Review of Environment and Earth Sciences
2014 Vol.1, No.2, pp. 77-98
ISSN(e): 2313-8440
ISSN(p): 2409-2150
DOI: 10.18488/journal.80/2014.1.2/80.2.77.98

WELL LOG SEQUENCE STRATIGRAPHIC AND PALYNOLOGICAL ANALYSIS OF LATE MIOCENE TO PLIOCENE AGBADA FORMATION, SOUTHWESTERN NIGER DELTA BASIN, NIGERIA

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ABSTRACT

Sequence stratigraphic interpretation of Chev-1, 2, and 3 wells offshore western Niger delta basin was carried out based on the vertical relationship of the lithofacies associations, electronic well-log, palynologic and foraminiferal data and the existing stratigraphic framework of the Neogene succession in the Niger delta basin. Each well was analyzed in terms of the system tracts, maximum flooding surfaces and sequence boundaries. The recovered palynomorphs together with planktonic foraminifera suggest Late Miocene to Pliocene age. The palynological assemblages exhibit cyclic changes which are here related to the sedimentary evolution.Eighteen depositional sequences were recognized; there are five in Chev-1, ten in Chev-2 and seven in Chev-3. Three of those in Chev-1 and Chev-2 are correlatable while one is correlatable between Chev-2 and 3. These sequence stratigraphic data are matched with existing global standard biostratigraphic zonation scheme and global eustatic curve in order to allow a correlation of sequence beyond local and regional scales.

Keywords: Depositional sequence, System tracts, Palynomorph, Well-Log, Sequence stratigraphy, Foraminifera.

Contribution/ Originality

The study contributes to the existing literature on the Niger Delta Basin by integrating sedimentology, biostratigraphy, well logging and sequence stratigraphy to detect depositional sequences that can serve as reservoirs to substantially increase the oil reserves in the basin. It documents eighteen sequences based mainly on palynological signature in the basin.

1. INTRODUCTION

The underlying concepts and principles of sequence stratigraphy have recently become handy among the exploration experts in the oil and gas industry. This discipline is assisting the biostratigraphers, geophysicsts, petroleum geologists and others to jointly analyze oil well data and update old ones to solve exploration and production problems.

The concept of modern sequence stratigraphy according to Adebayo [1] is used to place geological surfaces, which represent relative sea rises and falls, within a chronostratigraphic framework. It is a process-oriented approach to the interpretation of sedimentary successions and draws upon the understanding of depositional processes to describe or predict the occurrence, extent, and geometry of sedimentary facies. The fundamental processes that control the variation in strata patterns and lithofacies distribution are accommodation and sedimentation. Accommodation is created by a combination of subsidence and sea level changes while the filling of the basin is a consequence of sediment supply, which is controlled by the combined effects of basin geometry, physiography, provenance, and climate. Consequently, sequence stratigraphy helps in the recognition and prediction of reservoir, seal and source-rock facies, thus reducing uncertainties at the exploration stage and improving correlation of reservoir units for exploitation [2].

The most valuable attribute in sequence stratigraphic interpretation is that it can be used to generate a geologically sound model consistent with available multidisciplinary data. Each type of data contributes to the different pieces of geological puzzle encountered by the geoscientists working in the oil industry. For example, seismic data provide the large-scale framework of stratal geometries, both locally and regionally. Well-log interpretation may supply finer scale information on lithology and depositional systems. Biostratigraphic data may be used to ascertain condensed sections, chronostratigraphic surfaces, paleobathymetry, and climatic conditions. Thus, expertise in these disciplines as well as an integrative strategy is required to generate this model, implying the need for a multidisciplinary interpretation team.

The fundamental unit of sequence stratigraphy is a depositional sequence usually called a sequence. It is defined by Adeonipekun [3] as a relatively conformable succession of genetically related strata arranged in system tracts and bounded top and base by unconformities and their correlative conformities. The depositional sequence was subdivided into lowstand, transgressive, and highstand systems tracts on the basis of internal surfaces that correspond to changes in the direction of shoreline shift from regression to transgression and *vice* versa [4]. Stratigraphically important system tracts surfaces are, by convention, characterized by extinction and first appearance datum of globally recognized marker species of planktonic foraminifera and calcareous nannofossils [5].

Sequence-stratigraphic interpretations based on palynological analysis have proven to be effective in different geographic regions and time intervals. Some of these studies [6-14] have established the direct relationship between the palynological record and sea-level fluctuations. Poumot [6] was the first to tie cyclic patterns of terrestrial palynomorph distribution on tropical coastal settings to a sequence-stratigraphic framework. He correlated palynological assemblages dominated by fern spores and forest pollen to the lowstand, higher abundances of palm pollen to early sea-level rise and an increase of mangrove pollen to the later transgressive phase. Poumot [6] explained these fluctuations of pollen and spore assemblage composition on grounds of the environmental preferences of the parent plants and palynomorph transport. A similar pattern was described by Doust and Omatsola [7] who noticed that during lowstand deposition, palynological assemblages were dominated by terrestrial palynomorphs produced by both hydrophilic and xerophilic plants; highstand deposition was however characterized by an increase of palynomorphs derived from hydrophilic plants only. Chow [8] employed the ratio of the stratigraphic occurrence of the fossils of *Rhizophora* and *Camptostemon* for sequence stratigraphic deductions in offshore Sabah and Sarawak, Malaysia. The inverse relationship in the occurrence trends of the two genera in relation to system tracts was employed, noting that the ratio of *Rhizophora* : *Camptostemon* was high in HST and low in LST and TST. This discovery was used to solve problems that were beyond the resolution ability of the seismic method (due to the great depth) and the method was thus recommended for areas of poor foraminiferal and nannofossils data. In another study, [11] reported high spore content in lowstand system tracts and a gradually decreasing trend in spore abundance in transgressive systems tracts. The environmental preferences of certain groups of marine palynomorphs also provide valuable information on sea-level changes [9]; [15]; [16]; [17]; [14] (Figs. 1&2).

Morley [18] pioneered the attempt to employ palynology in sequence stratigraphic study in the Neogene Niger Delta when he compared the palynological characterization of system tracts from the Niger delta and Southeast Asia (India, Indonesia, and Malaysia). The study emphasized that in the Tertiary basins, application of palynology is principally in correlation rather than dating and concluded that the integration of data from both palynomorphs and marine microfossils (foraminifera, nannofossils) can provide a much better basis for system tracts interpretation than when used singly.

Well logging gives the oil industry the ability to evaluate formations, their porosity and fluids, and is instrumental in transferring what was once hit-and-miss into a science-based process. Most of the world's petroleum occurs in sedimentary rocks. The location of petroleum reserves requires an understanding of the nature of the rocks in which these reserves occur, and well logs are one of the primary sources for such data. Well logs are particularly useful in the description and characterization of sedimentary rocks and their pore fluids. Well logs are a fundamental method of formation analysis since they measure the physical properties of the rock matrix and pore fluids. They provide formation data not directly accessible by means other than coring. Well logs can be used to extend data obtained from core analysis to wells from which only logs are available. Utilizing log-derived measurements of such petro-physical properties makes it practical to determine, for example, lithology, porosity, shale volume, water and hydrocarbon saturation and type, when oil and/or gas are present and to estimate permeability, to predict water cut, calculate residual oil saturation, detect overpressured zones and correlate stratigraphy.The most common log types are spontaneous potential, resistivity, gamma ray, sonic, neutron, density, dipmeter and caliper. Spontaneous potential and gamma ray logs are commonly used for the interpretation of siliciclastic successions in lithological terms.Well logs analysis may serve several interrelated purposes including, at an increasing scale of observation, the evaluation of rock and fluid phases in the subsurface, the interpretation of paleodepositional environments based on log motifs, and stratigraphic correlations based on pattern matching and the recognition of marker beds [2].

Several palynological studies have been carried out in the Niger delta basin, however, despite the well-known occurrence of diverse palynomorph assemblages in the area, their application as a tool for sequence-stratigraphic interpretation has rarely been fully explored. In the present study, palynological data from three wells in the basin (integrated with other data) are analyzed and interpreted within a sequence-stratigraphic framework with a view toward understanding the important stratal horizons and determining their respective ages.

1.1. Geologic Setting

The Niger Delta Basin is situated in the Gulf of Guinea, located on the West African continental margin (Fig. 2). It extends throughout what [19] defined as the Niger Delta Province. The basin contains upper Cretaceous to Recent marine to fluvial deposits overlying oceanic crust and fragments of the African continental crust [20]; [21]. The Delta proper began developing in the Eocene. From the Eocene to the present, the delta has prograded southwestward, forming depobelts that represent the most active portion of the delta at each stage of development [20]. The depobelt are characterised by enormous progradational and agradational paralic sequences with some retrogradational marine deposits at intervals.The sedimentary sequence in the Tertiary basin consists in ascending order of three diachronous formations, namely: Akata (marine beds), Agbada (transitional sand-shale beds) and Benin (continental sediments) formations.

2. MATERIALS AND METHODS

Four types of data were used for the study, specifically, electronic well-log, lithologic, palynological and foraminiferal data (Plate) (See [22]; [23]; for some other palynomorphs used). The well-logs include gamma ray, resistivity, neutron and density logs. Each system tract exhibits a characteristic electronic log that is used in recognizing the particular sequence it represents. The composite logs available for Chev-1, 2, 3 wells distinguish the sedimentary components in terms of lithologies, paleoenvironments, maximum flooding surfaces, sequence boundaries, highstand, transgressive and lowstand system tracts. In addition, the coarsening and fining upward sequences correspond to progradational and retrogradational phases respectively (Fig. 3). The theoretical model used for this study to establish the character of deposition of the system tracts, and the miospores contained is discussed with reference to the models of Saller, et al. [24]; Morley [18]; Schioler, et al. [25] and Adebayo and Ojo [2].

3. RESULTS AND DISCUSSION

3.1. Sequence Stratigraphy of CHEV-1 Well

Sequence 1 (5,800-5,600ft)

This sequence is at the basal part of the stratigraphical interval considered for this well (Table 1). The lowest end of this interval is not well represented on the log. However, it is characterized by very high gamma ray and low resistivity. The only systems tract penetrated in this interval is highstand systems tract (HST). Flooding pattern is apparent at depth 5,700ft as marked by high foraminifera population and diversity with the appearance of *Globigerinoides obliquus* and *G. quadrilobatus*. *Globigerinoides immaturus* also occur at this level to mark a marine bioevent. The log pattern indicated that a fairly thick radioactive sandstone occupy the base of the studied interval of the well. The sequence boundary is located at a point marked by very low gamma ray and very high resistivity value located at depth 5,600ft.

Sequence 2 (5,600-5,050ft)

This sequence is well represented on the log and characterized by rapid alternation of sand and shale lithofacies at the lower segment while the upper part is defined by thick intercalated shales. A lowstand systems tract is located within interval 5,600-5,490ft. It is made up of sand bodies separated by thin shale beds. The lithofacies are deposited in environments that vary from channel fill at the base to upper shoreface at the top. This tract is characterized by arenaceous foraminifera such as *Alveolophragmium crassum* and *Ammobaculites* ssp.

The transgressive systems tract ranges from 5,490-5,300ft. It is characterized by frequent alternation of sand and shale facies as a result of unstable sedimentation processes. Upward coarsening sequences are exhibited occasionally. The sediments are probably deposited in a lower shoreface paleoenvironment. The maximum flooding surface is present at depth 5,300ft, characterized by high gamma ray and very low resistivity compared to its surrounding and base occurrence of *Retistephanocolporites gracilis*. The presence of *Neogloboquadrina dutretrei* at 5,400ft corroborated this marine event, which is equivalent to 5.0 Ma. The highstand systems tract (5,300-5,050ft) has two main thickly bedded shales of about 70ft in thickness, intercalated by thin sands. The facies is light grey in colour, fissile and fairly ferruginized in nature within clay laminae. The sediment is suggested to have been deposited in a marine setting. The sequence boundary is located at depth 5,050ft where there was a change from aggradational log pattern to progradational marking the 3.7Ma SB event

Sequence 3 (5,050-4,300ft)

This interval is well represented on the log. The lower part consists of thick sandstone body with intervening clay laminae while the upper part consists of cyclical sedimentary packages comprising moderate to thick shale beds with thin intervening sandstones. The lowstand systems tract is located at interval 5,050-4,940ft. It is characterized by very thick sandstone of about 260ft and associated clay breaks with a paloenvironment that varies from channel fill to upper shoreface. However, a retrogradational sequence is well established within this interval from the occurrence of fining upward sequence.

The transgressive systems tract occurs within 4,940-4,620ft; composed of intercalation of sand and shale facies deposited in upper shoreface but probably lower shoreface at the base of the interval. This tract is characterized by an improvement in the occurrence of calcareous benthics and the presence of a few planktics. The maximum flooding surface is placed at depth 4,620ft, characterized by very high gamma ray and sharp decrease/very-low resistivity value and marked by the occurrence of dinoflagellate cysts, *Marginulina costata*, *Lenticulina inornata* and *Quiqueloculina lamarkiana*. The highstand systems tract ranges from interval 4,620-4,300ft. The interval is composed of moderately thick shale units with intervening sandstone bed of about 40ft thick with upward coarsening units of a progradational sequence deposited in a typical marine setting. The highest foraminiferal population and diversity of the analyzed interval lies within this sequence, marking the 2.7Ma marine event of Catuneanu [5].

Sequence 4 (3,560-4,400ft)

This interval is wide and complex in term of sedimentation processes. The upper part is composed of cyclical depositional packages. The sequence boundary is located at 4,325ft, defined by relatively low gamma ray and sharp increase in resistivity values while the maximum flooding surface is placed at 3,755ft with very high gamma ray and very low resistivity values. The lowstand systems tract is located within interval 4,400-4,260ft. It is a fairly thick sandstone body of about 140ft, characterized by moderately low gamma ray and very low resistivity values. The sediments are suggested to have been deposited in the channel-levee complex and lower shoreface environments. The transgressive systems tract ranges in depth from 3,755-4,245ft. The upper and lower parts of this interval are sandy shales separated by thin shale facies. The sand-shale ratio decreases upward, depicting an occasional progradational interval within an overall retrogradational sequence. The sediments within this interval are deposited in different environments such as marine, lower shoreface and upper shoreface. The highstand systems tract is located at 3,560-3,755ft. It is about 195ft thick, dominated by shale facies separated by thin sand beds except the upper section that contains relatively thick sand interbeds. Therefore, this interval is further defined by upward coarsening sedimentary package referred to as progradational sequence. This sequence is deposited in environment that varies from marine through lower shoreface to upper shoreface settings.

Sequence 5 (3,560 – 3,160ft)

This interval is characterized by the alternation of sand and shale facies. The sequence boundary is located at 3,430ft, marked by a sharp base, very low gamma ray and high resistivity values. This is supported by the occurrence of shell fragments and the absence of foraminifera. This level is probably equivalent to 2.4 Ma marine event of Catuneanu [5] The lowstand system tract lies within the intervals of 3,350-3,560ft. It is characterized by relatively thick sandstone body with short intervening shale units. However, the transgrssive systems tract lies between intervals 3,160ft and 3,350ft. It is predominantly shaly at the base but becomes sandy towards the upper limit of the interval. The depositional environment varies from channel fill to upper shoreface within the lowstand system tract and from upper shoreface to lower shoreface within the trangressive systems tract. Foraminifera and palynomorph populations and diversities are relatively low.

3.2. Sequence Stratigraphy of CHEV-2 Well

Sequence 1 (8,992-8,615ft)

This is an incomplete sequence because the sequence boundary and lowstand systems tract are not penetrated. The transgressive systems tract is located between intervals 8,992-8,690ft

(Table 2). The interval is made up of shale units separated by sandstone beds. The large separation of the neutron-density logs and relative abundant occurrence of foraminifera indicate that the shale units are mainly marine in nature, whereas the sandstone beds are of lower shoreface at the upper part but vary from upper shoreface to lower shoreface for the basal sandstone unit. The maximum flooding surface is placed at 8,690ft. This surface is marked by the maximum separation between the neutron-density values. However, the highstand systems tract lies between intervals 8,690-8,615ft and characterized by upward increase in resistivity values. The sediments are mainly intercalated sands and shales deposited in lower shoreface setting.

Sequence 2 (8,615-8,385ft)

This interval is relatively short-ranged in depth. The sequence boundary is located at 8,595ft on the basis of low gamma rays and high resistivity values. The lowstand system tract is located within the interval 8,615-8,565ft. The basal part is marked by low to high gamma rays and high resistivity indicating a radioactive sandstone bed. The radioactive channel sands are characterized by little or no separation between the neutron and density porosities in a depth plot. The transgressive system tract lies between intervals 8,565-8,435ft. It is defined by high gamma ray and low resistivity values. The sediments contained are mainly heterolithic in nature and deposited in a lower shoreface environment. This resulted in an upward decrease in clay content. The maximum flooding surface is located at 8,435ft on the basis of high gamma ray and very low resistivity values compared to their surroundings. The highstand systems tract lies between 8,435-8,385ft. It is characterized by upward increase in resistivity values for the flooding surfaces. The gradual coarsening upward of prograding shoreface deposit from marine shales to lower shoreface sands is clearly reflected in a bell-shaped neutron-density log separation.

Sequence 3 (8,385-8,050ft)

In this interval the maximum flooding surface is placed at 8,120ft which is characterized by relatively high gamma rays and very low resistivity. It also corresponds to the surface with very low neutron and density values compared with its surroundings. The sequence boundary is located at 8,330ft; this is defined by low gamma ray and high resistivity values. The lowstand systems tract lies between 8,385-8,235ft, a section characterized by sandstone body of about 150ft thick. The interval is further defined by very low gamma ray and maximum resistivity values. The sandstones are typical of the channel fill at the upper end while the lower part houses upper and lower shorefaces sandstones. The transgressive systems tract straddles the intervals between 8,235-8,120ft, and characterized by shale facies. The interval comprises of three storey sedimendary packages characterized by upward decrease in neutron-density plots. The higstand systems tract lies between intervals 8,120-8,050ft. It is characterized by uphole increase in the neutron-density value. The interval is predominantly shaly with intervening sandstone beds.

Sequence 4 (8,050-7,765ft)

The lower portion of this sequence is sandy while the upper part is predominantly shaly. The maximum flooding surface is located at 7,860ft on the basis of very high gamma ray, low resistivity and uphole increase in neutron and porosity values. This is supported by the first appearance of *Ammobaculites strathearnesis* marking the recognition of 6.0Ma bioevent [5]. The sequence boundary is placed at 7,590ft on the basis of relatively high neutron and density values, high resistivity and relatively low gamma ray. The lowstand systems tract lies between 8,050-7,915ft, is characterized by relatively low gamma ray and very high resistivity values. This is composed of sandstone bodies with intervening shale streaks. The very high neutron-density values also point to the presence of sandstone deposits. The globular or bell shaped porosity plots suggest a lower shoreface depositional setting interbedded with channel filled sandstone.

The transgressive systems tract of interval 7,860-7,763ft is very short in thickness and characterized by upward-fining sequence. The interval is composed of intercalated sandstone and shale facies.The predominantly shaly interval 7,869-7,765ft represents the highstand systems tract. It is characterized by one storey sedimentary package showing coarsening upward sedimentary sequence (progradational depositional sequence).

Sequence 5 (7,765-6,885ft)

This commences with a lowstand systems tract, which covers the interval 7,765-7,470ft. It is dominated by basal channel fill sandstone with characteristic upward-coarsening log motifs. The sandstone facies consists of stacked lower shoreface and upper shoreface at the upper and lower segments respectively. The transgressive systems tract (7,470-7,005ft) consists of upward-fining gamma log patterns with the highest point and a corresponding lowest resistivity value. The highstand systems tract interval (7,005-6,885ft) is characterized by an aggradational log pattern and a diagnostic upward-coarsening trend. At 6,880ft, a sequence boundary with characteristic change from aggradational to progradational log patterns is recognized.

Sequence 6 (6,885-5,935ft)

Lowstand systems tract (6,885-6,710) is predominantly dominated by sandstone facies. The interval is defined by thick channel-filled sandstone at the upper part while the lower part is of lower shoreface heterolith deposit. The transgressive system tract interval (6,710-6,305) is characterized by overall upward-fining gamma log patterns peaking at 6,305ft and a corresponding lowest resistivity value. This depth is the maximum flooding surface which corresponds to 5.0Ma of Catuneanu [5]. The highstand systems tract (6,305-5,935ft) is characterized by a coarsening-upward log patterns and aggradational log motifs characteristic of channel deposits. The sequence boundary located at 5,935ft corresponds to the lower diversity of sporomorphs at this level.

Sequence 7 (5,935-5,420ft)

The lowstand system tract lies within 5,935-5,730ft interval. Upward coarsening distributary channel deposits characterize this tract. This is supported by the very low gamma ray and little or no separation between neutron and density signatures. Sporomorphs population is equally high. The transgressive tract of this sequence commences at 5,730ft with an overall fining-upward log motif, which terminates at 5,630ft. The interval is characterized by rapid alternation of sand and shale facies. The maximum flooding surface is placed at 5,630ft on the basis of highest relative neutron porosity value and the corresponding lowest resistivity compared to the surrounding flooding surfaces. The highstand systems tract ranges from 5,630-5,420ft. It is characterized by upward-increasing resistivity and upward-decreasing neutron-porosity. The thick marine shale sequence consists of three-storey stacking pattern separated by sandstone bodies as reflected by the bell-shaped neutron-density log. The sequence boundary located at 5,335ft corresponds to 3.7Ma SB.

Sequence 8 (5,420-5,000ft)

The lowstand systems tract (5,420-5,300ft) is characterized by two blocky shaped sandstone bodies defined by very low gamma ray and supported by little or no separation between the curve-plot of neutron and density porosities. The transgrssive systems tract ranges from 5,300-5,155ft. It is characterized by the alternation of shale and sand lithofacies of the lower shoreface environment. The top of this tract marked the maximum flooding surface as shown by very high gamma ray, very low resistivity responses and the highest foraminiferal population. The highstand systems tract (5,155-5,000ft) is a one-storey sedimentary package. The sequence boundary is located at 5,000ft depth.

Sequence 9 (5,000-4,470ft)

The lowstand systems tract lies within 5,000-4,880ft interval. It is mainly composed of sand with some retrogradational materials at the upper part. The transgressive systems tract (4,880-4,600ft) is made up of shales with minor sand beds. The characteristic very high gamma ray, high neutron-density and very low resistivity logs placed the maximum flooding surface at 4,600ft. The interval 4,600-4,470ft belongs to the highstand systems tract. It is mainly a shaly facies capped by sandstone. This coarsening-upward log pattern is characteristic of aggradational to progradational log motif, which is delimited by a sequence boundary at 4470ft.

Sequence 10 (4,470-4,075ft)

This sequence is incomplete as it consists of only the lowstand and transgressive systems tracts. The lowstand systems tract (4,365-4,470ft) is composed of whitish to brownish coloured sandstone, which is moderately and poorly sorted. The LST might have been deposited within the distributary channel to upper shoreface environments. The transgressive systems tract (4,365-4,075ft) is characterized by sand and shale facies suggesting a range from typical marine shale at the base through lower shoreface to upper shoreface. The maximum flooding surface is placed at

4,075ft based on the very high gamma ray, very low resistivity and very high neutron and density responses at this level. A sequence boundary is at 4,470ft. It is characterized by very low gamma ray, relatively high and moderate values of neutron and density logs.

3.3. Sequence Stratigraphy of CHEV-3 Well

Sequence 1 (8,635.5-8,300 ft)

This interval lies at the lowermost part of the well log provided for this study. HST and part of

the TST are the only tracts represented in this sequence. Maximum flooding surface is located at 8,475ft (Table 3). The level also has the widest separation between the neutron and density depth plot. The occurrence of *Qinqueloculina microcostata* (a benthic) and *Hastigerina praesiphifera* (a planktic) support an inner to middle neritic setting. The sequence is terminated at 8,300ft with a change in log patterns, which marks the sequence boundary that is equivalent to the 8.5 Ma marine event of Catuneanu [5]. The very low foraminiferal population and diversity at this level corroborate this.

Sequence 2 (8,300-8,170ft)

This sequence consists of moderately thick shales and comparatively thicker sandstone beds. The lowstand systems tract lies between interval 8,300-8,260ft. It is made up of sandstone layers with intervening shale breaks. The blocky shaped and sharp based gamma ray indicate that the upper sandstone facies is deposited in channel fill environment while the underlying ones vary from upper shoreface to lower shoreface setting. The TST lies between interval 8,260-8,230ft. It is characterised by fining upward signatures of a transgressive marine setting. This system tract terminates at 8,230ft with a MFS. The MFS is located at 8,230ft based on the relatively high gamma ray and very low resistivity. The HST occupied the interval between 8,230-8,170ft. This tract is characterised by increase in both neutron and density porosity values. It also depicts an upward coarsening sedimentation in an offshore marine environment. The sequence boundary is located at 8,170ft on the basis of low gamma ray with sharp base, very high resistivity and a decrease in neutron – density values.

Sequence 3 (8,170-7,825ft)

This sequence is characterized by sand and shale facies. The lowstand system tract lies within 8,170-8,020ft. It is heterolithic in nature and suggests channel fill and lower shoreface deposits. The TST is located within the interval 8,020-7,870ft with a fining upward signature. This log pattern is terminated at 7,870ft with MFS. The HST (7,870-7,825ft) is relatively thin, consisting of light grey and fissile glauconitic shale. At 7,825ft, a sequence boundary equivalent to 7.4 Ma event of Catuneanu [5] is recognised.

Sequence 4 (7,825-7,200ft)

The lower part of this sequence is mainly sandy with interfering shale breaks. The LST covers the interval between 7,825-7,680ft, composed of thick sandstones with shale breaks and is depicted by blocky shaped log, which suggests a channel fill setting. The TST lies between 7,680-7,575ft with the characteristic upward reduction in resistivity values. Therefore, at 7,575ft, a maximum flooding surface equivalent to 7.0 Ma marine event is indicated. This is supported by the foraminiferal population and diversity, which peaked at 7,550ft. The HST (7,575-7,200ft) is a multi-storey sedimentary package. It is characterised by upward coarsening lithofacies sequence of an overall prograding system. The SB is placed at 7,200ft on the basis of very low gamma and relatively high resistivity values compared to its surroundings. Very low population and diversity of foraminifera were also recorded at this level, which corresponds to 6.7 Ma marine event of Catuneanu [5].

Sequence 5 (7,200-6,435ft)

This sequence is very extensive consisting of very thick shale intervals of about 600ft with thin sand beds. The lowstand systems tract is rather short (7,200-7,120ft) and mainly made up of channel fill sandstones at the top with lower shoreface to offshore marine deposits at the lower part. The transgressive systems tract lies between 7,120-7,020ft. It is terminated by the maximum flooding surface located at 7,020ft based mainly on log patterns, lithology and palynoecological groups. The highstand systems tract covers the intervals between 7,020ft and 6,435ft while the sequence boundary is located at 6,435ft corresponding to 6.2 Ma event.

Sequence 6 (6435-5485ft)

This sequence is thick and complex in term of sedimentational processes. The upper and middle parts are composed of cylindrical depositional packages. The lowstand systems tract is located within interval 6,435-6,300ft. A minor retrogradational phenomenon is manifested in this predominantly progradational interval by fining-upward signature. The transgressive systems tract lies within 6,300-5,915ft. Its fining-upward nature is depicted by the presence of alternating sand and shale facies at the lower part and a predominantly thick heterolith (sandy shale) at the upper part. The maximum flooding surface is at 5,915ft where there is a maximum separation of neutron-density signatures, very high gamma ray and very low resistivity marking the 6.0 Ma event. The highstand systems tract (5,915-5,485ft) is about 300ft thick, it is deposited in the lower shoreface to offshore marine setting. The sequence boundary is at 5,485ft, characterised by relatively low gamma ray and a change from non-separated to moderately separated neutron-density signatures.

Sequence 7 (5485-4850ft)

The lower part of this sequence is composed of thick sandstone beds separated by thin shale facies. The middle part is predominantly shaly while the uppermost part is not well represented by the log. The maximum flooding surface is placed at 5180ft where there is a high gamma ray and low resistivity values.

The correlation of the depositional sequences of the three wells was carried out based on the constructed chronostratigraphic panel (Fig 4). According to Van Wagoner, et al. [26], the regressive infilling nearshore marine and outer neritic sandstones should be the target for good productive reservoirs. Van Wagoner, et al. [27] also have documented that hydrocarbons are pooled within the Miocene third-order LSTs, which yielded a focused model for development of abundant, undiscovered Miocene reserves in the northern Gulf of Mexico shelf province. Therefore, correlation of wells in the shallow offshore Niger Delta and the identification of petroleum targets can be faced with less hardship if the palynological signature and the related marine events can be predicted. When prospecting, prediction of sand at specific locations is required while the prediction of sand-body geometries is desired during field delineation and development. However, sand are not distributed evenly across the offshore basin floor either stratigraphically or arealy [28], hence, locating these sand bodies requires the prediction of sand fairways (river channels into the offshore sites). This is achievable with a good knowledge of the sequence architecture of a basin from shallow to deep-water setting. The LST sand that lies directly on 3.7 Ma sequence boundary is more extensive in Chev-2 (200ft thick) than CHEV-1 (60ft thick), indicating that the fairway of one of the delta lobes [29] in the western part of the basin was along CHEV-2 during this period. The percentage of planktic foraminifera in the studied wells supported this assertion because CHEV-2 has the lowest (8%) confirming the suggestion of Whiteman [30] that clastic materials brought offshore through river channel destroys marine-dependent microfaunas.

4. CONCLUSION

This study revealed that 18 depositional sequences were recognized, five for CHEV-1, ten for CHEV-2 and seven for CHEV-3. Three of those in CHEV-1 and 2 are correlatable while one is correlatable between CHEV-2 and 3. A total of six marine maximum flooding surfaces within Late Miocene to Late Pliocene were recognized when the significant palynological signatures obtained in this study were integrated with foraminiferal, electronic logs and lithologic studies. These are 7.4, 7.0, 6.0, 5.0, 2.7 and 2.0 Ma [5], having a resolution in the order of ≤1 Ma and being locally applicable in shale-dominated facies. This work compares very favourably with planktonic foraminiferal and nannofossil zonation scheme [26]. It should however, be noted that it is not in all cases that these palynological events are exactly co-eval with the marine events, though, they are in such cases close to them, either above or below.

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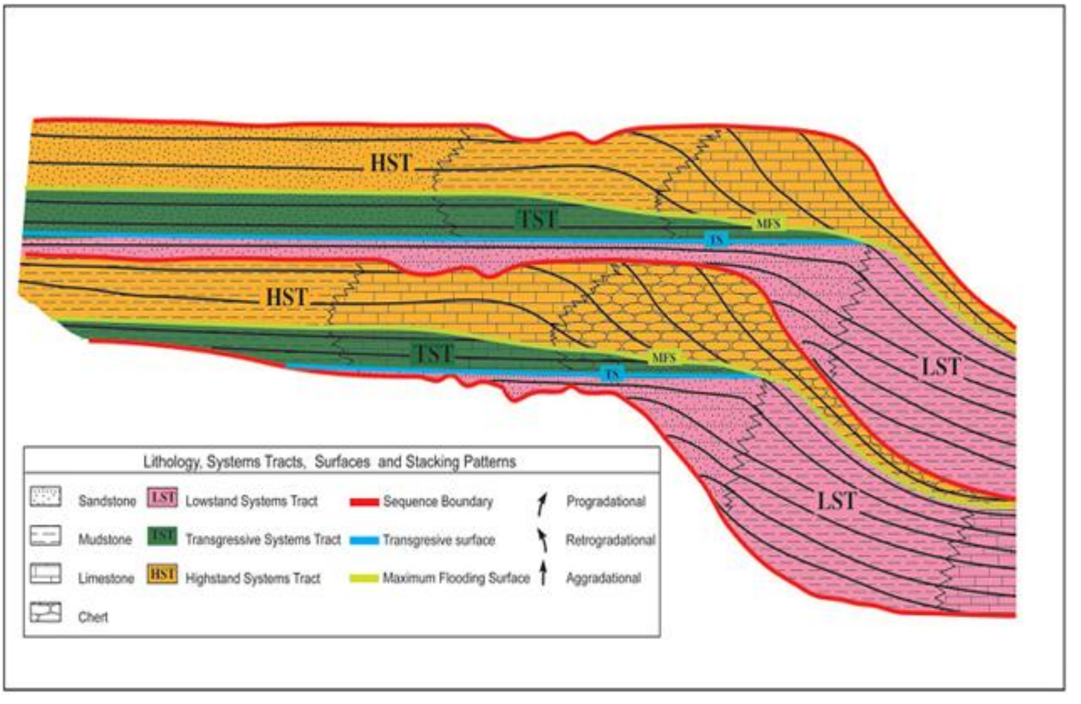


Fig-1. Schematic model showing the distribution of palynological assemblages from onshore– offshore and their relationship to an idealized sequence-stratigraphic section (After[14]).

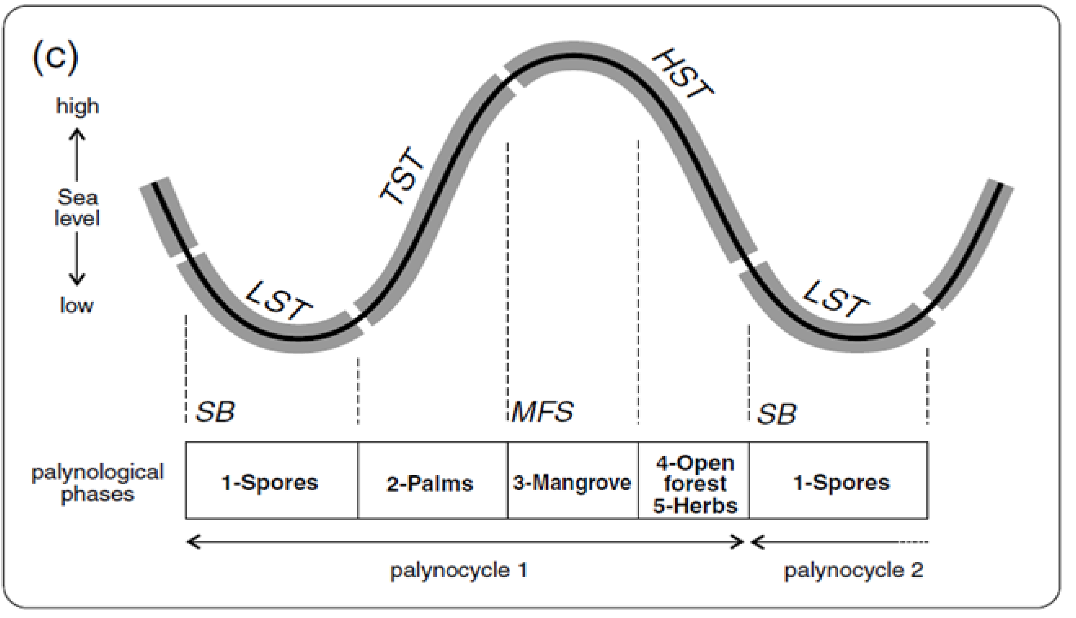


Fig.-2. Correspondence between the phases of the palynocycles and the depositional systems of the sequence stratigraphic analysis SB= sequence boundary, MFS= maximum flooding surface [13, 23].

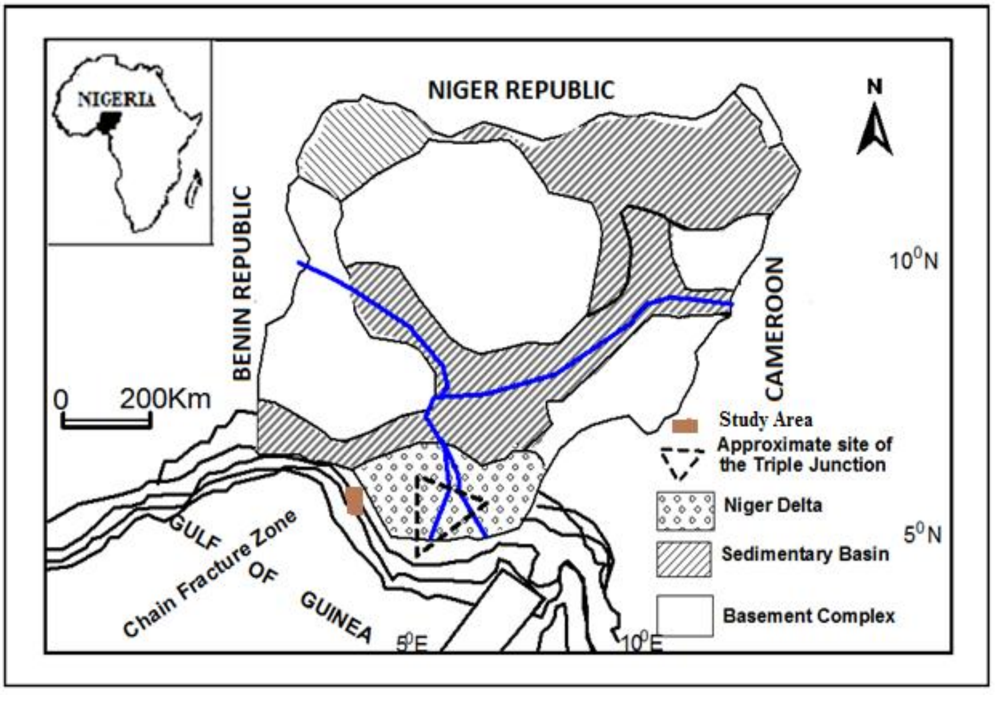
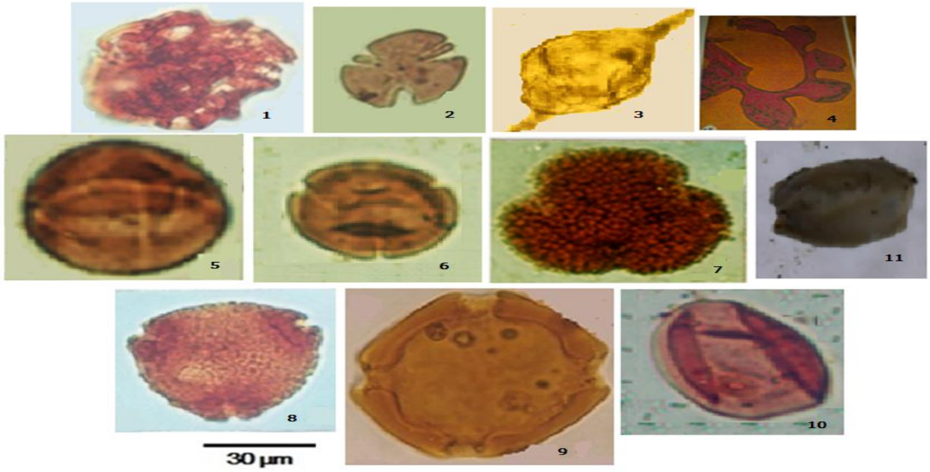


Fig 3. Sedimentary Basins in Nigeria Showing the Niger Delta Basin and the Study Area (Modified from [30, 31]; Benkhelil [4], [32]).



Peregrinipollisnigericus, 2.*Psilatricolporitesoperculatus*, 3.*Palaeocystodinum spp*., 4.Microforaminiferal wall lining, 5-6.*Zonocostitesramonae*, 7.*Retitricolpitesbendeensis*,

8.*Retibrevitricolporitesobodoensis*,9.*Pachydermitesdiederixi*,10.*Monoporitesannulatus*,

11.*Quinqueloculinalamarckiana*(foraminifera).

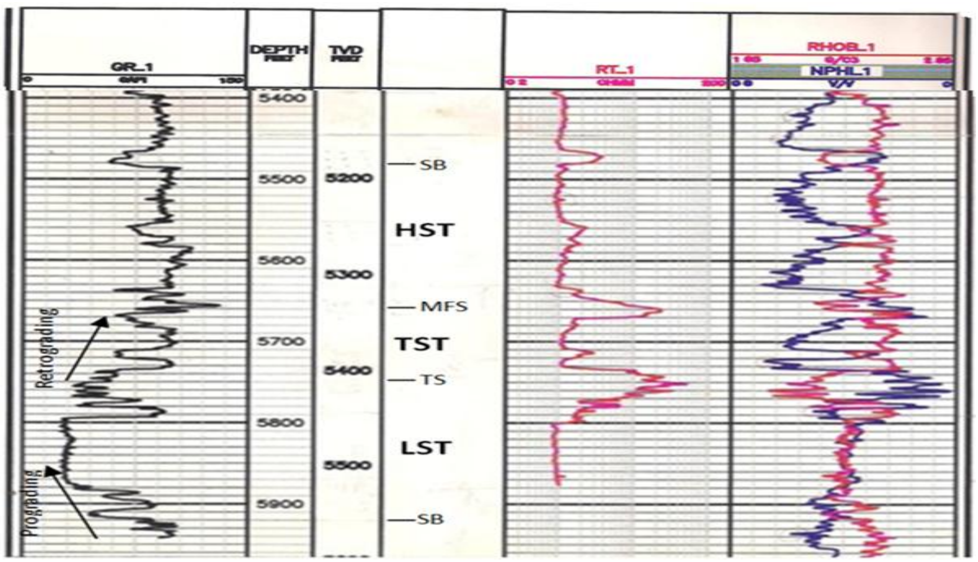


Fig- 4.A Section of the Well Log of Chev-2 well.

Table-1. Sequence Stratigraphy of Chev-1 Well

DEPTH FT	EPOCH	Evamy, et al. [33]	SEQUENCE (This Work)	SYSTEM TRACT (This Work)	AGE After Haq, et al. [11] (Ma)	BIO EVENTS
3150	LATE PLIOCENE	P900	5	3250 TST		
3500				LST 3430	SB 2.4	Top *Retitricolpites bendensis*; Top *Retibrevitricolpoites obodoensis*
			4	HST 3755		
4000				4000 TST		
4500; 4750				LST 4400	2.7	Base *Podocarpus milanjianus*
5000			3	HST 4620		
5300	EARLY PLIOCENE	P800		TST 4920	SB 3.7; 5.0	Uphole decrease of *Zonocostites ramonae*; Base *Retistephanocolporites gracilis*
5600				5050 LST	SB 5.5	Base *Nymphaea lotus*
6000			2	HST 5300		
	LATE MIOCENE			TST 5500		
				5600 LST		
			1	5700		
				HST 5800		

Table-2. Sequence Stratigraphy of Chev-2 Well

DEPTH FT	EPOCH	Evamy, et al. [33]	SEQUENCE	SYSTEM TRACT	AGE After Haq, et al. [11] (Ma)	BIO EVENTS
	EARLY PLIOCENE	P880	10	4365 TST		
				4470 LST		
4500			9	4600 HST		
				TST 4700	3.4	*Marginulina costata*
				4900 LST		Quantitative top
5000				HST 5155	SB 3.7 3-9	*Bridellia cf. ferruginea*
5500			8	5300 TST		Quantitative top *Psilatricolpitesoperculatus*
				5420 LST		
		P870	7	5630 HST		
6000				5730 TST		
				LST 5935	SB 4.2	
6500			6	HST 6305	5.0	Quantitative top *Cyperussp*
				TST 6710		*Ampycorynascalaris caudata*
7000				L;ST 6810		
	LATE MIOCENE	P860	5	7005 HST		
7500				TST 7470		
				LST 7765		
			4	7860 HST		
8000				7915 TST	SB 5.5	
		P850		8050 LST	6.0	
			3	8120 HST		Qantitative base *Nymphaea lotus*
				8235 TST		
				8385 LST		
8500			2	8435 HST		
				8565 TST		
				8615 LST		
			1	8690 HST		
				TST		

Table-3. Sequence Stratigraphy of Chev-3 Well

DEPTH FT	EPOCH	Evamy, et al. [33]	SEQUENCE	SYSTEM TRACT	AGE After Haq, et al. [11] (Ma)	BIO EVENTS
4150						
			7			
5000				5180 HST		
				5390 TST		
				5485 LST		
		P850			?SB5.5	Minimmum occurrence *Zonocostitesramonae*
			6	HST		
				5915	6.0	FAD: *Lenticulina costata*
6000						FAD: *Spirosplectammina wrightii*
				TST 6300	SB6.2	Top occurrence *Peregrinipollis nigericus* (*Brachystegia cf.eurycoma*)
				6435 LST		
7000		P840	5	HST	6.4	Base occurrence *Cyperus* spp.
				7020	SB 6.7	
				7120 TST	7.0	FAD: *Textularina96oncave*
		P830		7200 LST		
			4	HST 7575	SB 7.4	
8000				7680 TST		FAD: *Orbulinauniversa*
				7825 LST	?8.2	Acme *Psilatricolporites operculatus*
			3	7870 HST	SB ?8.5	
				8020 TST		
				8170 LST		FAD: *Globigerinoides obliquus*
			2	8230 HST		
				8260 TST		
				8370 LST		Uphole increase *Monoporites Annulatus*
			1	8475 HST		
	LATE MIOCENE			8635.5 TST		

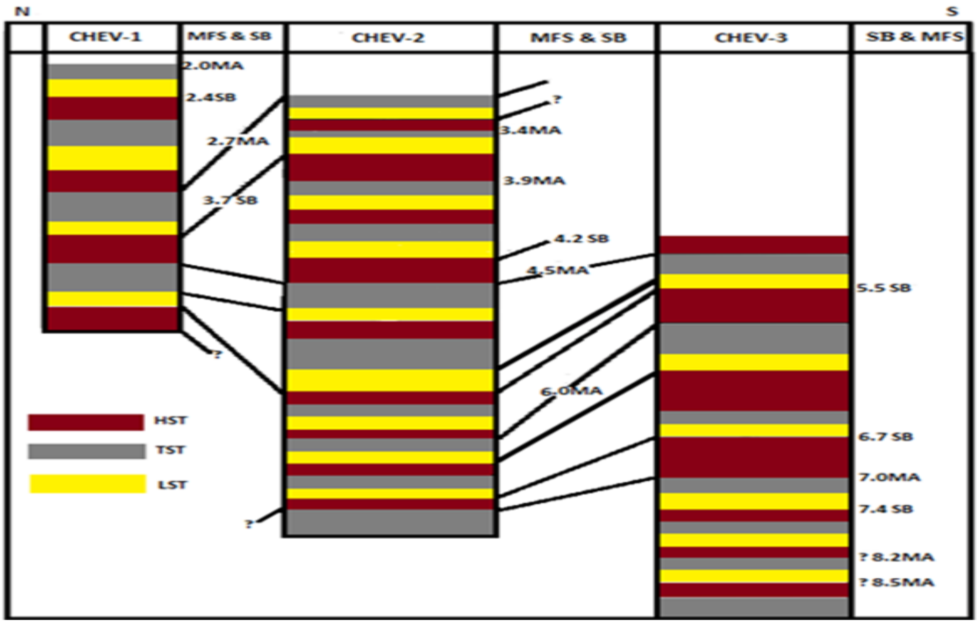
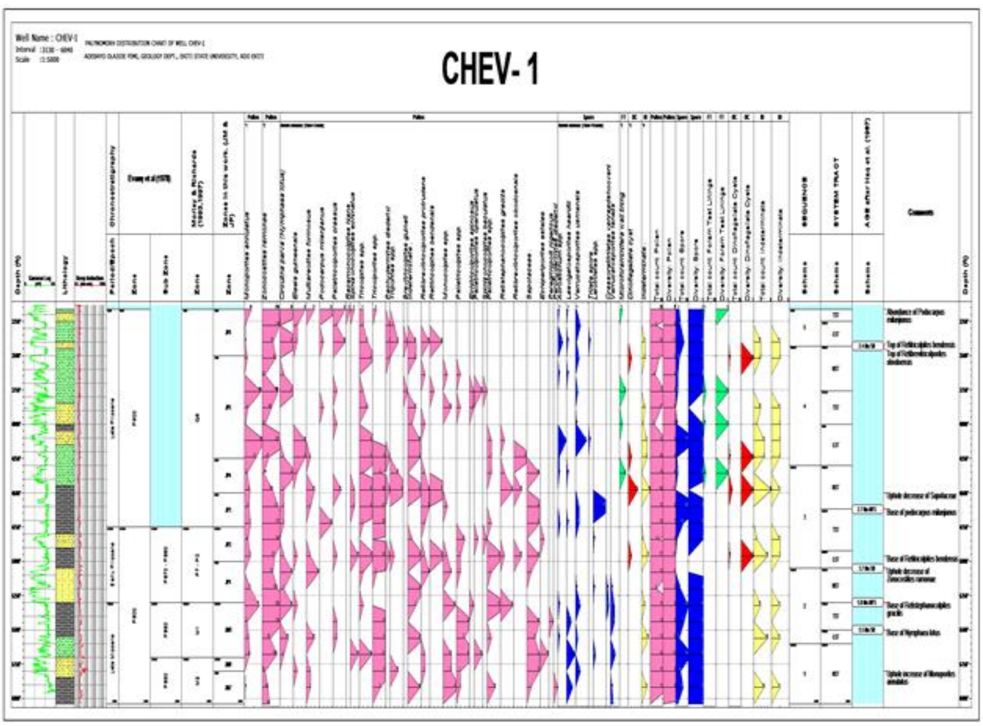
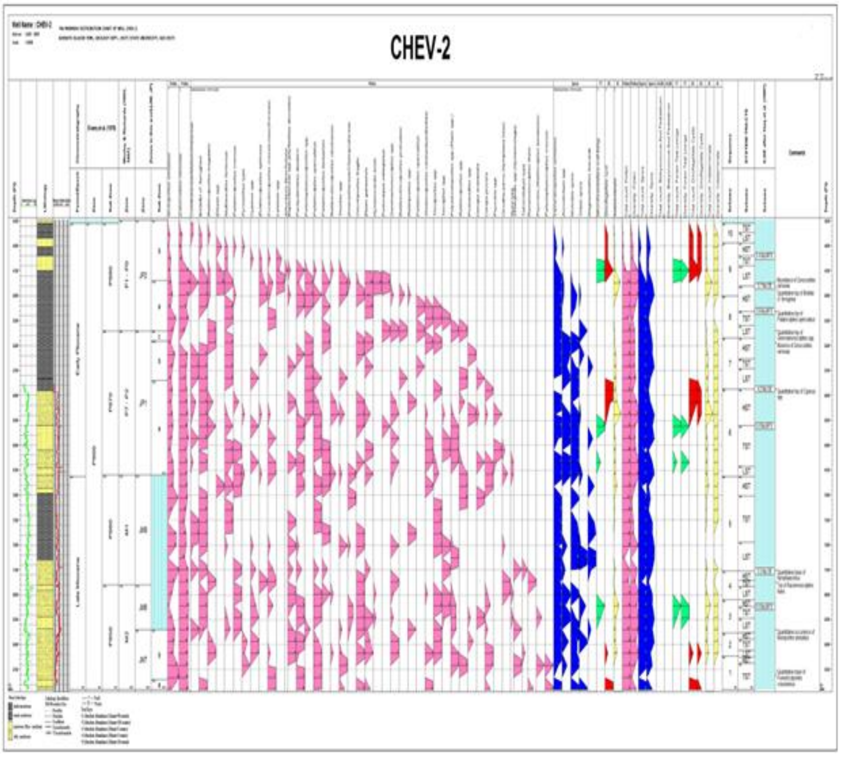


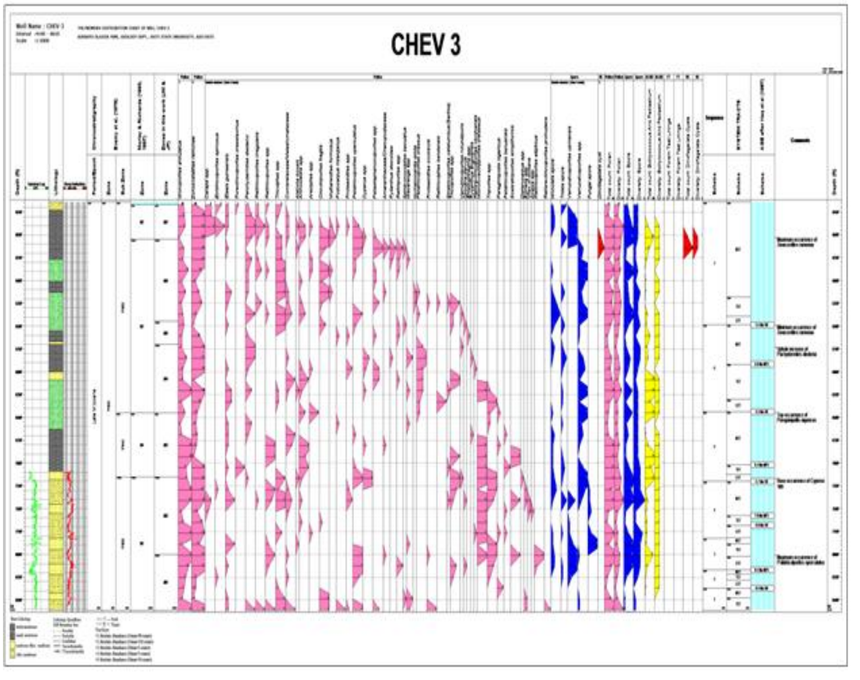
Fig-4. Correlation of the Depositional Sequences in Chev-1, 2, 3

MFS = Maximum Flooding Surface, TST = Transgressive Systems Tract, HST = Highstand Systems TractLST = Lowstand Systems Tract, SB = Sequence Boundary.

Palynostratigraphic Charts




CHEV-2


CHEV 3