidation (Tyson, 1995; Batten and Stead, 2005). LST consists of shoreface sands, with shale bands and have been considered among the best exploration targets since they form good reservoir. 15450-15350 ft, 13680-13500 ft and 11340-11300 ft were the intervals at which LST was encountered.

Maximun Flooding surface

The Maximum Flooding Surfaces (MFS) represent the fullest areal development (apex) of a major condensed section where marine influence has encroached the greatest distance beyond the shelf. Maximum Flooding Surface is a correlatable physical surface that commonly represents the maximum shale point between the fining upward (backstepping) transgressive system tract and the coarsening upward (forestepping) highstand system tract (Reijers *et al*., 1996). Maximum Flooding Surface is a downlap surface and is usually associated with major faunal and floral abundance and diversity peaks. Maximum Flooding Surface is further marked or identified by Highest Gamma Ray Log values, Lowest Resistivity Log values, High Spontenous Potential Log values and Low Sonic Log peak. These are the characteristics of the shaliest part of the major condensed sections (Reijers *et al*., 1996). MFS was encountered at 14930 ft and 12780 ft.

The surfaces were dated 15.9 Ma and 15.0 Ma by correlation to the Niger Delta Cenozoic Chronostratigraphic Chart which contains the eustatic curves of Vail (1987) and the global sea level cycles of Haq *et al*. (1988). The MFS falls between P680 zone and P730 subzone in the Niger Delta pollen zones contained in the Niger Delta Cenozoic Chronostratigraphic Chart and also corresponds to Chiloguembelina 3 shale marker species.

Sequence Boundaries (SB)

Sequence Boundaries refer to the erosional (unconformity) surfaces bounding depositional sequence. They are formed during the relative lowering and during lowstand of sea level. They are also recognised on the log as sharp lithologic contacts within progradational sequences or as the points of change between coarsening upward (forestepping) HST and fining upward (backstepping) TST. SB is further characterised by a major shift in the biofacies assemblages from

deeper below the Sequence Boundary to shallower above the boundary (Armentrout, 1991). SB was encountered at 15470 ft, 13690 ft and 11350 ft. It is dated 15.5 Ma and 13.1 Ma because of its stratigraphic position in the sequence. The SB immediately above 15.9 Ma and 15.0 Ma MFS is 15.5 Ma and 13.1 Ma (Figure 10) in the correlation of palynostratigraphic zones to the Niger Delta Cenozoic Chronostratigraphic chart.

Stratigraphic surface	**Age (Ma)**	Well BB-3
		Depth (ft)
SB	5.0	-
MFS	6.0	-
SB	13.1	11350
MFS	15.0	12780
SB	15.5	13690
MFS	15.9	14930
SB	16.7	15470
MFS	17.4	-
SB	17.7	-

Figure 10: Stratigraphic surfaces of well BB-3

Hydrocarbon Exploration Implications

The established palynostratigraphic zones and systems tracts find their usefulness in directing well trajectory**.** The sandstone units within the HST and LST interpreted as channels deposits form good potential reservoirs within the well BB-3. The shale units of HST and TST serve as excellent top and bottom sealing rock for hydrocarbon in the reservoir sand. These shale units could equally serve as good source rocks. The shale units (seals) of TST and HST, and resrvior rocks of LST and HST combined to form the stratigraphic traps for hydrocarbon accumulation in the studied

well that could be targeted during hydrocarbon exploration. The Condensed Section together with the associated MFS serve as regional seals and source sediments in the field.

6. SUMMARY AND CONCLUSION

Palynofacies and sequence stratigraphic analysis were carried out on the strata penetrated by well BB-3 using ditch cutting samples and wireline logs provided by SNEPCO. A total of eighty-two (82) ditch cutting samples within the intervals 10700-15600 ft were analysed. The standard method of sample preparation for palynofacies was followed. The palynofacies analysis yielded low to abundant representation of *Zonocostites ramonae*, fungal spores/hyphae, species of *Sapotaceoidaepollenites* and *Laevigatosporites* with minimal *Monosporites annulatus*. Few species of marine indicator palynomorphs recorded include *Operculodinium centrocarpum, Lingulodinium machaerophorum, Achomosphaera ramulifera, Spiniferites ramosus.* The palynomaceral recovered consists of abundant small to large sizes of palynomacerals 1 and 2, moderate occurrences of palynomacerals 3 and 4 in the studied wells.

They are generally poorly to moderately sorted. Accessories materials are dominated by ferruginous materials, shell fragments and with some occurrences of mica flakes and glaconite. The lithologic, textural and Gamma Ray Log data indicate that the entire studied intervals in the three wells belong to the Agbada Formation.

The studied intervals were dated Early Miocene to Middle Miocene based on the stratigraphic age range of the recovered diagnostic marker species.
Three palynostratigraphic zones were proposed in the well BB-3 using the international stratigraphic guide for establishment of biozones. *Pachydermites diederixi, Crassoretitriletes vanraadshoveni* and *Belskipolis elegans* zones which are proposed to be taxon range zone were established in well BB-3. These three zones erected in the studied wells are equivalent to P680, P720 and P740 subzone of Evamy *et al*. (1978).

Three Highstand Systems Tracts, three Lowstand Systems Tracts and three Transgressive Systems Tracts were recognised, based on the Gamma Ray Logs pattern, lithology and palynofacies. Two chronostratigraphic surfaces such as Maximum Flooding Surface and three Sequence Boundary were also recognized and dated accordingly with by correlation to Niger Delta Cenozoic chronostratigraphic chart and the global sequence cycle chart of Haq *et al*. (1988).

The study showed good correlations of the lithology and Systems tracts that could help in directing well drilling operations. The sandstone and shale units of the systems tracts are excellent hydrocarbon reservoirs targets and sealing rocks respectively.

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