PALYNOFACIES, LITHOFACIES AND SEQUENCE STRATIGRAPHY OF THREE H-WELLS, OFFSHORE WESTERN NIGER DELTA BASIN, NIGERIA

BY

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PhD/SPS/2015/652

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SEPTEMBER, 2021

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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL, FEDERAL UNVERSITY OF TECHNOLOGY, MINNA, NIGERIA, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY (PhD) IN GEOLOGY (BIOSTRATIGRAPHY OPTION)

SEPTEMBER, 2021

ABSTRACT

The study investigated the palynofacies, lithofacies and sequence stratigraphy of three wells located within shallow offshore of the Western Niger Delta Basin in Nigeria. The data utilised in the study were obtained from three wells named HA-001, HB-001 and HD-001. The study aimed at improving present correlatable biostratigraphic zones in the shallow offshore of the Western Niger Delta Basin. Seventy-six, ninety-six and seventy-seven ditch cutting samples within the depth intervals of 750-11610 ft, 4100- 13160 ft and 4875-12090 ft in HA-001, HB-001 and HD-001 respectively were analysed. The standard acid palynological method of sample administration for palynofacies, integration of wireline log motifs and distribution of index accessories for sedimentological attributes, paleoenvironmental and sequence stratigraphic studies, palynofacies colours for thermal maturity were employed. The study established two new assemblage biozones namely *Cyperaceaepollis* sp. – *Nympheaepollis clarus*, and *Stereisporites* sp. within the sedimentary intervals penetrated in the wells. The *Cyperaceaepollis* sp. – *Nympheaepollis clarus* biozones were further subdivided into *Nympheaepollis clarus – Echitriletes pliocenicus and Cyperaceaepollis* sp. – *Elaeis guineensis* subzones. The Late Miocene age is associated with the biozones. Colours of palynomacerals recovered indicated that thermal organic maturity ranges from optimum petroleum generation to early gas generation. The lithologic, textural and wireline log data indicated that the intervals studied in the HA-001 well belong to the Benin Formation and Agbada Formation, while HB-001 and HD-001 belong entirely to Agbada Formation. Index minerals and accessories are dominated by ferruginous materials, glauconite pellets, carbonaceous detritus, shell fragments and pyrites plus minor mica flakes. Lower delta plain, delta front and prodelta environment of deposition were inferred for the studied well intervals under changing dry and wet paleoclimate. The palyno-ecological groupings consisted of freshwater taxa 41.17%, mangrove taxa 37.64%, savanah taxa 16.38%, rainforest taxa 4.77% and montane taxa 0.07%; freshwater taxa 46.06%, mangrove taxa 27.38%, savanah taxa 21.26%, rainforest taxa 3.29% and montane taxa 1.07%; freshwater taxa 58.80%, mangrove 17.45%, savanah taxa 16.77%, rainforest taxa 4.77% and montane taxa 0.56% in the three studied wells respectively. Sand bodies which represent sub-environments within these settings are deposited in sequences. The systems tracts recognised are Lowstand Systems Tracts (LST), Transgressive Systems Tracts (TST) and Highstand Systems Tracts (HST) with stratigraphic surfaces such as Sequence Boundary (SB) and Maximum Flooding Surface (MFS). Four MFS (9.5 Ma), (7.4 Ma), (6.0 Ma) and (5.0 Ma) were identified within the studied intervals by matching with existing global palynostraticgraphic zonation scheme and global eustatic curve. The Lowstand Systems Tracts (LST) and the Highest Systems Tracts (HST) are potential hydrocarbon reservoirs. A good correlation existed in the wells due to similarities in the lithofacies, stratigraphic surfaces and palynostratigraphic zones. Two new biostratigraphic biozones were firmly established and they belong to Highstand Systems Tracts (HST) which are potential hydrocarbon reservoirs. These biozones are assigned Late Miocene age.

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ABBREVATIONS/GLOSSARIES AND SYMBOLS

CNL	Compensated Neutron Log
FDO	First Downhole Occurrence
Ft	Feet
HCl	Hydrochloric Acid
HF	Hydrofluoric Acid
HNO	Nitric Acid
HST	Highstand Systems Tracts
LDO	Last Downhole Occurrence
LDT	Lithodensity Log
LST	Lowstand Systems Tracts
Ma	Million Years
PM	Palynomacerals
SB	Sequence Boundary
Sp.	Species
TST	Transgressive Systems Tracts

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

The onshore Niger Delta Basin has become mature and its exploration has shifted to offshore. The integration of various geological methods such as palynological, palynofacies, paleoenvironmental and sequence stratigraphic analyses are needed for the understanding of the subsurface geology and development of its hydrocarbon potentials. The occurrence of hydrocarbon in Niger Delta Basin has increased the interest of many researchers in the sedimentologic and biostratigraphic characteristics of the basin. The discovery of commercial deposits of hydrocarbon in 1956 began the establishment of the Niger Delta as a world-class petroleum province (Kulke, 1995).

The science of petroleum exploration and production is multi-disciplinary with each discipline complementing each other. One of these disciplines is palynology, coined by Hyde and Williams in 1944 and defined by Erdtman (1969) as the study of pollen and spores of plants. Both pollen and spores share a few common characteristics such as being produced as a result of meiotic cell division. They also possess a wall that is remarkably resistant to microbial attack. This is due to the presence of Sporopollenin in their exine. The abundance of forms of pollen and spores can be used to determine biostratigraphic sequences, establish correlations and make paleoenvironmental reconstructions. Palynological analysis includes palynofacies (kerogen) analysis and palynomorph analysis.

Palynofacies was first conceptualized by Combaz in 1964 to describe the quantitative and qualitative palynological study of the total particulate organic matter assemblage. Palynofacies analysis involves the identification of individual palynomorph, plant debris and amorphous components, their absolute and relative proportions, size spectra and preservation states (Combaz, 1964 and 1980)

Kerogen is the most commonly used term to describe the particular organic matter. Durand (1980) and Brooks (1981), highlighted various definitions of this term. It is used to explain the dispersed particulate organic matter of sedimentary deposits that is not soluble in hydrochloric (HCl) and hydrofluoric acids (HF). Palynomorphs, phytoclasts and amorphous organic matter are the three main groups of morphorlogical constituents that can be recognized within kerogen assemblages. Palynomorph refers to all HCl and HF resistant organic-walled microfossils. Phytoclast was introduced by Bostick (1991) to explain all dispersed clay to fine sand-sized particles of plant derived Kerogen (Jansonius and McGregor, 1996).

Some of the uses of palynofacies include; identification of regressive-transgressive trends in stratigraphic sequence, characterization of the depositional environments, deriving correlations at levels below biostratigraphic resolution and producing detailed organic facies models.

Lithofacies is explained as basic genetic unit which are distinguished by same sedimentary texture and lithology, which can reflect specific hydrodynamic conditions. Miall (1985) proposed lithofacies grouping method and employed lithofacies nomenclature to classify sedimentary texture and lithology of rocks, which enabled a convenience for the study of sedimentary facies. Lithofacies analysis is the basis for studying architectural texture element of sedimentary sand bodies (Fryirs and Brierley, 2013). With the extensive application of this method of architectural texture element analysis (Zhang *et al.*, 1994), depositional systems are interpreted. Lithofacies classification involves; characteristics of colour, grain size, sedimentary texture and sorting. In lithofacies nomenclature, selecting too few lithofacies attributes to distinguish different lithofacies should be avoided. According to Compbell and Hendry (1987), the main attribute for lithofacies analysis are sedimentary texture and grain size.

Based on available data, sequence stratigraphic interpretation can yield a great geological model. Well-log interpretation may generate detailed results on lithologies and depositional systems. Fossil data may be used to delineate sequence boundaries, chronostratigraphic surfaces, condensed sections and climatic conditions. Therefore, each discipline coupled with integrative efforts are needed to produce this model.

The most vital surface in sequence stratigraphy is the sequence boundary. When sea level falls below coastal sediments, sediments from fluvial origin will spread out to the basin where deposition takes place due to availability of more accommodation space. This allows weathering and erosion of nearshore coastal sediments resulting in an unconformity called the sequence boundary (Coe, 2005). As a result of relative sea level fall, the occurrence of marine sporomorphs and amorphous organic matter decreases. The amount of the land derived sporomorphs and phytoclasts increase (Carvalho *et al.*, 2006).

As there is an increase in sea level after a lowstand, the rate of increase continues to a point where the rate of increase in accommodation space is more than the sediment influx. This relative increase in sea level produces the first major marine flooding surface known as a transgressive surface. This surface is characterized by the change in deposition from progradational or aggradational parasequence to a retrogradational or landward parasequence (McLaughlin, 2005; Coe, 2005).

The maximum flooding surface tops the transgressive surface and indicates the most landward position of the shoreline. It is the surface where marine encroachment has gone greatest distance beyond the shelf Retrogradational stacking pattern changes to aggradational or progradational. High levels of bioturbation, glauconite, phosphate, organic matter and deep marine fossils are signatures of the maximum flooding surfaces due to slow sedimentation rates. Amorphous organic matter are increased and amount of phytoclasts are reduced (Carvalho *et al.,* 2006).

Lying on top of the sequence boundary is the lowstand systems tract and it marks the end of the sea level fall and the time before sea level rise, leading to the most basinward shift in facies. The characteristic stacking patterns are aggradational or slightly retrogradation. The lowstand systems tracts is bound at the base by the sequence boundary which is the maximum level of exposure and erosion of underlying strata. Older fossiliferous sediments can be exposed to erosion by relative sea level fall, leading to the occurrence of reworked biofacies once there is relative increase in sea level. Abundant terrestrial pollen can be found in marine lowstand deposits due to fluvial transport of organic material to oceanic basin (McLaughlin, 2005).

A rise in relative sea level leads to the deposition of the trangressive systems tract and a landward shift in facies. The top of transgressive systems tract is marked by the maximum flooding surface and the base marked by the transgressive surface. The rate of increase in accommodation space surpasses the sediment supply during this period leading to a retrogradational stacking patterns of sediments. The base of the maximum flooding surface is the highstand systems tracts while the sequence boundary bounds these systems tracts at the top. There is a decreasing accommodation for sediments indicating a period of a slowing rate of relative sea level rise. The amount of sediment being supplied exceeds the volume of accommodation space, leading to a progradation of the shoreline basinwards and a change upward from aggradational to progradational stacking pattern (Catuneanu, 2006; McLaughlin, 2005 and Coe, 2005).

1.2 Statement of the Research Problem

Industry workers in the Niger Delta Basin have relied on usage of alpha-numeric method for biozonation purposes while some researchers have also used the same method to establish their biozones (Evamy *et al.*, 1978; Morley and Richards, 1993; Ajaegwu *et al.*, 2012 and Olayiwola and Bamford, 2016). Hence, standardised biozonation scheme which is in line with the international stratigraphic guideline for the establishment of biozones is necessary.

Some researchers made use of only palynomorphs to analyse paleoenvironment of deposition in the Niger Delta Basin (Oyede, 1992; Bankole, 2010 and Bankole *et al.*, 2014). Tyson (1995), Durugbo (2013), Chukwuma-Orji *et al* (2017) and Okeke and Umeji (2018). explained the usage of palynofacies in analysing paleoenvironment of deposition. Research works on palynomorphs and palynofacies for paleoenvironmental analysis are quite limited. Published works on the integration of pollen and spores' biostratigraphy and biozonation, palynofacies, sedimentology and sequence stratigraphy of the Tertiary Niger Delta Basin are scarce to few.

Generally, there are no complete basin wide microfossils biozones for the Niger Delta Basin due to the structural dynamics, varied sedimentation pattern and paleoenvironment of deposition during the basin evolution. The palynology, sedimentology and sequence stratigraphy will therefore provide new insights into the subsurface geology of the study area.

1.3 Justification for the Research

Research works on biostratigraphy and sequence stratigraphy in the prolific Niger Delta Basin are still ongoing. Palynostratigraphic zones should be established in conformity with international stratigraphic guide. This will enable generation of standard biozonation schemes in the Niger Delta Basin. Exact delineation of system tracts, biozones and correlation are necessary for the discovery of bypassed hydrocarbons to ensure a favourable exploration of both thin and thick reservoirs.

The study attempts a classification of biostratigraphic zones using internationally accepted standard guidelines while incorporating palynofacies and sedimentological data with those of wireline in order to achieve a proper stratigraphic sequence and correlation across the HA-001, HB-001 and HD-001 wells in the Niger Delta Basin.

The need for an integrated approach using palynofacies, sedimentology, wireline logs and sequence stratigraphy in the exploration of petroleum for a more favourable outcome has necessitated this research work.

1.4 Aim and Objectives of Study

The aim of the research is to carry out palynofacies, lithofacies and sequence stratigraphic interpretations of the studied wells in the Niger Delta Basin with the view of developing the application of biostratigraphy in exploration activities which has drifted into offshore region. The following are the objectives:

i. Extract palynomorphs and palynofacies;

ii. Produce a palynostratigraphic zonation of the wells using their microfloral contents;

iii. Assign ages to the strata penetrated by the three wells using their palynomorph contents;

iv. Determine the maturation of the well intervals with palynofacies analysis;

v. Infer the paleoenvironment of deposition of the strata penetrated by these wells using palynomorphs, wireline log motifs, sedimentological attributes and palynofacies;

vi. Generate a sequence stratigraphic framework for the three studied wells from Niger Delta Basin;

vii. Correlate the three wells with the aid of microfloral, lithofacies and depositional sequences

1.5 Location of Study Area

HA-001, HB-001 and HD-001 wells lie within latitudes 4º 09' 10.9" N, 4º 08' 48.6" N and 4º 05' 59.6" N and longitudes 6º 14' 1.8" E, 5º 58' 40.5" E and 6º 24' 28.6" E respectively within the shallow offshore area, western Niger Delta Basin, Nigeria.

The names of the wells have been coded by Shell Production and Development Company due to proprietary reasons. The location of the wells is shown in Figure 1.1.

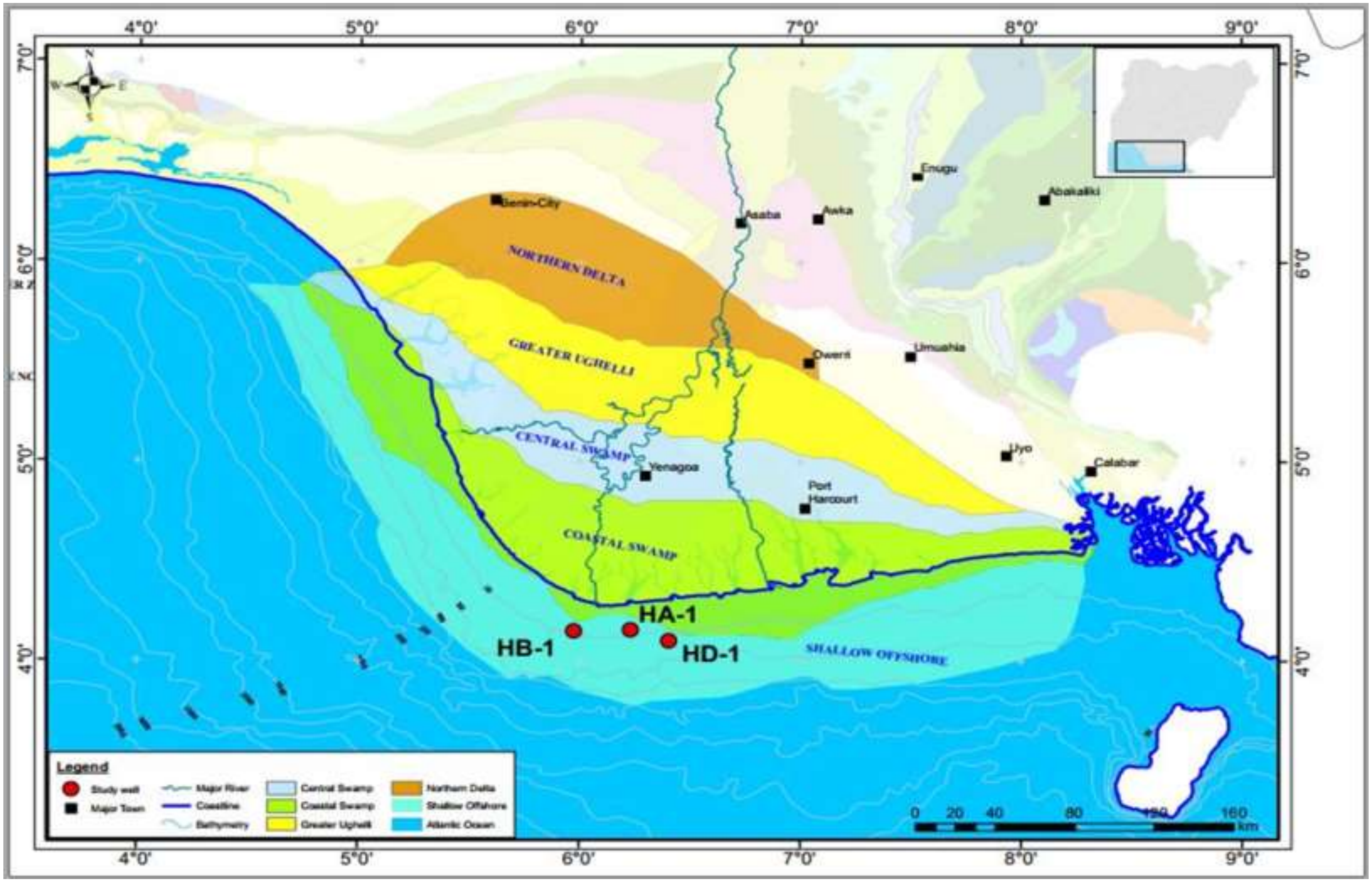


Figure 1.1: Location Map of the study area within the shallow offshore depobelt of the Niger Delta Basin (Modified after Samuel, 2009; Oluwajana, 2019)

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Previous Works

The initial contributions to our knowledge of microflora in Nigeria were made by Van Hoeken-Klinkerberg (1964, 1966) and Clarke (1966). Clarke (1966), identified *Peregrinipollis nigericus* as a new species in the Upper Tertiary Niger Delta Basin, similarly, Clarke and Frederiksen (1968) recovered and described eight new species of pollens and assiged to three new genera *Marginipollis, Areolipollis* and *Nummulipollis* in the sediments of Late Tertiary strata in Nigeria. They concluded that these forms are related to modern families Acanthacea and Lecythidaceae.

The most comprehensive contribution to our knowledge on Palynology of the Niger Delta Basin was made by Germeraad *et al.* (1968). Their study was based on the palynomorph assemblages of the Tertiary sediments of three tropical areas: parts of South America, Asia and Africa (Nigeria). Based on selected zonal marker species, they recognized three major zones: Pan-tropical, Trans-atlantic and Intracontinental zones.

The established pan-tropical zones are:

i. *Proxapertites operculatus* zone (Senonian-Eocene)
ii. *Monoporites annulatus* zone (Middle Eocene)
iii. *Verrucatosporites usmensis* zone (Upper Oligocene)
iv. *Magnastriatites howardi* zone (Upeer Oligocene-Lower Miocene)
v. *Crassoretitriletes vanraadshooveni* zone (Upper Lower Miocene)
vi. *Echitriocolporites spinosus* zone (Middle Miocene - Recent)

The *Proxapertites operculatus* and *Magnastriatites howardi pan-tropical* zones were further subdivided into five transatlantic zones:

i. *Proteacidites dehaani* zone (Senonian)

ii. *Retidiporites Megdalensis* zone (Paleocene)

iii. *Retibrevitricolporites triangulatus* zone (Lower Eocene)

iv. *Cicatricosisporites dorogensis* zone (Oligocene)

v. *Verrutricolporites rotundiporis* zone (Lower Miocene)

Ajaegwu *et al.* (2012) carried out palynostratigraphic and paleoenvironmental studies of eastern Niger Delta Basin. The diagnostic palynomorphs recovered permitted the zonation and dating of the analyzed sections. The First Appearance Datum (FAD) of *Nymphaeapollisclarus* and increase in *Monoporitesannulatus* were utilized in assigning Late Miocene to Early Pliocene age for the studied section. Paleoenvironmental interpretation of the strata penetrated by the well showed overall environment range from coastal to marginal marine.

Olajide (2013) analyzed the strata penetrated by CHEV-2 well in the offshore Niger Delta Basin and the sediments were deposited during the Miocene age. The stratigraphic range of *Relitricolporites irregularis, Psilatricolporites crassus, Echitricolporis spinosus, Zonocostites ramonae, Foveotricolporites crassiexius, Monoporites annulatus, Psilatricolporites operculatus, Multiareolites formosus, Podocarpus milanjianus* and some other marker species were used to demarcate five informal palyonological zones in his study area.

Ola *et al.* (2013) studied the palynomorphs from FB-1 well in the Niger Delta Basin and identified four informal biozones A, B, C and D based on the occurrence of fossil species: *Retitricolporities crassus, Racemonocolpites hians, Retibrevitricolporites obodoensis* and *Retribrevitricolprites protrudens*. The interval studied was deposited between Late Miocene and Early Pliocene. Five sequence stratigraphic significant surfaces: 7.4 Ma, 6.0

Ma, 5.0 Ma, 3.8 Ma and undated maximum flooding surface could be inferred from the interval studied.

Palynomorphs contents from Del-2 well in southwestern part of the Niger Delta Basin were used to date and deduce the depositional environment of its strata by Ojo and Gbadamosi (2013). A sequence stratigraphic interpretation was also attempted for some strata of the well. The strata penetrated are dated Early-Late Pliocene based on the occurrence of *Racemonocolpites hians Retistephanocolpites gracilis, Praedapollis obodoensis, Peregrinipollis nigericus, Mulliareolites formosus, Verrutricolporites rotundiporis and Gemmanocolpites* sp.. Three depositional environments, shallow, deep and open marine were deduced with the occurrence of *Monoporites annulatus* and *Zonocostites ramonae*. One candidate sequence boundary and three systems tracts were deduced to occur within the studied interval

Oloto (2014) recognized four dinocysts and two pollen and spores' zones respectively in the palynological studies of Igbomotoru-1 well, Niger Delta Basin. The pollen and spores zonations consisted of *Verrucatosporites usmensis* and *Magnastriatites howardi* zones. The zones have been subdivided into beds of Upper Miocene, Lower Pliocene and Upper Pliocene to Pleistocene age. Combined palynologic, maceral and sedimentological data indicate that deposition occurred close to shore in a marine environment that became progressively shallower up section.

According to Boggs (2006) and Reijers (2011), in cyclic lithofacies successions, two types are recognised based on the processes that form them. These are authocyclic and allocyclicsuccessions (Figure 2.1). Authocyclic successions are the results of local sedimentary

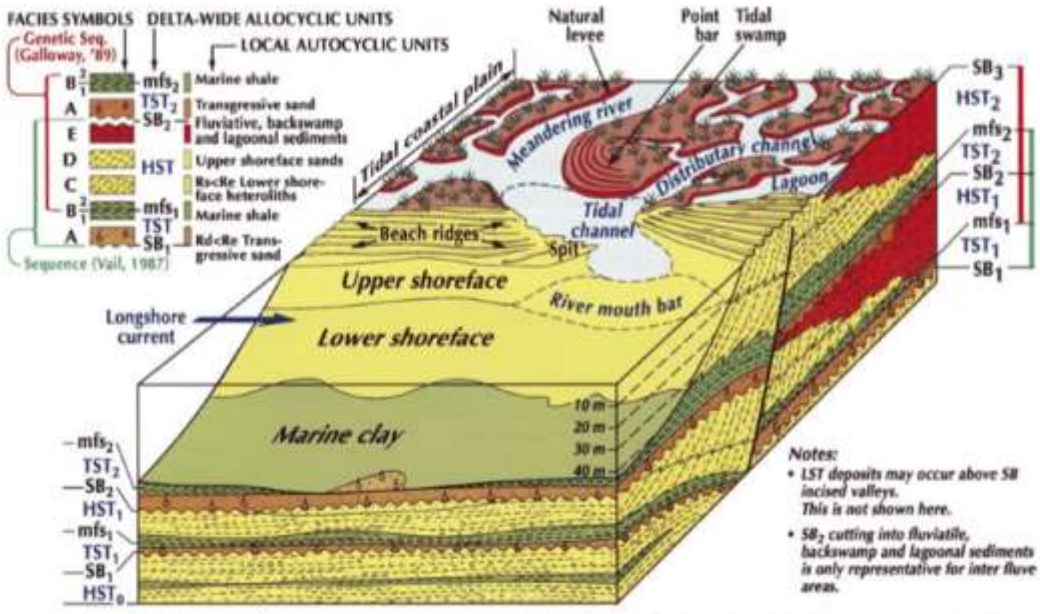


Figure. 2.1: Geomorphology, cyclic sedimentation and an active fault in the Tertiary Niger Delta coastal zone (Reijers, 2011)

processes which takes place within a basin. For instance, as switching delta lobe due to repeated progradation and retreat, channel meandering and delta avulsion. Their resultant beds are devoid of good lithostratigraphic continuity. On the other hand, allocyclic successions are controlled by variations in mechanisms that are external to the basin such as climate changes, tectonic movements and sea level flunctuations.

Adojoh *et al*. (2015) studied the palynocycles, palaeoecology and system tracts of Miocene Okan-01 well in Niger Delta Basin. The age was identified as Miocene based on the first and last appearance datum of *Verutricolporites rotundiporis* (BZ6), *Racemonocolpites hians* (BZ4), *Operculodinium centrocarpum* (BZ2), and *Magnastriatites howardi* (BZ1). Nine climatic cycles were recognised and used to infer the depositional cycles that indicate recurrent palynological sequences and vegetation changes based on the sea level changes. The wet cycles suggest highstand trangressive systems tracts while the dry cycles indicate lowstand systems tracts.

Atta-Peters *et al.* (2015) carried out palynofacies and source rock potential analyses on samples from ST-7H well, offshore Tano Basin. Five palynofacies associations were identified using relative abundances of palynomacerals. The oxygenation conditions of the depositional environments were determined subsequently. Aptian to Maastrichtian age have been confirmed using index palynomorphs.

Lucas and Ebahili (2017) studied the palynofacies of sedimentary intervals of Ogbabu-1 well in Anambra basin using sedimentologic and palynological criteria. Shallow marine environment of deposition was delineated for the studied intervals while the major lithologies encountered were sand and shale. The spore colour index of 4.5 confirms the source rock is immature for the generation of hydrocarbon within the studied interval.

2.2 Megatectonic History and Geology of the Niger Delta Basin

From the viewpoint of size and thickness of sediments, the Niger Delta Basin (Figure 2.2) is the most important sedimentary basin in Nigeria. Again, the region is also the most important from the economic standpoint as its petroleum reserves supply a large part of the country's foreign exchange earnings.

The Niger Delta Basin covers a land mass in excess of 105,000 km^2 (Avbovbo, 1978) and falls within longitudes 3° and 9° E and latitudes 4° and 6° N (Nwachukwu and Chukwura, 1986). It stretches in an East-West direction from southwest Cameroun to the Okitipupa Ridge. At its summit, it is situated southeast of the confluence of the Niger and Benue Rivers and bordered in the west by the Benin Flank and in the east by the Calabar Flank. It is bordered in the north by older tectonic elements such as the Anambra Basin, Abakaliki Uplift and Afikpo Syncline, and in the south by the Gulf of Guinea (Stoneley, 1966; Evamy *et al.,* 1978; Ejadawe, 1981). It is an arcuate shaped (Allen, 1965; Short and Stauble, 1967) and a prograding high energy constructive lobate delta (Whiteman, 1982).

It lies largely in the Gulf of Guinea to the Southwest of the Benue Trough and comprises the most important Cenozoic construction in the South Atlantic.

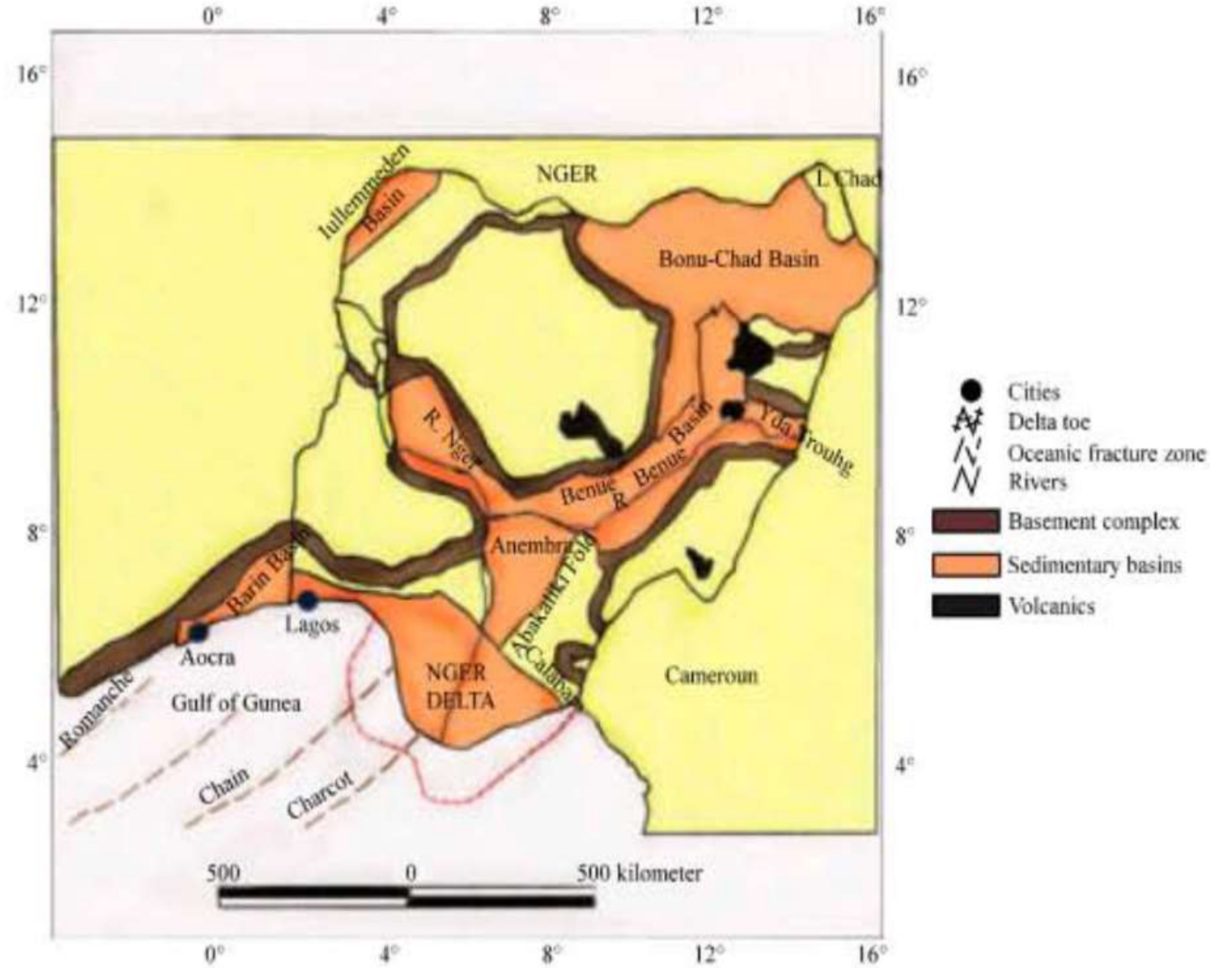


Figure 2.2: Regional Setting of Cenozoic Niger Delta Basin (Knox and Omatsola, 1989)

There is a general consensus that the present Niger Delta Basin is constructed on an oceanic crust from the pre-continental drift (Stoneley, 1966) which indicates an important overlap of NE Brazil on the present Niger Delta Basin series of geological and geographical observations such as the presence of a series of linear subdued and alternatively positive and negative anomalies beneath the Niger Delta Basin, interpreted by Burke *et al.* (1971) as seafloor spreading lineations (Mascle, 1976).

Three major rounds of sedimentation have been established in the Niger Delta Basin as well as other parts of the southern Nigerian Sedimentary Basin (Short and Stauble, 1967; Murat, 1972). These are the:

i. Lower Cretaceous to Santonian Cycle (oldest);

ii. Campanian to Paleocene Cycle; and

iii. Paleocene/ Lower Eocene to Date Cycle (youngest)

The third sedimentary round, beginning in the Paleocene/ Early Eocene, is accountable for the major part of the delta's growth. The Niger Delta Basin oil province with its money-making oilfields is restricted to the area enclosed by a thick sequence of rocks belonging to the youngest (Tertiary) sedimentary cycle. The three major dethronement environments typical of deltaic environments (marine, paralic and continental) are visible in the Niger Delta (Murat, 1972; Evamy *et al.,* 1978).

The delta is casted by a set of older, stable megatectonic elements (Figure 2.3). These are:

(a) The Benin Flank – which is the subsurface continuation of the West African Shield. It marks the NW rim of the basin. It is a gently plummeting monoclinal flank. It comes to an end along the NE – SW trending flexure or fault zone called the Benin Hinge Line.

(b) The Calabar Flank – is the subsurface extension of the Oban Massif. It marks the eastern fringe of the delta. It is comparable to, but more multifaceted than, the Benin Flank. It splits off along the Calabar Hinge Line which drifts Northwest – Southeast.

(c) The Senonian Abakaliki Uplift, and

(d) The Post-Abakaliki Anambra Benin: These units, positioned to the north of the delta through the Cenozoic.

The outlines of the Delta are restricted by the deep-seated faults along for example the Benin and Calabar Hinge Lines.

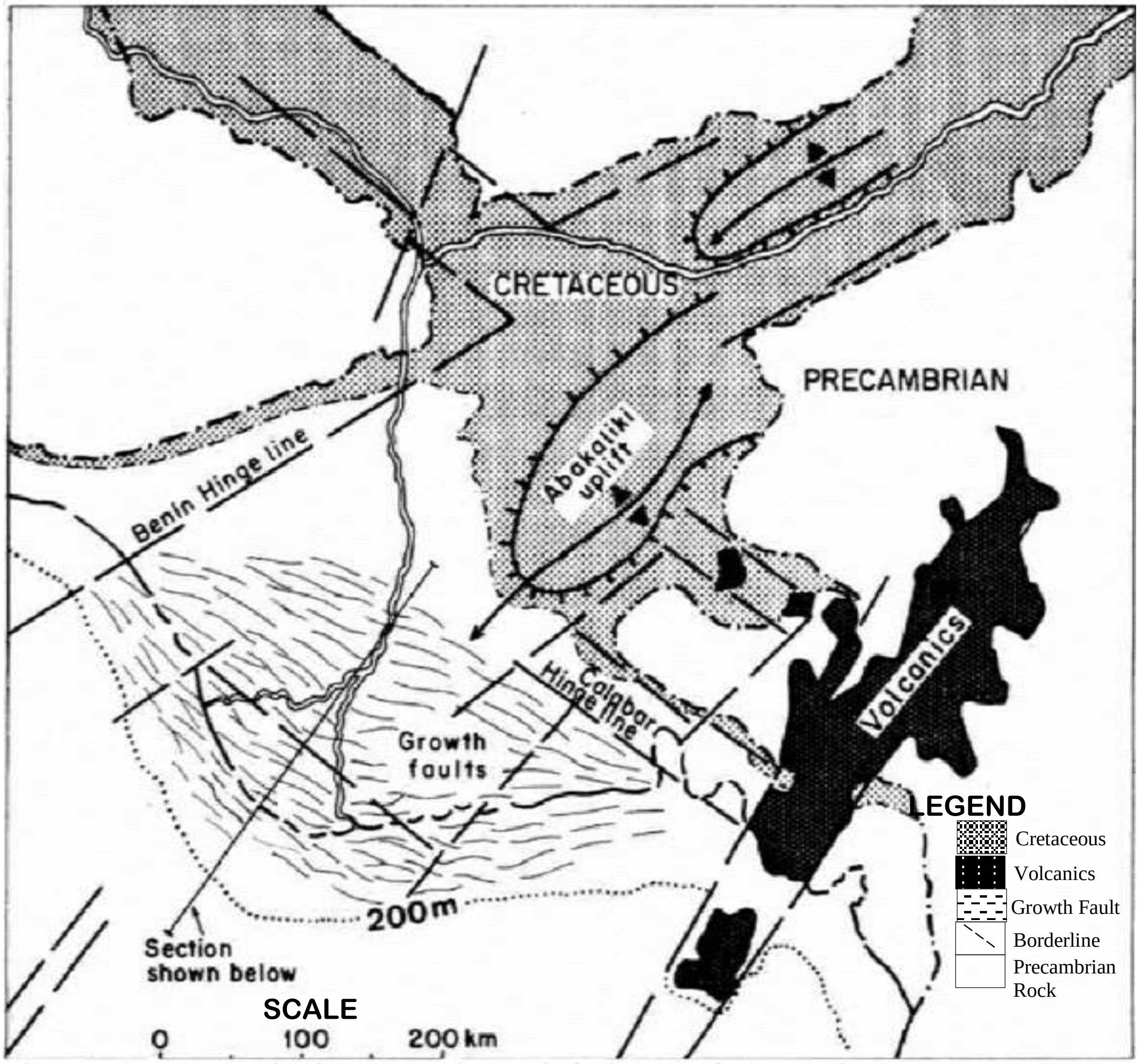


Figure 2.3: Megatectonic elements and growth fault area of Niger Delta Basin (Murat, 1972)

2.3 Stratigraphy of the Tertiary Niger Delta Basin

2.3.1 Introduction and Present-Day Deltaic Deposition

The Niger Delta Basin comprises an advance of terrestrial deposits into a high energy marine environment. At present, deposition comes about at the same time under fully terrestrial (fluviatile) conditions, under conditions where there is interaction between terrestrial and marine influences (paralic) and under fully marine conditions (Frankl and Cordry, 1967).

Consequently, a wide but thin lens of sediments of continental, gravely or very sandy terrestrial deposits take place, which alter seaward to sandy and clayey fluviatile and marine sediments, which in turn change into marine clays.

The history of the delta since its origin in the Paleocene/Early Eocene is one of a major deterioration with a gradual southward offlap of such macro lenses (Frankl and Cordry, 1967). Thus, the string starting with coarse sandy deposits and terminating with marine clays, is not only observed laterally, but is encountered also vertically in the Niger Delta Basin.

In cross-section (Figure 2.4) a time stratigraphic unit of such deltaic sediments is typically S–shaped or sigmoidal (Merki, 1972). The formations are therefore, strongly diachronous, their age becoming increasingly younger in a down drop direction and ranging from Paleocene to Recent.

2.3.2 Outcrops of the Tertiary Niger Deltaic Deposition

The Paleocene marine Imo shales, which envelopes a wide area of southern Nigeria, were overlain by lower Eocene deposits which are less maritime in nature. A creation typical of this development is the Ameki Formation, which comprises of sands, marls and limestone and which is not found in the eastern half of the delta. According to Frankl and Cordry (1967) in the middle to the upper Eocene, the Ameki Formation becomes sandier and is succeeded by the principally sandy Ogwashi-Asaba Formation of most likely Oligocene and Miocene age.

The sands, lignites, and occasional streaks of the Ogwashi-Asaba Formation are in turn overlain by the yellow and white continental sands and gravels of the Miocene to Recent Benin Formation.

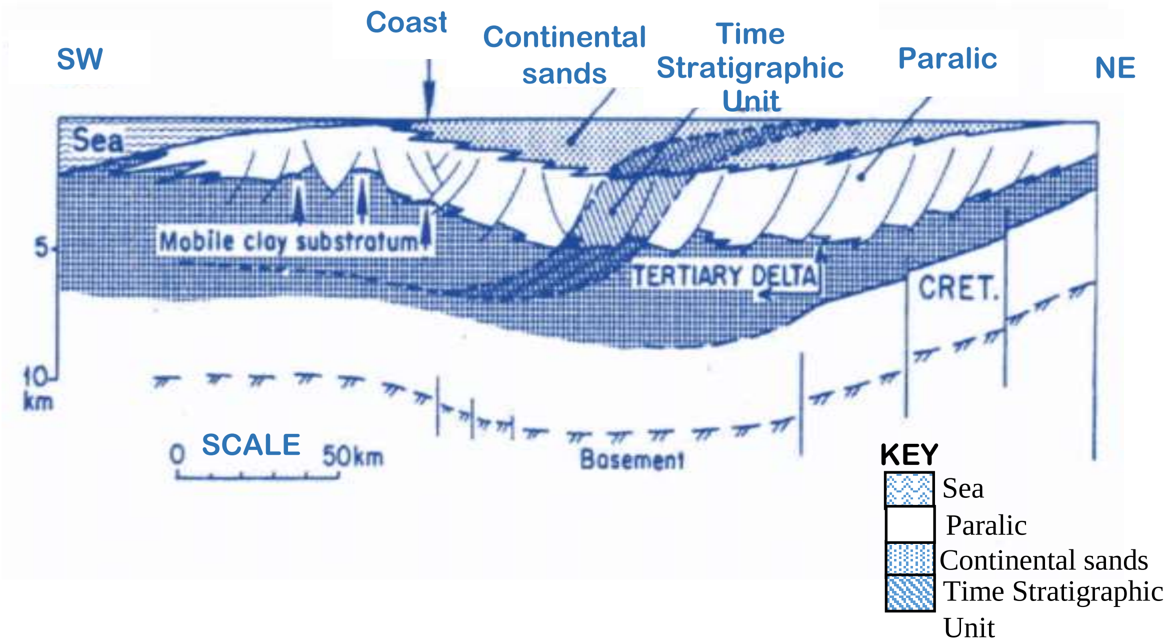


Figure 2.4: Schematic section perpendicular to the coastline (Merki, 1972)

From the above summary, it can be established that the same sequence recognised earlier for present day deposits (Figure 2.5) are continental to paralic to fully marine (from the surface, downdip). The same sequence has also been established for the beneath the surface deposits. Short and Stäuble (1967) have correlated the surface and subsurface formations (Table 2.1).

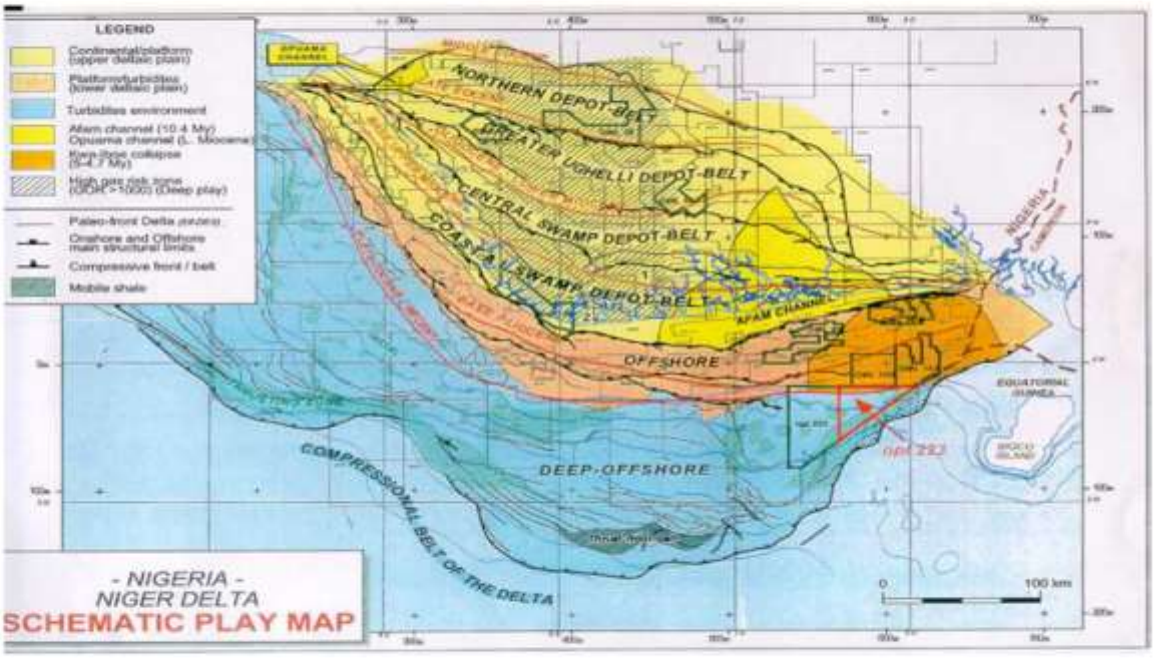


Figure 2.5: Present Terrain and Sedimentary Environment of Niger Delta Basin (After Merki, 1972)

Table 2.1: Correlation of Surface and Subsurface Formations of the Niger Delta Basin Complex (After Short and Stauble, 1967)

SUBSURFACE			SURFACE OUTCROPS		
YOUNGEST KNOWN AGE		OLDEST KNOWN AGE	YOUNGEST KNOWN AGE		OLDEST KNOWN AGE
RECENT	**BENIN FORMATION** **Afam Shale Memeber**	OLIGOCENE	PLIO/PLEISTOCENE	**BENIN FORMATION**	MIOCENE
RECENT	**AGBADA FORMATION**	EOCENE	MIOCENE EOCENE	**OGWASHI-ASABA FORMATION** **AMEKI FM**	OLIGOCENE EOCENE
RECENT	**AKATA FORMATION**		L. EOCENE	**IMO SHALE**	PALEOCENE
EQUIVALENTS NOT KNOWN			PALEOCENE MAESTRICHTIAN CAMPANIAN CAMP/MAEST.	**NSUKKA FM** **AJALI FORMATION** **MAMU FM** **NKPORO SHALE**	MAESTRICHTIAN MAESTRICTIAN CAMPANIAN SANTONIAN
			CONAICIAN/ SANTONIAN TURONIAN ALBIAN	**AWGU FM** **EZE AKU FM** **ASU RIVER GROUP**	TURONIAN TURONIAN ALBIAN

2.3.3 Subsurface Formations

The recognised Tertiary sequence in the Niger Delta Basin consists, in ascending order, of the Akata, Agbada and Benin Formations (Figure 2.6). The strata are made up of an estimated 8,535 m of section at the estimated depocentre in the middle part of the Delta.

Gravity and magnetic data showed that the maximum thickness lies in the area between Warri and Port Harcourt (Doust and Omatsola, 1990).

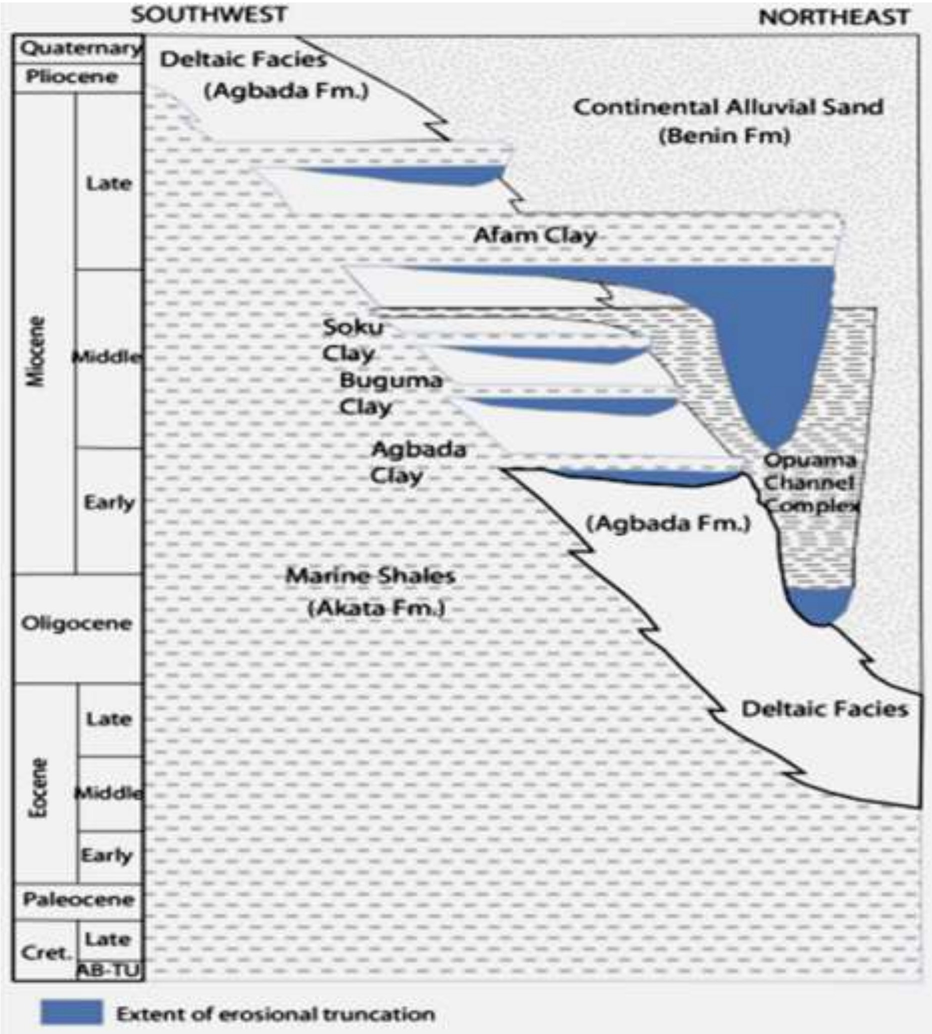


Figure 2.6: Stratigraphic Column showing the three Formations in the Niger Delta Basin (After Doust and Omatsola, 1990)

2.3.3.1 Akata Formation

This formation is typified by a uniform shale development as evidenced in Gamma and S.P. Logs. These prodeltaic shales are medium to dark grey, fairly, or at some places soft, gumbolike, and sandy or silty. The shales are less closely and firmly united or packed together and may include lenses of unusually high-pressured siltstone or fine-grained sandstone. Because most wells drilled in the Niger Delta Basin did not come across the bottom of the Akata Formation, an assessment of its thickness is possible only in the northern part of the delta where the Formation has been drilled through into the Cretaceous. The well drilled at the type section (i.e. Akata – 1 well) did not reach the Formation's bottom at the total depth of 3,680 meters.

Normally, Akata Formation contains abudant foraminiferal fauna. Planktic foraminifera may comprise more than 50% of the microfauna (Short and Stauble, 1967). The benthic foraminiferal collection indicates deposition of the shale on a shallow marine shelf. The known age of the formation ranges from Eocene to Recent (Asseez, 1976; Doust and Omatsola, 1990). However, it may be as old as the Paleocene.

2.3.3.2 Agbada Formation

This is made up of an irregular sequence of sandstones and shales of delta-front, distributary channel, and deltaic plain origin. The irregular string of sandstones and shales of the Agbada Formation has been revealed by Weber (1971) to be cyclical sequence of marine and fluvial deposits. The sandstones are medium to fine-grained, fairly clean and locally calcareous, glauconitic, and shelly. They comprise mainly quartz and potash feldspar with subordinate quantity of plagioclase, kaolinite, and illite. The shales are medium to dark grey, quite combined, and silty with local glauconite. They have mostly kaolinite (average value 75%) with small amounts of mixed-layer illite and montmorillonite.

At the middle part of the delta, the Formation reaches a maximum depth of 3,940 m and thins northward and toward the northwestern and eastern flanks of the delta. North of the Benin City – Onitsha – Calabar axis, the Agbada Formation is poorly developed or even not present at all. The shales of this formation contain microfauna which are best acquired at the bottom of individual shale units. The environment of these fossil assemblages ranges from littoral-estuarine to marsh types of fauna evolved at a water distance downwards of approximately 100 metres. The age of the Agbada Formation ranges from Eocene to Recent (Asseez, 1976).

2.3.3.3 Benin Formation

This formation is made up of mainly huge, very porous, freshwater–bearing sandstones, with local thin shale interbeds, which are rated to be of braided river origin. Mineralogically, the sandstones are made of dominantly quartz and potash feldspar and negligible quantity of plagioclase. The sandstones make up 70 to 100% of the formation. Where present, the shale interbeds more often than not contain some plant remains and dispersed lignite. The formation reaches a maximum thickness of 1,970 m at the Warri – Degema area, which concurs with that (i.e. depocentre) of the Agbada Formation.

Most companies exploring for oil in the Niger Delta Basin randomly describe the bottom of the Benin Formation by the innermost freshwater-bearing sandstone that shows high resistivity. However, Short and Stauble (1967) defined the base of the Benin Formation by the first marine foraminifera within shales, as the formation is non-marine in origin.

Avbovbo (1978) concurs with Short and Stauble (1967) and have also shown that the base of the freshwater in the delta sediments expands into the Agbada Formation and thus not coincident with the base of the Benin Formation. Composition, structure, and grain size of the sequence point to deposition of the formation in a continental almost certainly upper deltaic environment. The age of the formation varies from Oligocene (or earlier) to Recent (Asseez, 1976).

Beneath the surface of the eastern part of the Niger Delta Basin, a clay section, the "Afam Clay Member" is locally recognised. The member has the form of a canyon fill which strikes in a south – southeast direction, from somewhat north of Afam – 1 well to the west of the Imo River estuary. A maximum thickness larger than 8,000 m has been established for the member. No matching part to the Afam Clay Member is known in the recent (modern) Niger Delta Basin.

2.4 Depobelts and Structural Elements

Five offlapping siliciclastic sedimentation cycles have been asserted as being responsible for the deposition of the three beneath the surface Niger Delta Basin Formations – Akata, Agbada and Benin. These depobelts have widths ranging from 30 to 60 km and prograde southwestward 250 km over the oceanic crust into the Gulf of Guinea. They have been appropriately described by synsedimentary faulting that occurred in reaction to changing rates of subsidence and supply of sediment. The differences and alternatives of subsidence and sediment supply rates resulted in deposition of distinct depobelts. When further crustal subsidence of the basin could not be accommodated any longer, sediment deposition shifted seawards, forming a new depobelt.

Five major depobelts (Figure 2.7) are documented in the Niger Delta Basin Depobelt with each having its own sedimentation, deformation, and petroleum production history. The oldest is the northern delta province, superimposed comparatively shallow cellar. This depobelt has the growth faults that are described as the oldest, in general revolving with increase in seaward steepness. The second is the Greater Ughelli Depobelt.

The third, the central delta province swamp depobelt has well-articulated structures such as deeper rollover crest that shift seaward for any growth faults. It has two parts: Central Swamp Depobelts I and II, which are well known by some authors as distinct and separate depobelts.

The fourth depobelt, which is the Coastal Swamp Depobelt, is located in the far-away delta province. This is the most structurally multifaceted onshore depobelt owing to internal gravity tectonics on the modern continental slope. It also has two parts: Coastal Swamp Depobelts I and II also considered by some workers as separate entities.

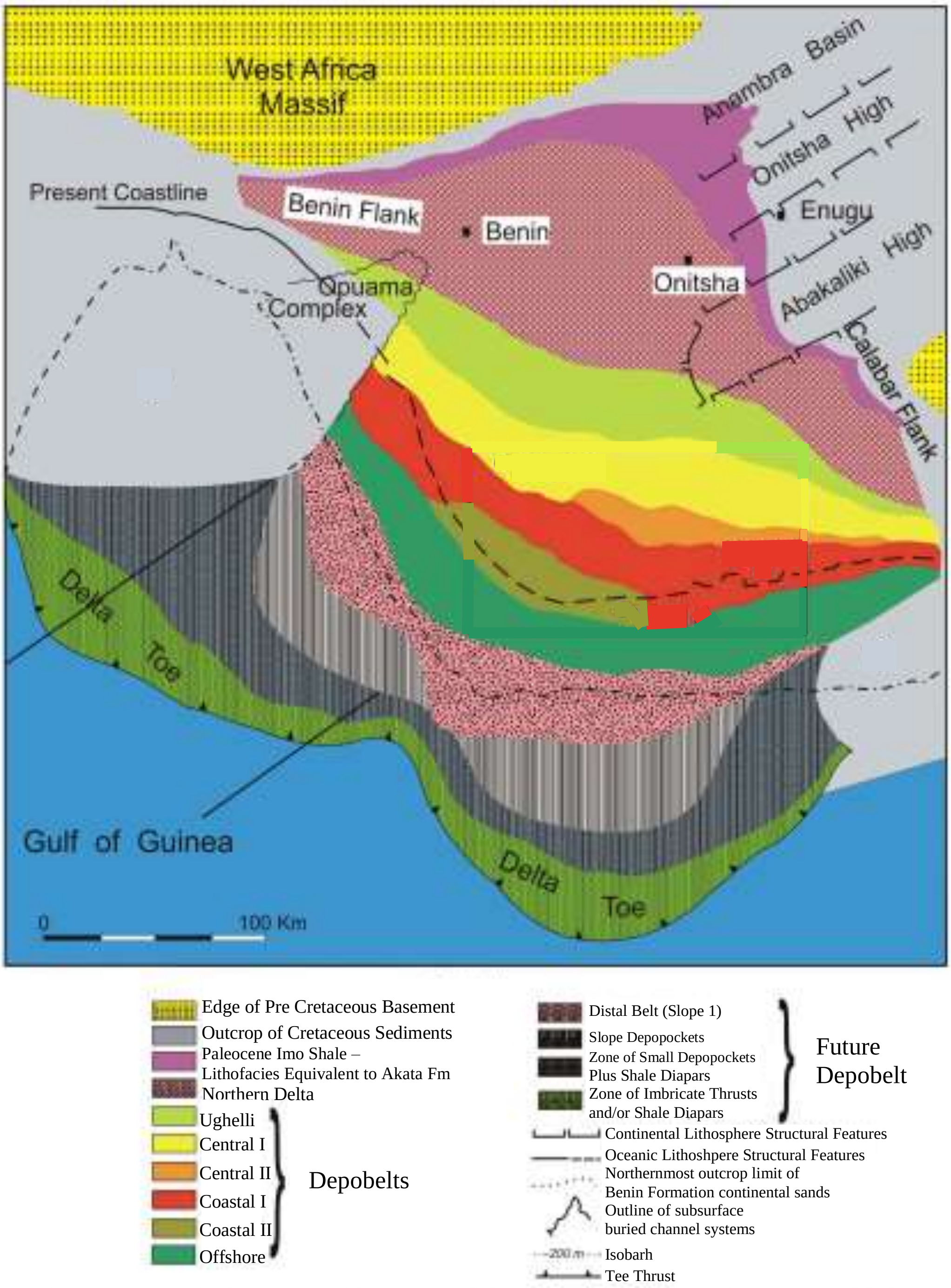


Figure 2.7: Regional Structural Elements and Depobelts of the Niger Delta Basin (Modified after Doust and Omatsola, 1990)

The fifth depobelt is the Offshore Depobelt. Again, this can be separated into Shallow Offshore and Deep Offshore Depobelts.

The delta sequence is deformed by synsedimentary faulting and folding. The processes and mechanisms involved in this deformation are still under active discussion. To understand the generation of the tectonic structures, the clay substratum (Akata Formation) must first be looked at closely. The great mass of marine clays of the Akata Formation, which underlie the fluviomarine and fluviatile deposits (of Agbada and Akata Formations), are under compacted and over-pressured. The clays contain free water and their bulk density is lower than the density of the overlying sands and compacted shales of the Benin and Agbada Formations. Differential loading of this "clay substratum" has formed gravitational instability to which the mobile clays reacted by lateral and upward flowage. This mechanism takes place beneath the surface of the Niger Delta Basin.

The deformation has affected the Akata and Agbada Formations. But the deposits are only affected by regional leaning due to behind schedule subsidence of downdip parts of the delta (Figure 2.8). The visible structures are growth faults and rollover anticlines connected with these faults on their downthrown (i.e. seaward) side.

The most common of beneath the surface structural phenomena on seismic reflection profiles is the growth fault (Figure 2.8). A growth fault can be defined as a fault that offset an active surface of deposition (Merki, 1972). It is qualified by thicker deposits in the downthrown block relative to the upthrown block (Weber, 1971). Deltaic growth faults vary from normal, 65^0 shear faults in the attitude of their fault planes. The main strike direction of these fault trends is in the region of parallel to ancient delta shorelines and seems to be free of the pattern of earlier fractures. The growth fault planes show a marked flattening with depth as a consequence of compaction.

A type of normal fault that develops and continues to move during sedimentation and typically has thicker strata on the downthrown, hanging wall side of the fault than in the footwall. Growth faults are regular in the Gulf of Mexico and in other areas where the crust is subsiding fast or being drawn apart.

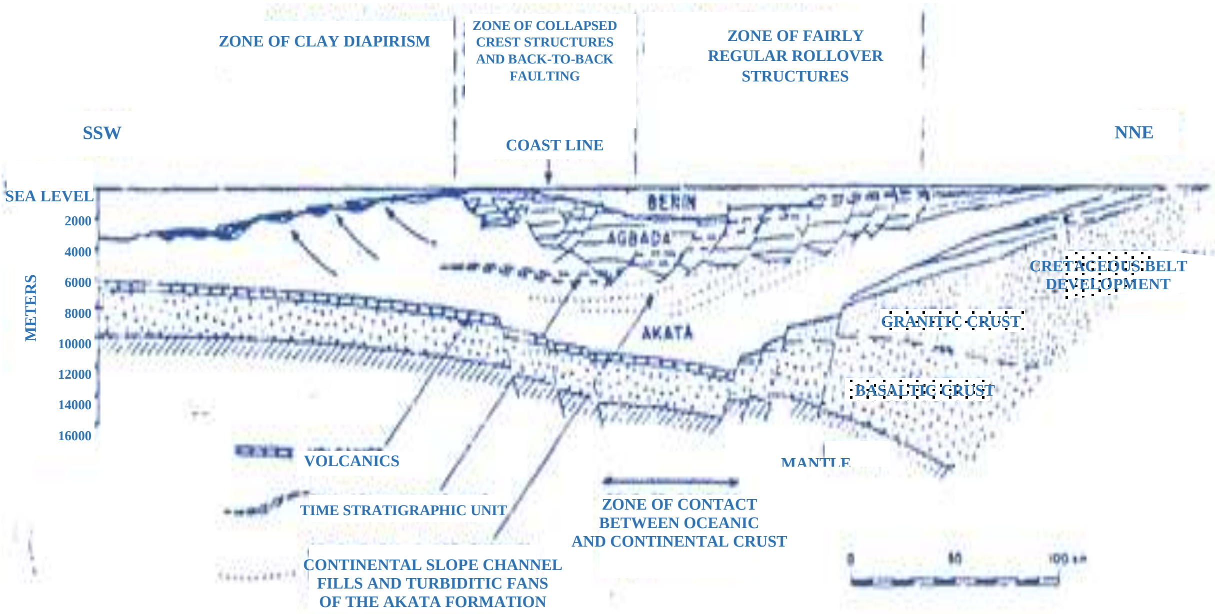


Figure 2.8: Schematic Dip Section of the Niger Delta Basin (Weber, 1971)

It has been established that the Niger Delta Basin growth faults have curved, concave upward fault planes. Movement along these fault planes results in warping of the sediments in the downthrown block in the fashion of an upturned drag along an axis analogous to the fault. This creates a so-called “rollover”, i.e. dip into the fault (Figure 2.9). Dip away from the fault may only occur at a later stage as a result of regional leaning. Gentle undulations along the axis of the structure supply closure in directions analogous to the fault (Merki, 1972).

Diapiric structures are present offshore on the continental slope. However, they are not confined to the Niger delta area as they crop up even south of Lagos. The nature of the diapirs remains hard to stipulate in the absence of drilling result. Delteil *et al.* (1974) preferred a clay-shale origin for these deformational structures (recall the under-compacted Akata Formation). However, Mascle *et al.* (1973) and Mascle (1976) anticipated instead that the large continental slope diapirs were made up of evaporates.

2.5 Economic Deposits

The Niger Delta Basin is one of the most prolific oil-producing areas in the world. According to Weber (1971), the delta is a more prolific province per unit of surface area than the Gulf Coast of Texas and Louisiana. Oil and gas are trapped by both rollover anticlines and by growth fault closures, the major reservoirs being the sands of the Agbada Formation. All commercial production of oil in the Tertiary Niger Delta Basin is thus from the deltaic sandstones of the Agbada Formation. The Benin and Akata Formations hold only several oil shows and gas stringers.

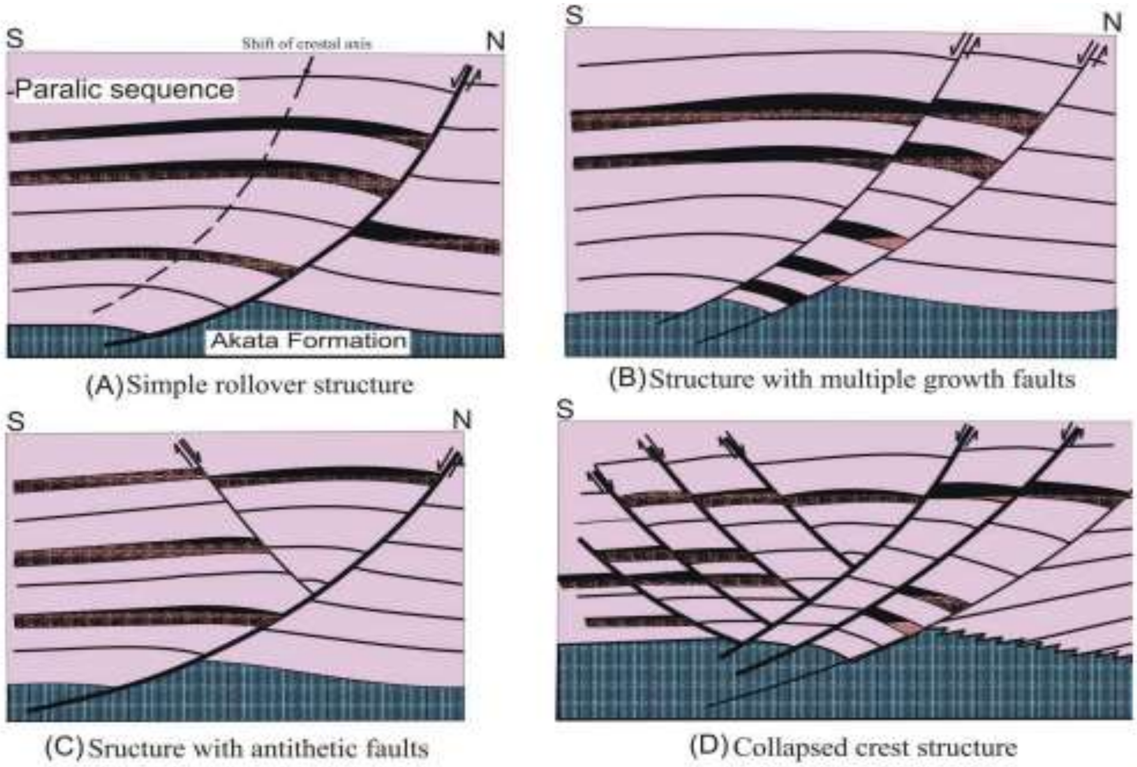


Figure 2.9: Principal types of oil field structures in the Niger Delta Basin with schematic indications of trapping configurations (Merki, 1972)

The source of the oil in the Niger Delta Basin is almost certainly the shales of the Akata Formation. Hydrocarbons generated in the Akata Formation in all probability migrated up dip through faults to build up in shallow reservoirs of the Agbada Formation. A school of thought, however, says some oil was generated from the shales of the Agbada Formation. Most of the oil currently being produced comes from strata of Miocene age (Frankl and Cordry, 1967; Weber and Daukoru, 1975).

In addition to petroleum, the allocation of fresh water bearing strata of the Niger Delta Basin is of substantial importance (Avbovbo, 1978). This is because these sections of the Benin and Agbada Formations later will be helpful in providing water to urban communities in the delta area.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

A total of two hundred and forty-nine (249) ditch cutting samples from three wells: HA-001, HB-001 and HD-001 within the intervals of 750 – 11600 feet, 4100 – 13160 feet and 4875 – 12090 feet respectively, were analysed for their palynomorphs and palynofacies contents. The other materials used are; beakers, weighing balance, liquid soap, brush, hot plate, potassium chlorate, 5 and 10 micron sieves, digital sonifier, water, pipette, cover slip, slide, optical adhesive, label, gloves and glass vial. Laboratory procedures involving samples preparation and analyses were carried out at Crystal Age Limited, Lagos, Nigeria.

3.2 Methods

3.2.1 Sample preparation for palynological analysis

Ten grammes of each sample were taken through numerous processes to extract the palynomorphs and palynofacies contents from the embedding sediments. The standard acid palynological techniques was employed as against the non-acid method which have been proved to be poor in palynomorph recovery (Riding and Kyffin-Hughes, 2006). The acid preparation techniques used are discussed in details below:

3.2.1.1. Hydrochloric acid treatment

Thirty milliliters of 10% HCl was added to each sample inside a plastic beaker and left in the fume cupboard till the following day. After decanting the acid, the samples were then washed with distilled water and sieved.

3.2.1.2. Hydrofluoric acid treatment

Thirty milliliters of 40% HF was added to the sample and left overnight in the fume cupboard so as to rid the samples of inorganic silicate. The sample was rinsed with distilled water thrice and then sieved using a 5 and 10 μm mesh sieves. A digital sonifier, which is an electric device, was used to filter away the remaining silicates, clay and mud.

3.2.1.3 Oxidation

Thirty milliliters of 60% HNO_3 was added to the sample residues and stirred, the mixture was left to oxidize for about three minutes as leaving it longer might cause reaction with palynomorphs present in the sample. Distilled water was then added to the sample to dilute the acid and then decanted after being left for about eight hours; the sample was then thoroughly rinsed with distilled water. The oxidation process was not done for palynofacies in order to avoid bleaching.

3.2.1.4 Centrifuging

Two drops of 10% HCl were added to acidify the sample and to enable its mixture with $ZnBr_2$ solution. All residues were then transferred into a centrifugal tube and centrifuged at a speed of 2500 revolutions per minute for five minutes. The top layer containing the palynomorph content was decanted into another labelled test tube while the remaining residue was further acidified, shaken, centrifuged and decanted. The residue was sieved with 5 and 10 μm sieves under slow running tap water. The residue on the sieve was carefully collected into a labeled test tube ready for mounting.

3.2.1.5 Mounting of the Slide

Each sample was first washed three times with distilled water, centrifuged and decanted then few drops of polyvinyl alcohol were added to the residue to remove the water present.

A cover slip of 32 mm by 22 mm was placed on the hot plate; a stirrer was then used to stir the residue for even distribution and to transfer some quantity of the residue to the cover slip on the hot plate and then left to dry. The cover slip was then placed on the labelled glass slide with few drops of Canada balsam used as the mounting medium. The glass slide was then left to dry. This process was used for each sample.

3.2.2 Observation and Identifying Techniques

The prepared slides for palynomorphs and palynofacies were studied, identified and counted under a light transmitted Olympus CX41 microscope using magnifications of x25 and x40 with relevant literature for description based on size, shape, structure, aperture and sculpture (Erdtman, 1952; Gonzalez-Guzman, 1967; Germeraad *et al*., 1968; Knaap, 1971; Legoux, 1978; Adegoke *et al*., 1978; Jan du Chene *et al*., 1978, Salard-Cheboldaef, 1975, 1976, 1978; Salami, 1983 and Agip, 1987). The classification scheme adopted for the microfloras encountered in this study was based on morphological forms (Figures 3.1 and 3.2). The morphological characteristics used are:

(i) types of apertures and their numbers

(ii) types of sculptural elements or ornamentation

The specimen name and the distribution were recorded on the analysis sheet while those palynomorphs with non-distinguishable features due to either fungal/bacterial attack, corrosion etc. were recorded as indeterminate pollen or spore.

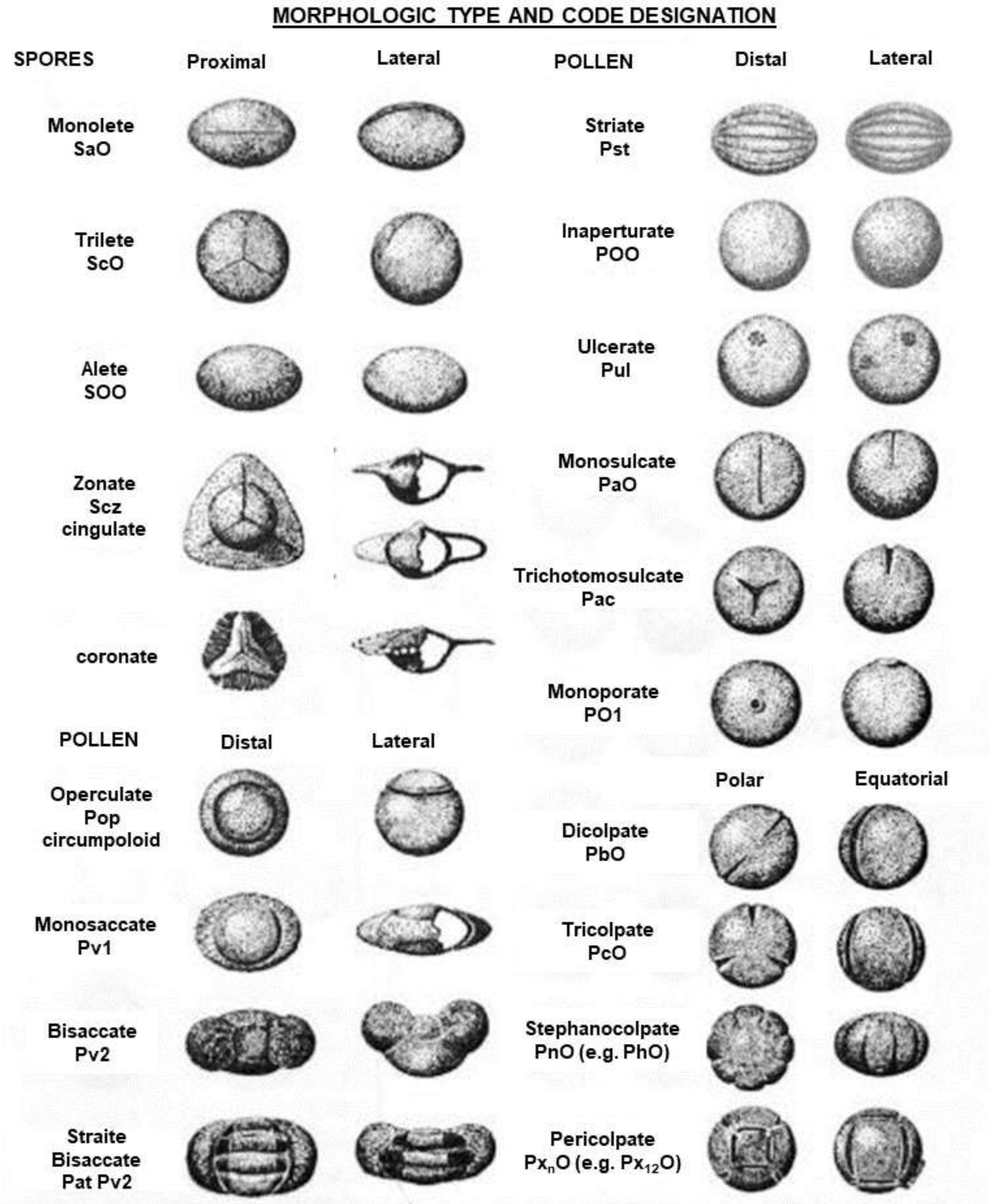


Figure 3.1: Pollen and spores morphological types (Traverse, 2007)

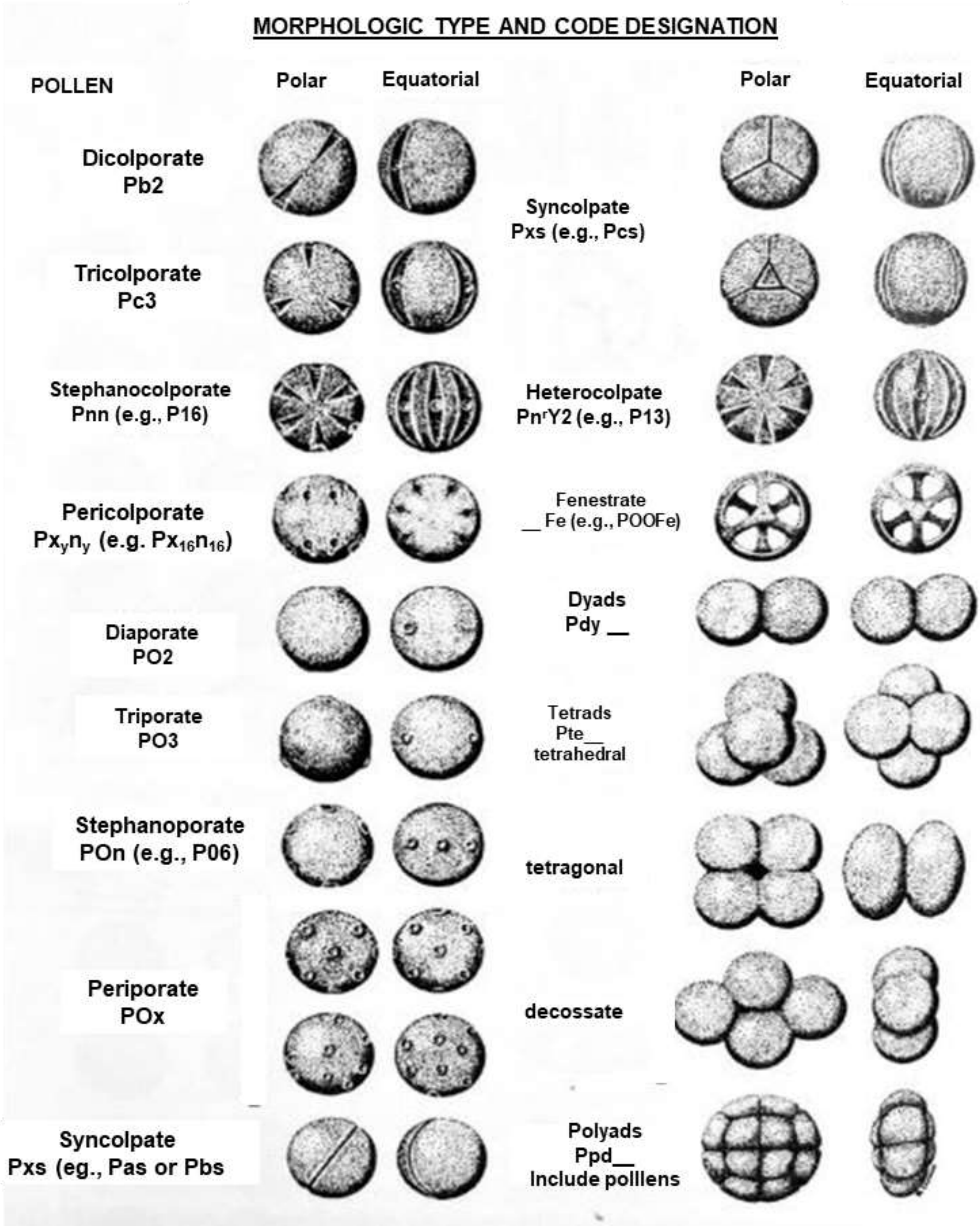


Figure 3.2: Pollen morphological types (Traverse, 2007)

Photographs of the palynomorphs and palynofacies were also taken using the attached Olympus DP12 digital camera. The recorded palynomorphs and palynofacies in the logging/analysis sheet were transferred into the computer for charting using the Stratabug biostratigraphic software. The resulting stratigraphic distribution chart was plotted on a scale of 1:8000 with the depth on the Y-axis and fossil distribution on the X-axis.

3.2.3 Palynostratigraphic Zonation

Detailed high resolution palynostratigraphic study was carried out on ditch cutting samples of the HA-001 (750-11510 ft), HB-001 (4100-13160 ft) and HD-001 (4870-12090 ft) wells. The palynostratigraphic biozonation of HA-001, HB-001 and HD-001 wells allows the delination of strata into biozones. A biozone is the fundamental unit of biostratigraphy defined by its characteristic and unique palynological markers within intervals of sedimentary strata. The recognised palynostratigraphic zones in this study were established by the International Stratigraphic Guide using the works of Murphy and Salvador (1999) and the North American Stratigraphic Code (Boggs, 2006). Figures 3.3 and 3.4 showed the major types of biozones as described by the authors.

3.3 Methods for Thermal Maturity Analysis

Diagenesis, catagenesis and metagenesis refer to immature, mature and postmature stages of maturation in terms of thermal evolution. During the 70s, palynofacies studies became a vital tool for assessing the hydrocarbon potential of sedimentary sequences. The composition of palynofacies and the colours of microflora preserved have been applied in the oil industries in determining the level of organic maturation and hydrocarbons source rock potentials.

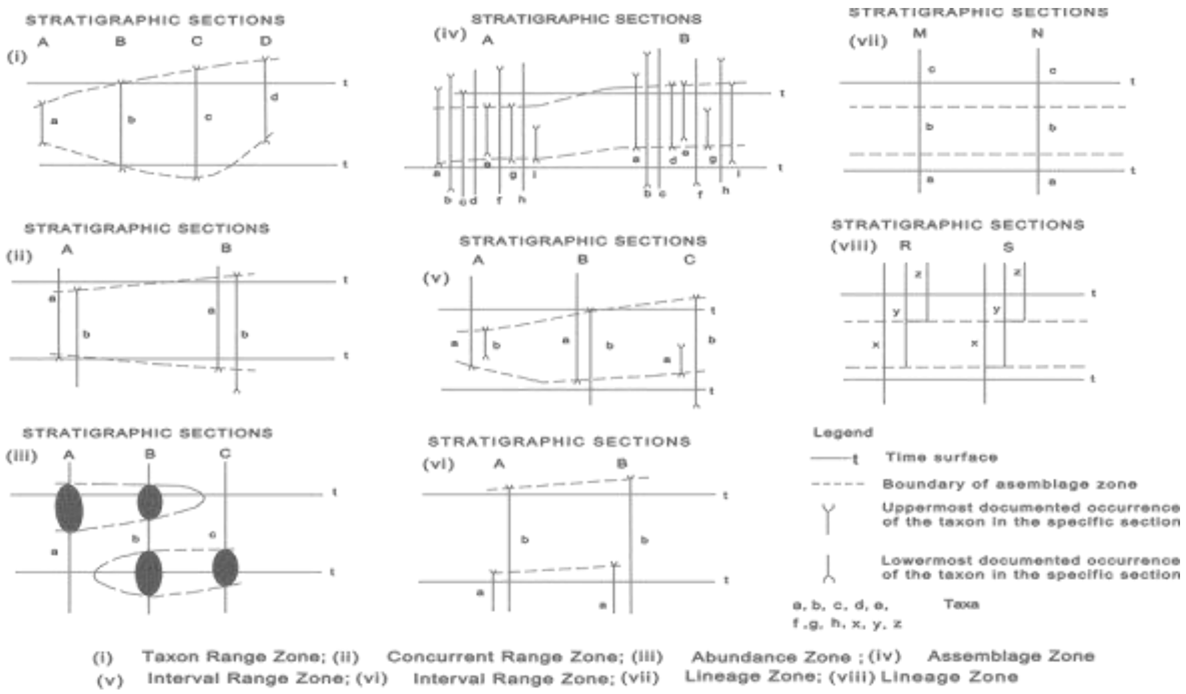


Figure 3.3 Principal types of biozones (Murphy and Salvador, 1999)

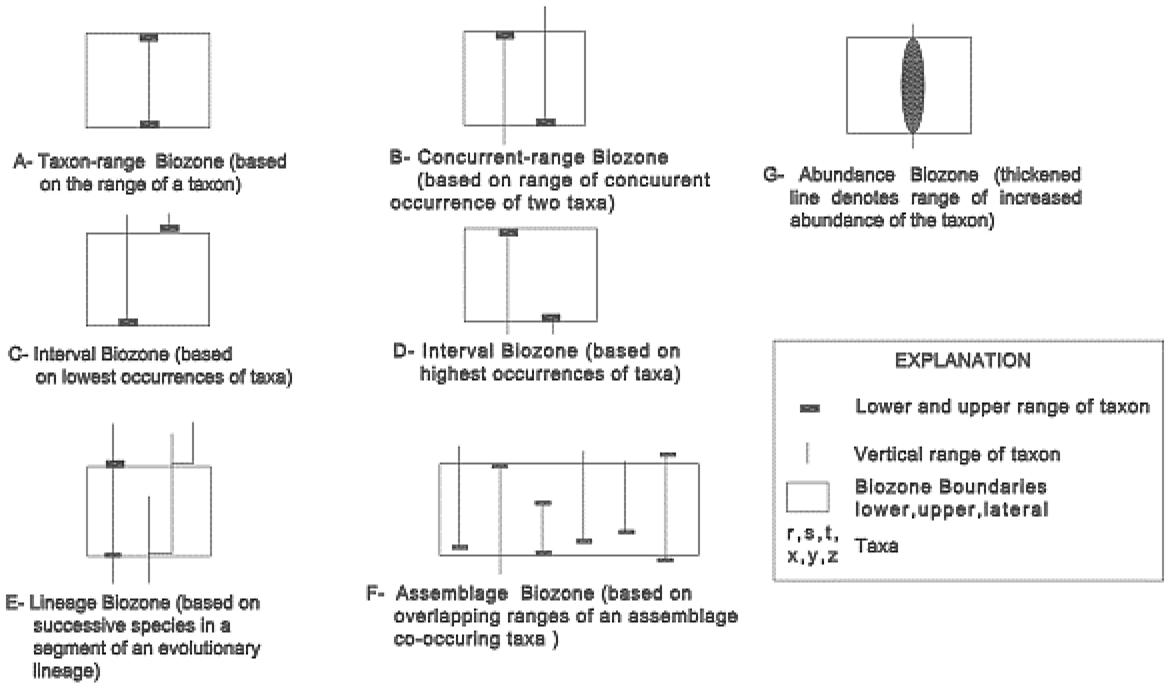


Figure 3.4: The different principal types of biozones (Boggs, 2006)

Microscopic study of dispersed organic matter under transmitted light during the 70s increased ideas in recognising the actual relation between the physical properties of dispersed organic particles and petroleum potential. The composition of palynofacies and the degree of thermal alteration of sedimentary rocks based upon changes in colour of miospores have been used in the oil industries in determining the level of organic maturation and hydrocarbon source rock potential. Staplin (1977), Dow (1977) and Batten (1981) showed that there are actual temperature points for the production of oil and gas.

However, a thermal alteration scale of Batten (1982) and Spore colour index chart of Pearson (1984) were adopted for this study (Figure 3.5). Palynofacies analysis is a fast, efficient and reliable method of determining hydrocarbon maturation level.

3.4 Sample Preparation for Lithologic and Sedimentological Analyses

The lithologic descriptions of the sedimentary successions of the three studied wells was done mainly by studying the Gamma Ray Log signatures, physical examination of the ditch cuttings samples and microscopic analysis of the washed samples.

3.4.1 Lithologic Description

Lithologic description was achieved through the physical examination of the samples and also by feeling between fingers. Fissile samples were observed to be shale while samples with fine to coarse grained sizes are the sandstone units. The lithologic description was made possible by the Gamma Ray and resistivity Logs because high and low values of Gamma Ray and Resistivity Logs denote shale and sandstone lithologies, respectively (Olayiwola and Bamford, 2016).

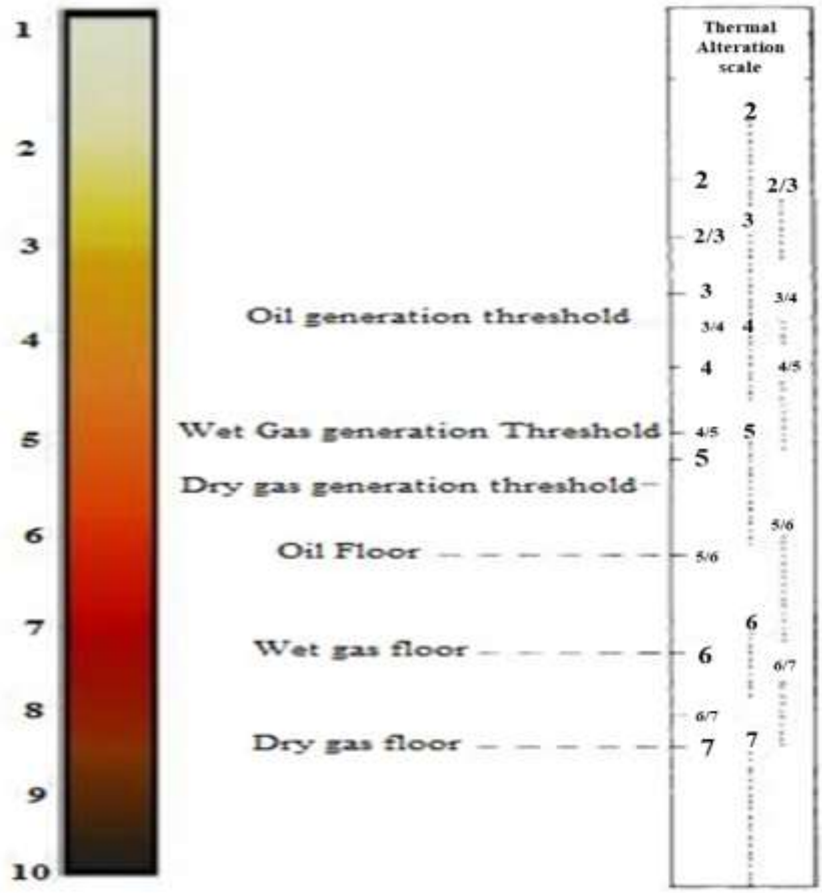


Figure 3.5: Relationship between thermal alteration and spore colour index of Batten (1982) and Pearson (1984) based on threshold of oil generation

The fining and coarsening upward signatures of the Gamma Ray patterns description by Sneider *et al.* (1978) and Beka and Oti (1995) were employed in this study (Figures 3.6 and 3.7). Funnel-shaped log patterns signify a coarsening upward trend and decreasing clay contents up section.

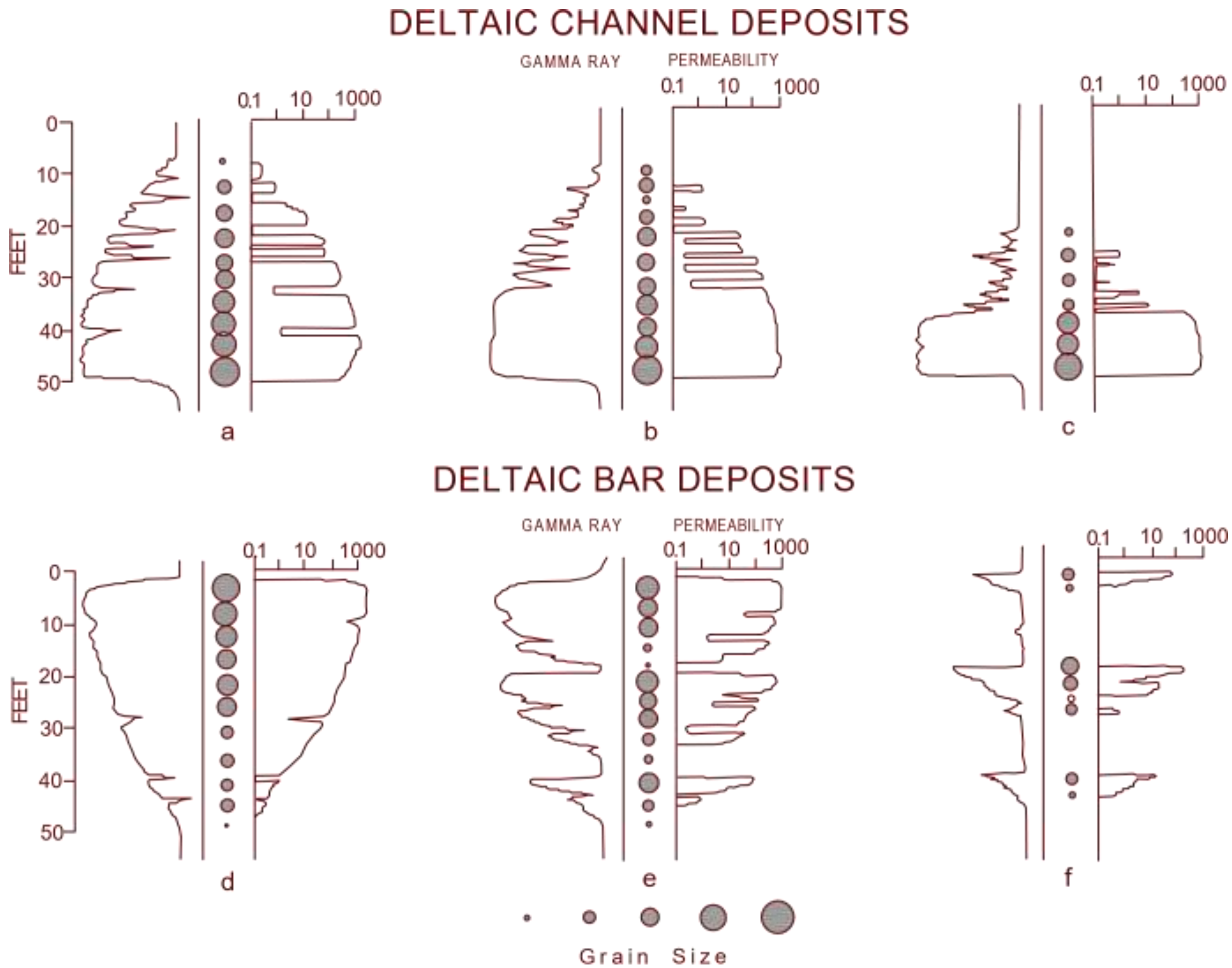


Figure 3.6: Typical log responses and permeability profiles of deltaic deposits (Sneider *et al*., 1978)

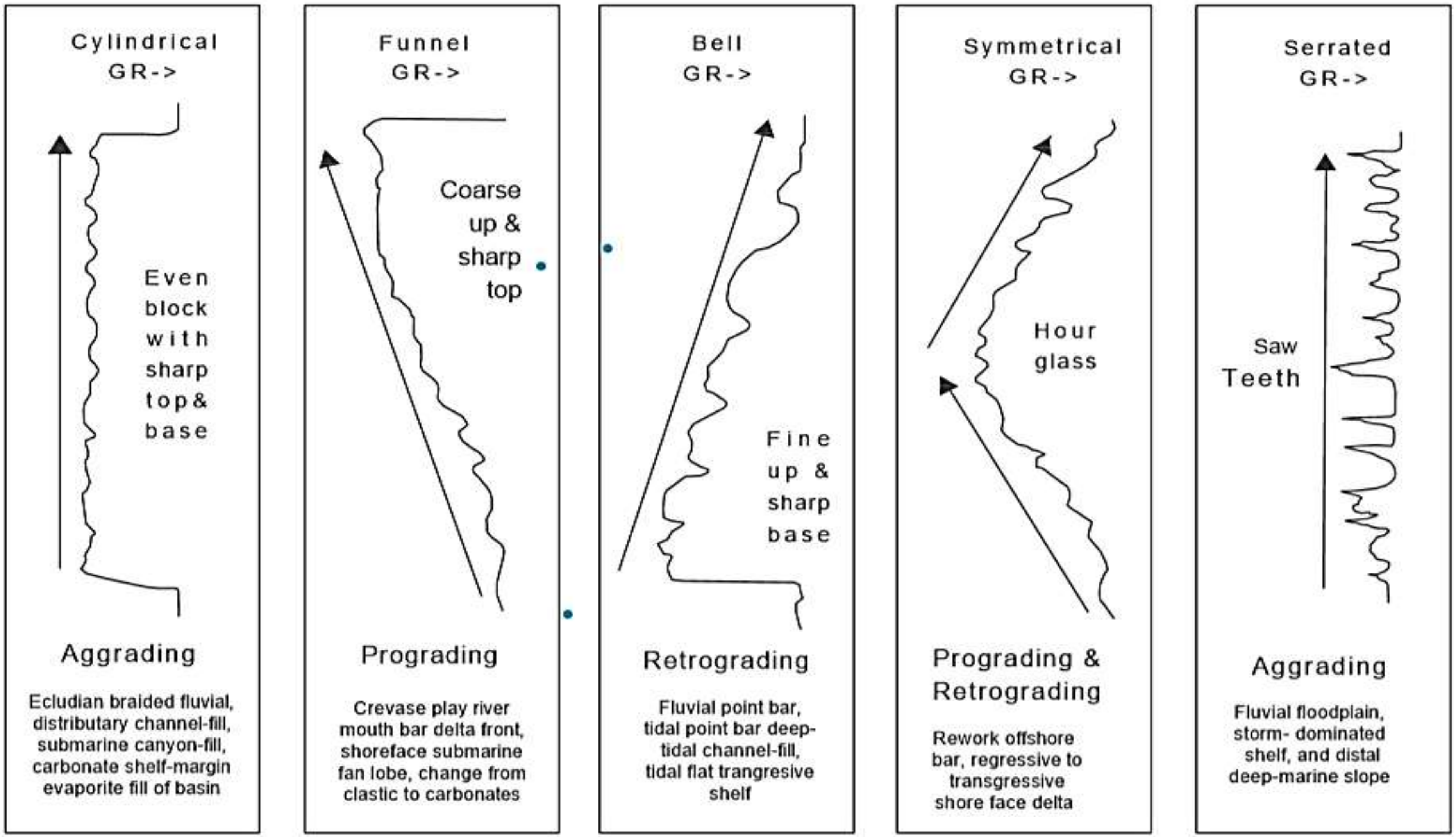


Figure 3.7: Different Well log signatures for different environments (Beka and Oti, 1995; Onyekuru *et al*., 2012)

Bell shaped log patterns on Gamma Ray Logs signify increase in clay contents upwardly or simply an upward addition to Gamma Ray value. Bell shaped log signatures are indicative of fluvial channel. This pattern clearly shows deltaic progradation and bar deposits (Figure 3.7). Cylindrical log motif denotes thick and evenly graded coarsegrained sandstone sequence which could be indicative of braided channel, tidal channels or subaqueous slump deposits. These are typically characteristic of beach sands, barrier bar sands and stream bars which are in turn features of deltaic environment. Serrated log patterns suggest intercalation of thin shales in a sandstone body, typically of fluvial, marine and tidal environments. Symmetrical log motifs indicate gradual increase and decrease in Gamma Ray values and this is as a result of progradation and retrogradation of clastic sediments.

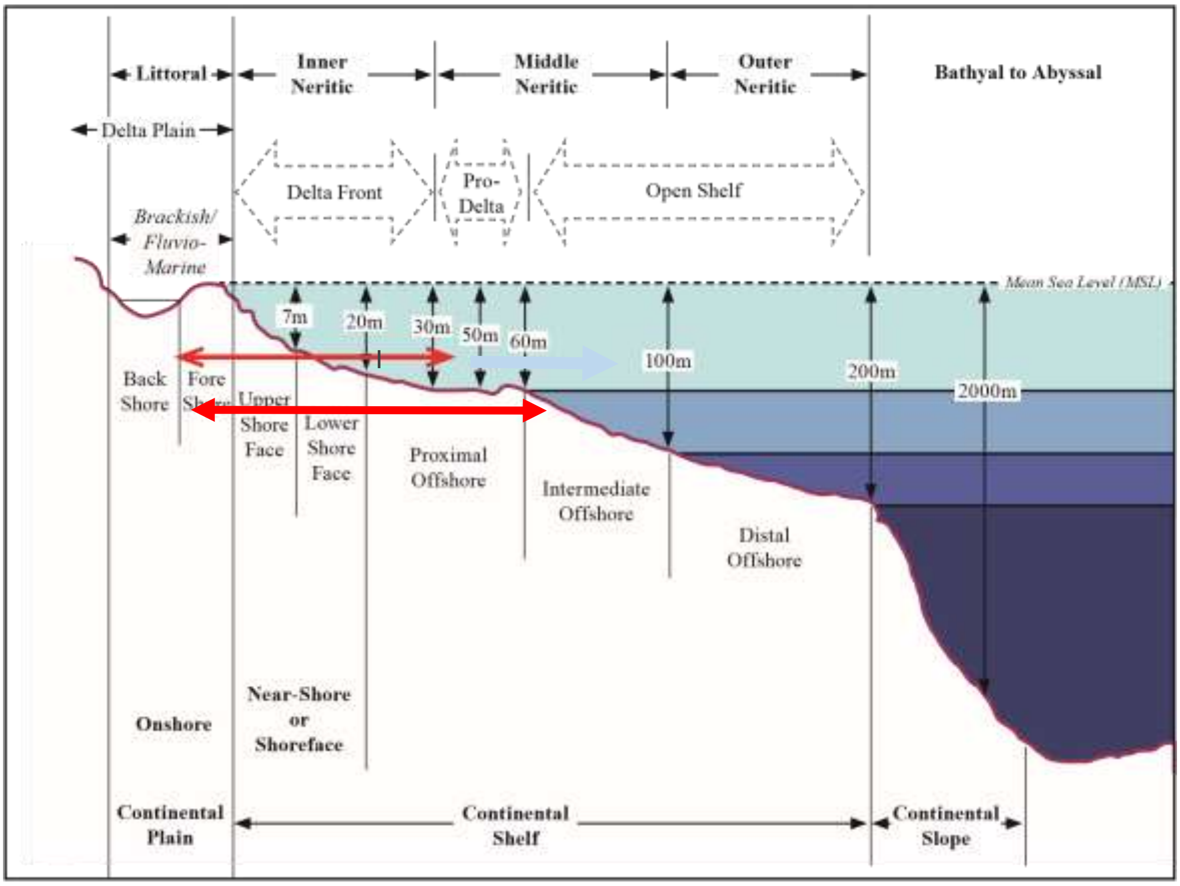
3.5 Methods for Paleoenvironmental Analysis

The paleoenvironmental interpretation of the sedimentary sections was carried out with the framework of the identified lithofacies sequence (Selley, 1976 and Sneider *et al.*, 1978). Deductions of paleodepositional environment of the studied wells were divided based on the following criteria:

i. Quantitative variations of the palyno-ecological groups of the studied palynomorphs.

ii. The palynomaceral type recovered from the studied samples: The coastal and marine depositional environments are categorised to possess unique and characteristics palynofacies (Oyede, 1992).

iii. The Gamma Ray Log signatures, lithological attributes and index accessory mineral were employed in the interpretation of paleoenvironments. The paleodepositional environment models used are shown in Figures 3.8 and 3.9.



key

Inferred depostional environments of HA 001, HB 001, and HD 001 wells

Figure 3.8: Depositional Environments and Bathymetric Range used in Paleoenvironmental Interpretations (Modified after Ijomah *et al.*, 2016)

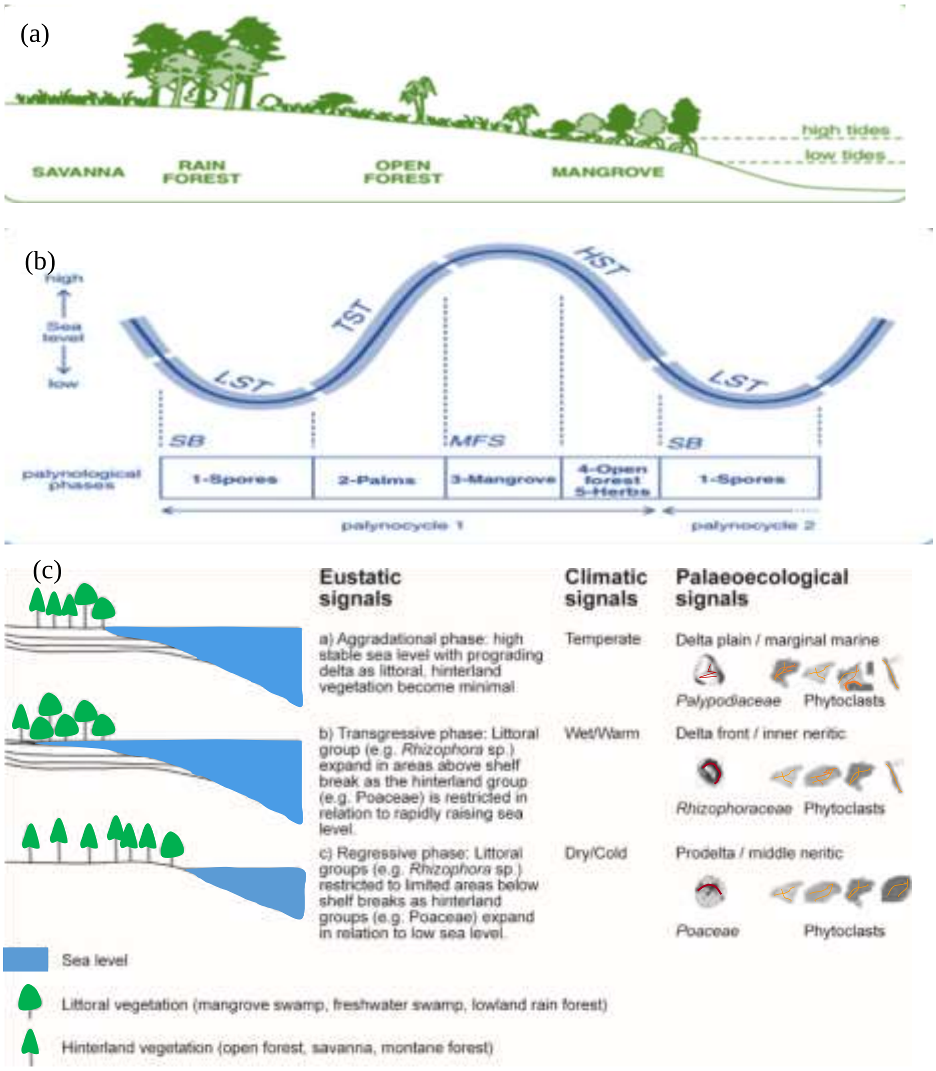


Figure 3.9: General Relationship between Palaeoecology, Palaeovegetation, Eustasy and Climate in the Tropical Setting (Modified after Adojoh *et al.*, 2015 and Chukwuma-Orji *et al.*, 2017)

3.6 Sequence Stratigraphic Analysis

Sequence stratigraphic involves the description, interpretation, classification and nomenclature of rock strata on the basis of their stratal stacking patterns and their stratigraphic relationships. All units and surfaces of stratigraphic sequence can be studied at different scales depending on the objective of the study and the type of available data which can include palynomorph, palynomaceral, well log signatures and ditch cutting samples. The model-independent approach of Catuneanu *et al*. (2011) cut across the different sequence stratigraphic methods and depends on a set of core principles. The approach is simpler than the methodology of any model, therefore promoting better flexibility in its application. The model-independent methodology of Catuneanu *et al*. (2011) Figure 3.10 was used for this study.

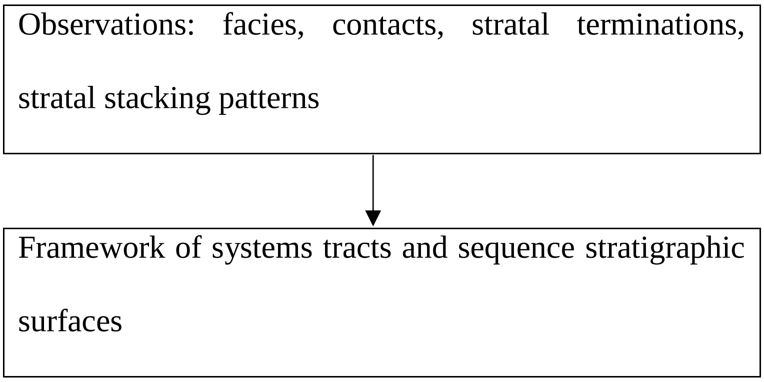


Figure 3.10: Model-independent method of sequence stratigraphic analysis (Catuneanu *et al.,* 2011)

It involves examination of the local data from the studied wells and the observation of the features that will aid the identification of stratal stacking patterns based on the available data.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Palynology of the Studied Wells

A total number of thirty-seven (37) palynomorph species were recovered and used for biozonation and dating of the HA-001 Well. There were no samples between 5200 – 5800 feet and 6800 – 8800 feet. The palynomorphs recovered include abundant land derived forms including *Zonocostites ramonae, Monoporites annulatus, Sapotaceoidaepollenites* sp., *Laevigatosporites* sp., *Achrostichum aureum, Verrucatosporites* sp., *Polypodiaceiosporites* sp., and charred gramineae cuticle. Moderate quantities of *Pachydermites diederixi*, *Psilatricolporites crassus, Retitricolporites irregularis* and *Nympheaepollis clarus* were also recovered. Abundant fresh water algae; *Botryococcus braunii* were also recorded. Dinoflagellate cysts were not encountered in this well.

Thirty-nine (39) palynomorph species were recovered and used for biozonationand dating of the HB-001 well. The palynomorphs recovered were well preserved, abundant and fairly diverse. These include abundant *Monoporites annulatus, Zonocostites ramonae*, *Sapotaceoidaepollenites* sp., *Corylus* sp., *Cyperaceaepollis* sp., *Pachydermites diederixi*, *Laevigatosporites* sp., *Verrucatosporites* sp., *Acrostichum aureum*, *Polypodiaceiosporites* sp. and abundant fresh water algae, *Botryococcus braunii*.

Fifty-six (56) palynomorph species were recovered and used for the age dating and biozonation of the HD-001 Well.The palynomorph species recovered include abundant *Zonocostites ramonae, Monoporites annulatus, Pachydermites diederixi, Psilatricolporites crassus, Retitricolporites irregularis, Retibrevitricolporites protrudens, Sapotaceoidaepollenites* sp., *Acrostichum aureum, Laevigatosporites* sp., *Verrucatosporites* sp., *Polypodiaceiosporites* sp. and *Stereisporites* sp.

Abundant fresh water algae, *Botryococcus braunii*, were also recovered between 4875 – 9240 feet. Spot records of dinoflagellate cysts were also recovered at 5790, 9240 and 9915 feet.

The works of Germeraad *et al.* (1968). Evamy *et al*. (1978) and Olayiwola and Bamford (2016) were employed for this study. The presence of palynological index species such as *Zonocostites ramonea, Nympheaepollis clarus, Cyperaceaepollis* sp, *Monoporites annulatus, Stereisporites* sp, *Echitriletes pliocenicus, Peregrinipollis nigericus, Corylus* sp, *Psilatricolporites crassus, Podocarpus milanjianus, Crassoretitriletes vanraadshooveni* and *Echiperiporites estelae* at some studied intervals of the wells were used to confirm the late Miocene age. The recovered palynological assemblages from the wells are similar to those earlier described in Nigeria, (Morley and Richard, 1993), Legoux (1978) and New Zealand (Raine *et al.*, 2015). Two assemblage biozones each were recognised in the studied wells. Assemblage biozone is the rock strata which is based on overlapping range of assemblage co-occuring taxa (Boggs, 2006). The biozone is defined by three or co-occurrence of more different taxa, which can be related. The assemblage biozone (Figure 3.4) has its boundaries delineated by the characteristic fossil assemblage's co-occurrence including appearance and disappearance of certain fossil taxa.

4.1.1 Palynostratigraphic Zonation and Biochronology of HA-001 Well

The well is moderately abundant and fairly diverse in pollen, spores and fresh water algae. The palynomorph assemblage is quantitatively dominated by hinterland (rainforest and savannah) and mangrove species such as *Sapotaceae, Psilatricolporites crassus, Laevigatosporites* sp., *Verrucatosporites* sp., *Zonocostites ramonae, Monoporites annulatus* and *Acrostichum aureum*.

The age succession established for the HA-001 well (750-11510 ft) was achieved using the palynoflora assemblages of marker and associate marker species assemblages recognised in the well. This aided in erecting two (2) assemblage biozones and two (2) subzones based on published works of Germeraad *et al.* (1968), Evamy *et al.* (1978) and Murphy and Salvador (1999) Figure 3.3.

The assemblage biozones were based on the established age range of marker and associate marker species that characterised the body of strata, Murphy and Salvador (1999). This age range of key palynoflora assemblages have their upper and lower boundaries marked by the periods of first downhole and last downhole occurrences of marker species e.g. Top ccurrence and Base occurrence respectively. These biozones can also be defined by the common occurrence, abundant and or significant reduction in the numbers of associate marker species recognised within the biozone. The results of palynological analyses (Figures 4.1 to 4.3) are presented in the palynomorphs and palynomacerals distribution charts of HA-001, HB-001 and HD-001 wells.

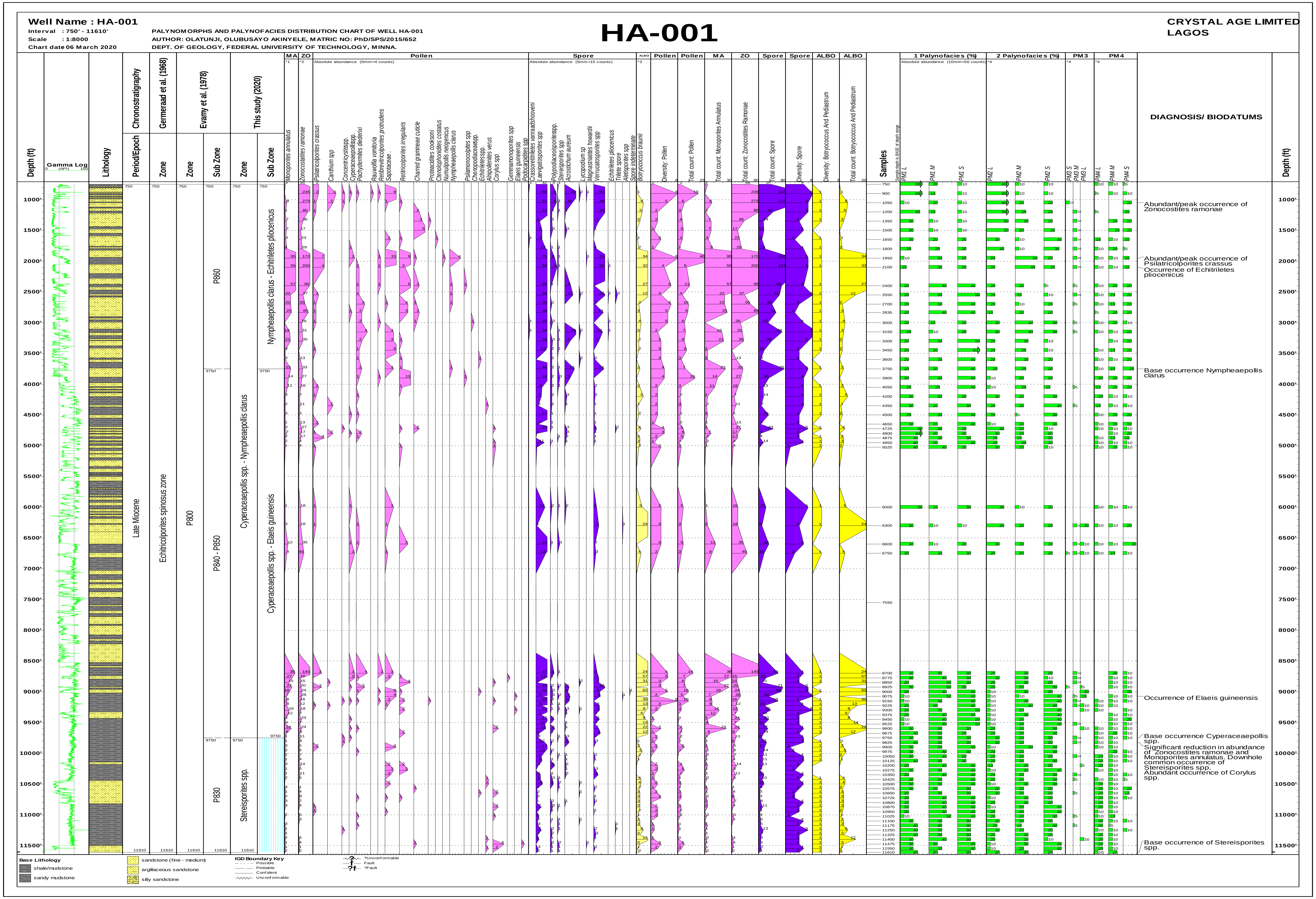


Figure 4.1: Palynomorphs and palynofacies distribution chart of HA-001 well

In this study the base occurrence of the marker species was used in defining the bases of the biozone identified.

Two (2) assemblage biozones were recognised in the study namely the *Cyperaceaepollis* sp. – *Nympheaepollis clarus* assemblage zone (750-9750 ft) and the *Stereisporites* sp. assemblage zone (9750-11610 ft). These were further divided into two (2) subzones namely; *Nympheaepollis–Echitriletes pliocenicus* subzone (750-3750 ft) and *Cyperaceaepollis-Elaeis guineensis* subzone (3750-9750 ft) These assemblage biozones were correlated with the *Echitricolporites spinosus* palynological zones of Germeraad *et al*. (1968) and the P860, P850-P840 and P830 palynological subzones of Evamy *et al*. (1978). Thus, a Late Miocene age is interpreted for the HA-001 well (750-11610 ft). Details of the biozones were discussed below.

Cyperaceaepollis sp – *Nympheaepollis clarus* Assemblage Zone

Depth: 750-9750 ft

Age: Late Miocene

Comparable palynological zone: *Echitricolporites spinosus* zone of Germeraad *et al*. (1968), P860 and P850-P840 palynological subzones of Evamy *et al*. (1978).

This biozone is characterised by the palynoflora assemblage of marker species such as *Cyperaceaepollis* sp., *Nympheaepollis clarus*, *Echitriletes pliocenicus* and *Elaeis guineensis*. The stratigraphic significant range of key marker species *Cyperaceaepollis* sp. and *Nympheaepollis clarus* lie within this assemblage zone. The occurrence of *Cyperaceaepollis* sp., at the depth 900 ft in the well suggests the actual top of the zone and it is stratigraphically higher than first sample analysed at 750 ft.

The lower limit is defined by the base occurrence of *Cyperaceaepollis* sp. marked at 9750 ft. This zone is further characterised by the abundant occurrences of *Zonocostites ramonae, Monoporites annulatus, Laevigatosporites* sp., *Pachydermites diederixi* and *Psilatricolporites crassus*. Two (2) subzones are recognised within this assemblage zone and discussed below:

Nympheaepollis clarus - Echitriletes pliocenicus subzone

Depth: 750-3750 ft

Age: Late Miocene (Messinian-Tortonian)

This is the youngest subzone recognised in the study and as such the top of this subzone is probably higher than the first sample analysed. The base of the subzone is defined by the base occurrence of *Nympheaepollis clarus* identified at 3750 ft.

The *Nympheaepollis clarus* subzone is further characterised by the abundant occurrence of *Zonocostites ramonae, Verrucatosporites* sp. and *Retitricolporites irregularis,* rare occurrence of *Numulipollis neogenicus,* fairly abundant *Monoporites annulatus* and common occurrence of *Sapotaceae* and *Nympheaepollis clarus.*

This subzone correlates with the *Echitricolporites spinosus* palynological zone of Germeraad *et al*. (1968), P860 subzone of Evamy *et al*. (1978) and the palynological zone of Olayiwola and Bamdford (2016).

Cyperaceaepollis sp. - *Elaeis guineensis* subzone

Depth: 3750-9750 ft.

Age: Late Miocene (Tortonian)

The top of this subzone is marked by the base occurrence of *Nympheaepollis clarus* at 3750 ft. The base is marked by the base occurrence of *Cyperaceaepollis* sp. defined at 9750 ft.

The occurrence of *Elaeis guineensis*, rare occurrence of *Aletesporites* sp. and *Retibrevitricolporites obodoensis*, reduced abundance of *Verrucatosporites* sp. and rare occurrence of *Acrostichum aureum* also characterised this subzone.

This subzone correlates with the *Echitricolporites spinosus* palynological zone of Germeraad *et al*. (1968) and the P850-P840 (undifferentiated) subzone of Evamy *et al*. (1978).

Stereisporites sp. Assemblage Zone

Depth: 9750-11610 ft

Age: Late Miocene (Tortonian)

This zone has been correlated with the *Echitricolporites spinosus* zone of Germeraad *et al.* (1968), P830 palynological subzones of Evamy *et al.* (1978).

This Assemblage zone is characterised by the occurrences of marker species such as *Stereisporites* sp., *Corylus* sp., low records of *Pachydermites diederixi* and *Canthiumidites* sp.

The top of the zone is marked at 9750 ft by the base occurrence of *Cyperaceaepollis* sp., while the base occurrence of *Stereisporites* sp. which marks the base of the zone was recognised at the last sample analysed.

The zone is further characterised by the significant reduction of *Zonocostites ramonae* and *Monoporites annulatus,* moderate records of *Corylus* sp., common occurrence of

Stereisporites sp., and lower records of *Pachydermites diederixi* compared to the higher zones.

4.1.2 Palynostratigraphic Zonation and Biochronology of HB-001 Well

Fairly diverse and moderately abundant palynomorphs were identified. The palynoflora assemblage is quantitatively dominated by rainforest and mangrove species such as *Verrucatosporites* sp*., Laevigatosporites* sp*., Zonocostites ramonae, Acrostichum aureum* and *Monoporites annulatus*. Fresh water algae such as *Botryococcus braunii* and *Pediastrum* sp. were also identified.

Two assemblage zones were recognised in the HB-001 well (4100-13160 ft) namely the *Cyperaceaepollis* sp.-*Nympheaepollis clarus* assemblage zone and the *Stereisporites* sp. assemblage zone. This was achieved by using the palynoflora assemblages of marker and associate marker species recognised in the well. The assemblage biozones were based on the established age range of marker and associate marker species that characterised the body of strata, Murphy and Salvador (1999).

This age range of key palynoflora assemblages have their upper and lower boundaries marked by the periods of first downhole and last downhole occurrences of marker species e.g. Top occurrence and Base occurrence respectively. Also, the biozones can be defined by the common occurrence, abundant and or significant reduction in the numbers of associate marker species recognised within the biozone. The palynostratigraphic of HB-001 well is presented in Figure 4.2 below:

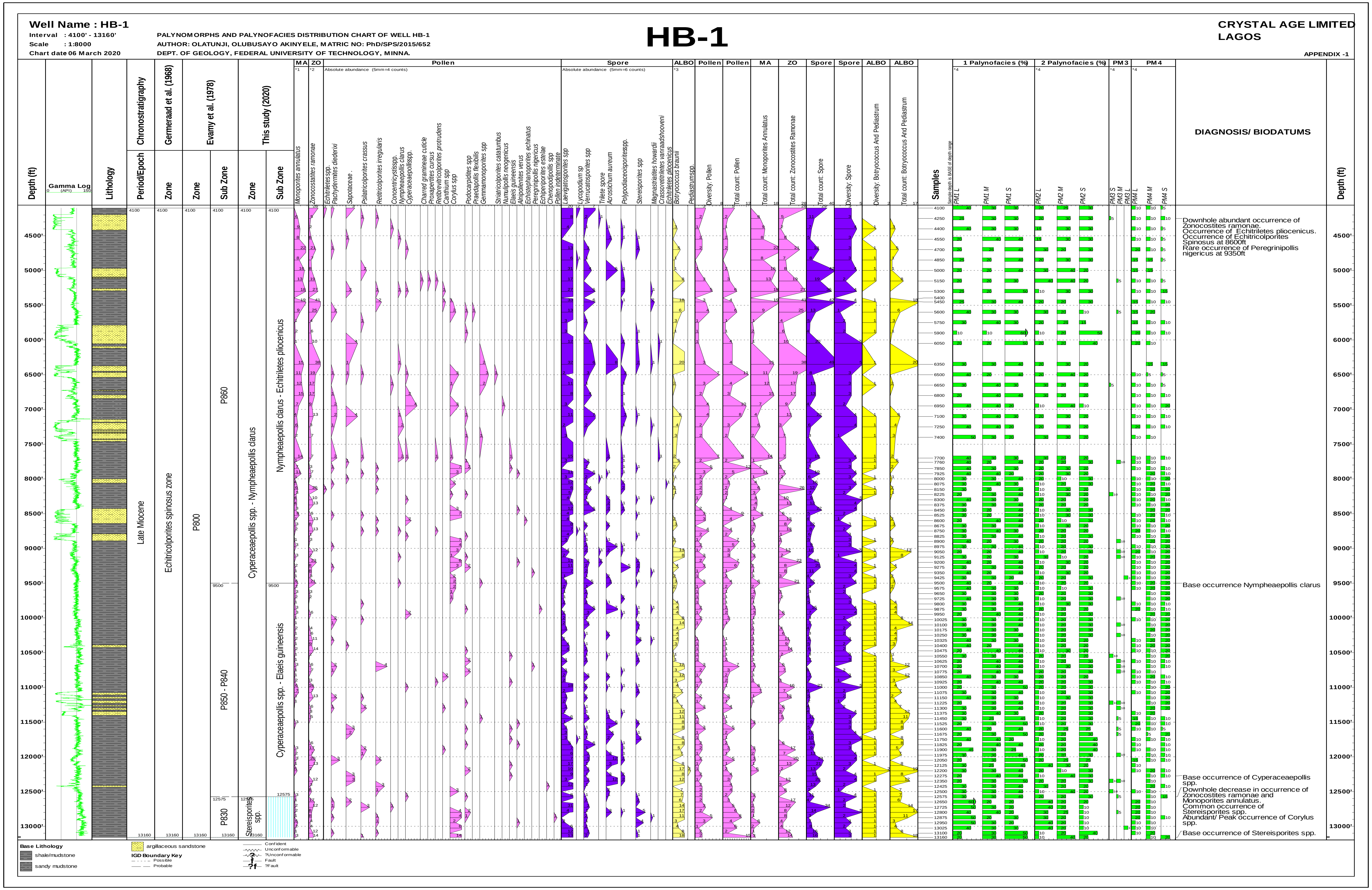


Figure 4.2: Palynomorphs and palynofacies distribution chart of HB-001 well

The assemblage zones were further divided into two (2) subzones namely; the *Nympheaepollis clarus – Echitriletes pliocenicus* subzone (4100-9500 ft) and *Cyperaceaepollis* sp. – *Elaeis guineensis* subzone (9500-12575 ft). The zones were correlated with the *Echitricolporites spinosus* palynological zones of Germeraad *et al*. (1968) and the P860, P850-P840 and P830 palynological subzones of Evamy *et al*. (1978). Based on these, a Late Miocene age is interpreted for the HB-001 well (4100-13160 ft). Details of the biozones are discussed below.

Cyperaceaepollis sp.- *Nympheaepollis clarus* Assemblage Zone

Depth: 4100-12575 ft

Age: Late Miocene

Comparable palynological zone: *Echitricolporites spinosus* zone of Germeraad *et al*. (1968), P860 and P850-P840 palynological subzones of Evamy *et al*. (1978). This assemblage biozone is the youngest in age and is approximately 8475 ft. thick succession of shale and argillaceous sandstones. The palynoflora marker species such as *Cyperaceaepollis* sp., *Nympheaepollis clarus, Echitriletes pliocenicus* and *Elaeis guineensis* characterised the interval. The stratigraphic significant range of key marker species *Cyperaceaepollis* sp. and *Nympheaepollis clarus* lie within this assemblage zone. The occurrence of *Cyperaceaepollis* sp. (4550 ft.), close to the measured top of the well suggests that its actual top of the zone is stratigraphically higher than first sample analysed at 4100 ft. The lower limit is defined by the base occurrence of *Cyperaceaepollis* sp. marked at 12575 ft.

Abundant occurrences of *Verrucatosporites* sp., *Zonocostites ramonae, Monoporites annulatus, Laevigatosporites* sp., *Pachydermites diederixi* and *Psilatricolporites crassus* quantitatively characterised the biozone. Two (2) subzones are recognised within this assemblage zone and discussed below:

Nympheaepollis clarus - Echitriletes pliocenicus subzone

Depth: 4100-9500 ft

Age: Late Miocene (Messinian-Tortonian)

The base of the subzone is defined by the base occurrence of *Nympheaepollis clarus* identified at 9500 ft. The *Nympheaepollis clarus – Echitriletes pliocenicus* subzone is further characterised by the abundant occurrence of *Zonocostites ramonae, Verrucatosporites* sp. and *Retitricolporites irregularis,* scanty to rare occurrence of *Peregrinipollis nigericus* and *Echitricolporites spinosus*, and common occurrence of *Sapotaceae* and *Nympheaepollis clarus.* This subzone correlates with the *Echitricolporites spinosus* palynological zone of Germeraad *et al.* (1968) and the P860 subzone of Evamy *et al*. (1978).

Cyperaceaepollis sp. - *Elaeis guineensis* subzone

Depth: 9500-12575 ft.

Age: Late Miocene (Tortonian)

The top of this subzone is marked by the base occurrence of *Nympheaepollis clarus* at 9500 ft. The base is marked by the base occurrence of *Cyperaceaepollis* sp. defined at 12575 ft. The occurrence of *Elaeis guineensis*, scanty occurrence of *Magnastriatites howardi* and *Echiperiporites estelae*, reduced abundance of *Verrucatosporites* sp. and *Acrostichum aureum* also characterised this subzone. This subzone correlates with the *Echitricolporitesspinosus* palynological zone of Germeraad *et al*. (1968) and the P850-P840 (undifferentiated) subzone of Evamy *et al*. (1978).

Stereisporites sp. Assemblage Zone

Depth: 12575-13160 ft

Age: Late Miocene (Tortonian)

This zone has been correlated with then *Echitricolporites spinosus* zone of Germeraad *et al.* (1968), P830 palynological subzones of Evamy *et al.* (1978). This Assemblage zone is characterised by the occurrences of marker species such as *Stereisporites* sp., abundant occurrence of *Corylus* sp. and common of *Pachydermites diederixi*.

Top of this zone is marked at 12575 ft by the base occurrence of *Cyperaceaepollis* sp. The base occurrence of *Stereisporites* sp. defines the base of this zone at the last sample analysed. The subzone is further characterised by the significant reduction the *Zonocostites ramonae,* common *Monoporites annulatus,* abundant records of *Corylus* sp., common occurrence of *Stereisporites* sp., and lower records of *Pachydermites diederixi* compared to the higher zones.

4.1.3 Palynostratigraphic Zonation and Biochronology of HD-001 Well

The well is fairly abundant and diverse in pollen, spores and fresh water algae with rare occurrences of dinoflagellate cysts. The palynoflora is quantitatively dominated by hinterland (rainforest and savannah) and mangrove species such as *Acrostichum aureum*. *Sapotaceae*, *Pachydermites diederixi, Psilatricolporites crassus, Laevigatosporites* sp., *Verrucatosporites* sp., *Zonocostites ramonae* and *Monoporites annulatus*

The age succession established for the HD-001 well (4870-12090 ft) was achieved using the palynoflora assemblages of marker and associated marker species recognised in the well. Two (2) assemblage biozones and two (2) subzones based on published works of

Germeraad *et al.* (1968), Evamy *et al.* (1978) and Murphy and Salvador (1999) were established for the studied intervals.

The assemblage biozones were based on the established age range of marker and associate marker species that characterised the body of strata, Murphy and Salvador (1999). These age range of key palynoflora assemblages have their upper and lower boundaries marked by the periods of first downhole and last downhole occurrences of marker species e.g. Top occurrence and Base occurrence respectively. Also, biozones can be defined by the common occurrence, abundant and or significant reduction in the numbers of associated marker species recognised within the biozone.

In this study, the base occurrence of the marker species was used in defining the bases of the biozone identified. The palynostratigraphic chart of HD-001 is presented in Figure 4.3 below.

Two (2) assemblage biozones were recognised in the study namely: the *Cyperaceaepollis* sp. – *Nympheaepollis clarus* assemblage zone (4870-10890 ft) and the *Stereisporites* sp. assemblage zone (10890-12090 ft). These were further subdivided into two (2) zones namely; the *Nympheaepollis clarus – Echitriletes pliocenicus* zone (4870-7965 ft) and *Cyperaceaepollis* sp. – *Elaeis guineensis* zone (7950-10890 ft).

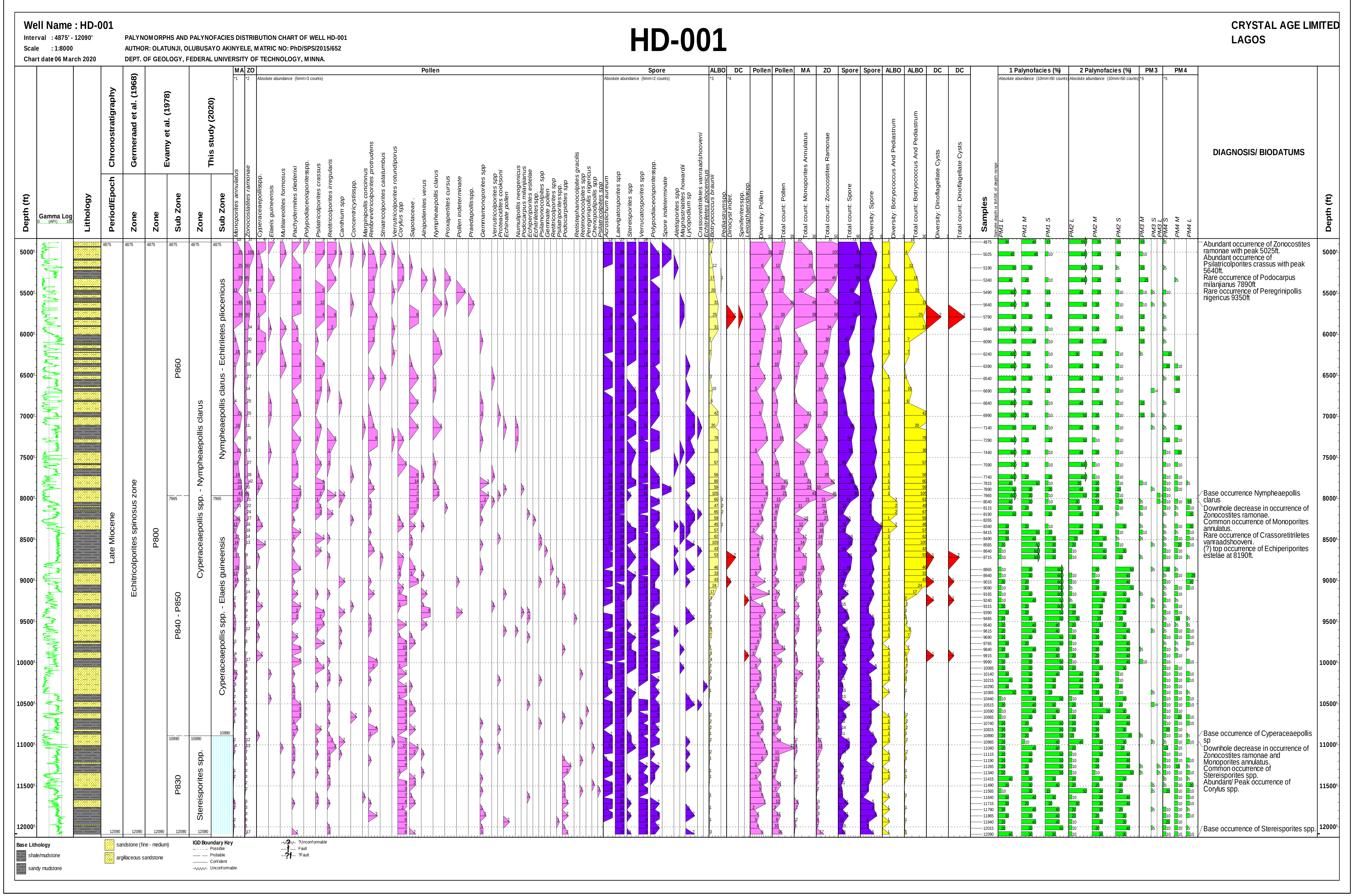


Figure 4.3: Palynomorphs and palynofacies distribution chart of HD-001 well

Two (2) assemblage biozones were recognised in the study namely: the *Cyperaceaepollis* sp. – *Nympheaepollis clarus* assemblage zone (4870-10890 ft) and the *Stereisporites* sp. assemblage zone (10890-12090 ft). These were further subdivided into two (2) zones namely; the *Nympheaepollis clarus* – *Echitriletes pliocenicus* zone (4870-7965 ft) and *Cyperaceaepollis* sp. – *Elaeis guineensis* zone (7950-10890 ft). These assemblage biozones were correlated with the *Echitricolporites spinosus* palynological zones of Germeraad *et al*. (1968) and the P860, P850-P840 and P830 palynological subzones of Evamy *et al*. (1978). Thus, a Late Miocene age is interpreted for the HD-001 well (4870-12090 ft). Details of the biozones were discussed below:

Cyperaceaepollis sp – *Nympheaepollis clarus* Assemblage Zone

Depth: 4870-10890 ft

Age: Late Miocene

Comparable palynological zone: *Echitricolporites spinosus* zone of Germeraad *et al*. (1968), P860 and P850-P840 palynological subzones of Evamy *et al*. (1978). The common occurrences of key palynoflora marker species such as C*yperaceaepollis* sp., *Nympheaepollis clarus*, *Echitriletes pliocenicus* and *Elaeis guineensis* characterised this assemblage zone.

The stratigraphic significant range of key marker species *Cyperaceaepollis* sp. and *Nympheaepollis clarus* lie within this assemblage zone. The occurrence of *Cyperaceaepollis* sp. at the 4870 ft of the well suggests that its actual top occurrence of the marker is stratigraphically higher than first sample analysed at 4870 ft. The lower limit of the biozone is defined by the base occurrence of *Cyperaceaepollis* sp. marked at 10890 ft.

This zone is further characterised by the abundant occurrences of *Pachydermites diederixi*, *Zonocostites ramonae*, *Monoporites annulatus, Laevigatosporites* sp. and *Psilatricolporites crassus*. Two (2) subzones are recognised within this assemblage zone and discussed below:

Nympheaepollis clarus - Echitriletes pliocenicus subzone

Depth: 4870-7965 ft

Age: Late Miocene (Messinian-Tortonian)

This is the youngest subzone recognised in the study. The base of the subzone is defined by the base occurrence of *Nympheaepollis clarus* identified at 7965 ft. The *Nympheaepollisclarus-Echitriletes pliocenicus* subzone is further characterised by the abundant occurrence of *Zonocostites ramonae, Psilatricolporites crassus Verrucatosporites* sp. and *Pachydermites diederixi,* rare occurrence of *Podocarpus milanjianus* and *Peregrinipollis nigericus,* fairly abundant *Monoporites annulatus* with common occurrence *Nympheaepollis clarus.* This subzone correlates with the *Echitricolporites spinosus* palynological zone of Germeraad *et al*. (1968) and the P860 subzone of Evamy *et al*. (1978).

Cyperaceaepollis sp. – *Elaeis guineensis* subzone

Depth: 7965-10890 ft.

Age: Late Miocene (Tortonian)

The top of this subzone is marked by the base occurrence of *Nympheaepollis clarus* at 7965 ft. The base is marked by the base occurrence of *Cyperaceaepollis* sp. defined at 10890 ft. The common occurrence of *Cyperaceaepollis* sp. and *Retibrevitricolporites obodoensis*, rare occurrence of *Crassoretitriletes vanraadshooveni* and *Elaeis guineensis*, top occurrence of *Echiperiporites estelae* at 8190 ft and reduced abundance of *Zonocostites ramonae* with scanty records of *Spiniferites* sp. and *Leoisphaeridia* sp. also characterised this subzone.

This subzone correlates with the *Echitricolporites spinosus* palynological zone of Germeraad *et al*. (1968) and the P850-P840 (undifferentiated) subzone of Evamy *et al*. (1978).

Stereisporites sp. Assemblage Zone

Depth: 10890-12090 ft

Age: Late Miocene (Tortonian)

This zone has been correlated with the *Echitricolporites spinosus* zone of Germeraad *et al.* (1968) and P830 palynological subzones of Evamy *et al.* (1978). This Assemblage zone is characterised by the occurrences of marker species such as *Stereisporites* sp., *Corylus* sp., low records of *Pachydermites diederixi* and *Canthiumidites* sp.

The top of this subzone is marked at 10890 ft by the base occurrence of *Cyperaceaepollis* sp., while the base occurrence of *Stereisporites* sp. marks the base of this subzone as the last sample analysed. The subzone is further characterised by the significant reduction of the *Zonocostites ramonae* and *Monoporites annulatus,* abundant records of *Corylus* sp., common occurrence of *Stereisporites* sp., and lower records of *Pachydermites diederixi* compared to the higher subzones.

4.1.4 Palynostratigraphic Zones Correlation of HA-001, HB-001 and HD-001 Wells

There is a good correlation of *Cyperaceaepollis* sp, *Nympheaepollis clarus* and *Stereisporites* sp. zones across the three wells (Figure 4.4).

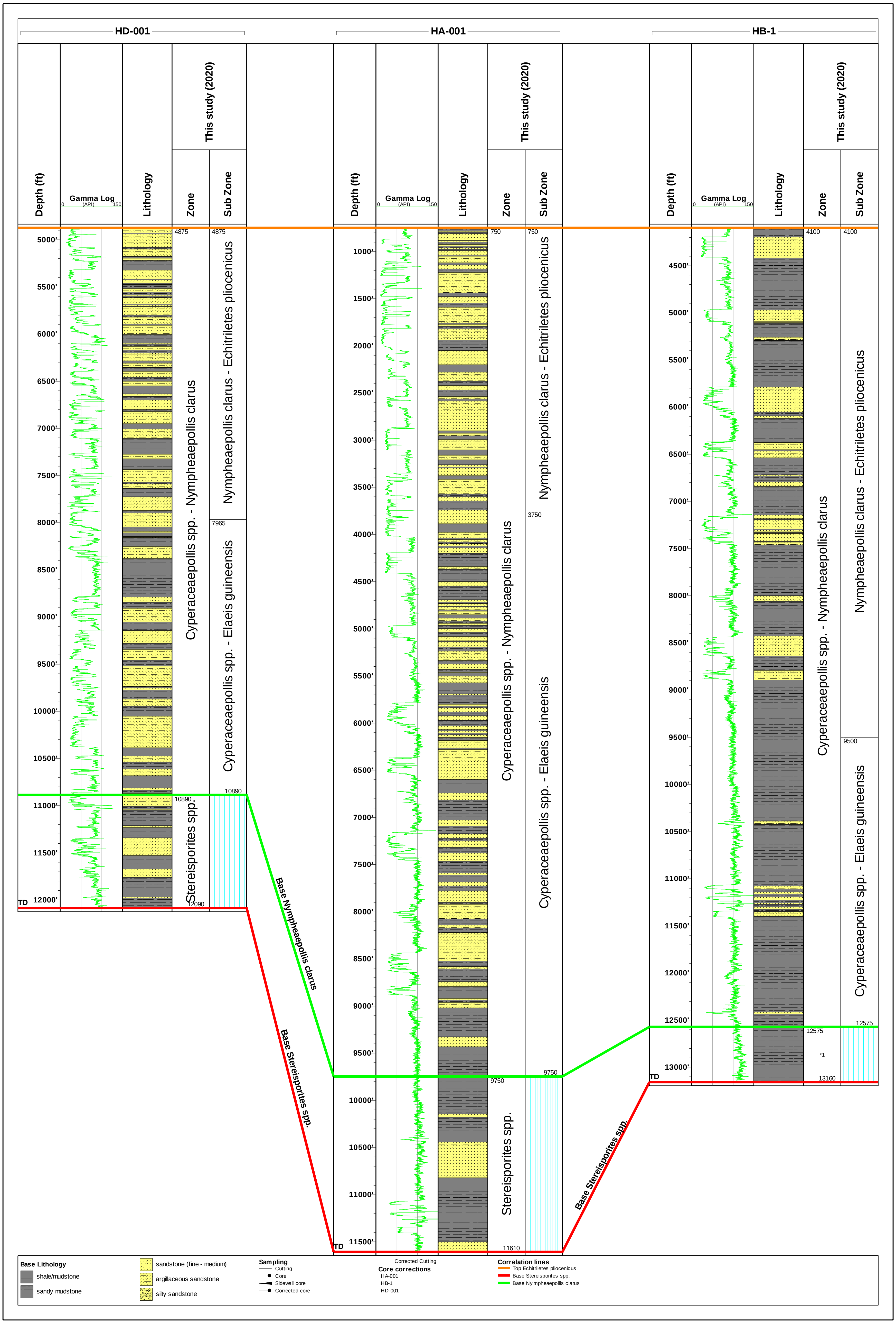


Figure 4.4: Correlation chart for palynostratigraphic zones and subzones of HA-001, HB-001 and HD-001 wells

The occurrence of similar diagnostic taxa at zonal boundaries have been used to make the correlations. There are variations of depth at which the zonal boundaries correlate in the three wells due to lateral variation in thickness or faulting of penetrated strata.

The established zones were further correlated with the works of Evamy *et al*. (1978) in the Niger Delta Basin (Figure 4.5). Similar palynological marker species such as *Zonocostites ramonea, Nympheaepollis clarus, Cyperaceaepollis* sp. and *Steriesporites* sp. were used in biozonation of this study.

Abundant top occurrences and quantitative base increase or decrease of diagnostic species have been employed in this study. Similarly, Evamy *et al*. (1978) established palynostratigraphic zones using abundant top occurrences, increase or decrease and quantitative base occurrences of diagnostic species. Evamy *et al*. (1978) marked the base of P860 subzone with the base occurrence of *Nympheaepollis clarus*. The base occurrence of the species is used to mark the base of *Nympheaepollis clarus – Echitrilite pliocenicus* subzone in this study. The established P860 subzones of this study correlates with the work of Olayiwola and Bamford (2016) due to the presence of similar species employed in establishment of biozones (Figure 4.5). The top of P860 is marked by the abundant occurrence of *Psilatricolporites crassus.*

The palynomorph zones of Olayiwola and Bamford (2016) were correlated to the long ranging *Echitricolporites spinosus* zone of Germeraad *et al.* (1968) in the Late Miocene, which correlates to the zones of this study (Figure 4.5).

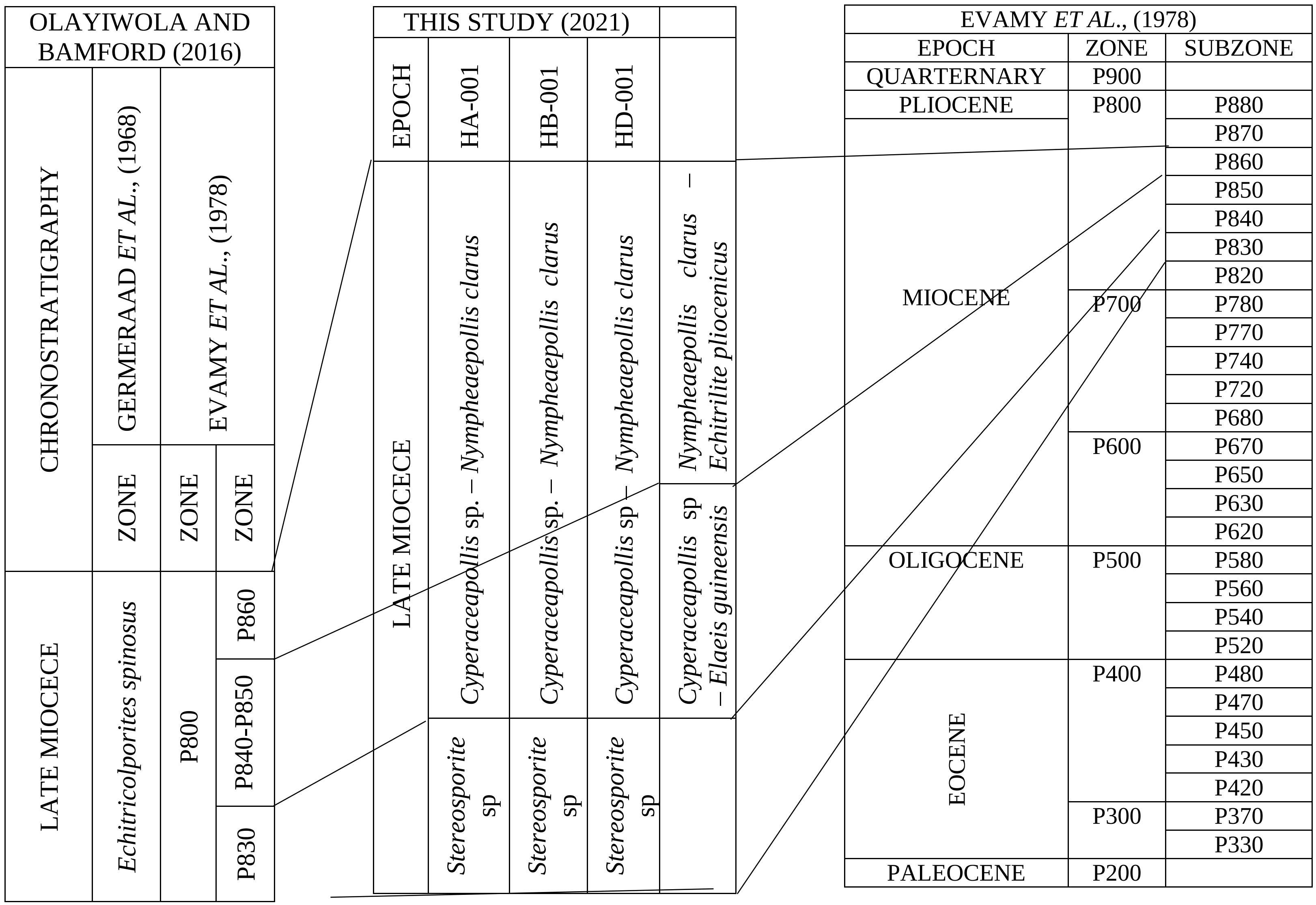


Figure 4.5: Correlations of the palynostratigraphic zones of study well with those of some workers in the Niger Delta Basin

4.2 Palynomacerals

The three wells generated few to abundant amount of organic matter (Lorente, 1990). There is a high recovery of palynomaceral 1 and 2 with palynomaceral 3 and 4 yielding low recoveries (Plate I, Figures 4.1 to 4.3). The classification of the palynomacerals is based on the description of Lorente (1990), Van der Zwan (1990), Tyson (1995) and Traverse (2007).

4.2.1 Palynomaceral 1 (PM 1)

The recovered palynomaceral 1 (Alganite) from this study appeared to be orange-brown to dark brown in colour, opaque, structureless, irregular in shape, variable in preservation and of dense material. It is heterogenous and of higher plant in origin and some are product of exudation processes such as the gelification of plant debris in the sediments. Palynomaceral 1 contains small, medium and large sizes of flora debris, humic gel-like substances and resinous cortex irregularly shaped materials.

4.2.2 Palynomaceral 2 (PM 2)

From this study, palynomaceral 2 (Exinites) appeared to be brown-orange structured material of irregular shape. It has platy like structured plant materials, algae debris and a little amount of humic gels and resinous substances. It has more buoyancy than palynomaceral 1 because of its thinner lath-shaped attribute.

4.2.3 Palynomaceral 3 (PM 3)

The recovered palynomaceral 3 (Vitrinite) from this study is pale to brown in colour, relatively thin, irregular in shape, translucent and randomly contains stomata. It contains structured plant material mostly of cuticular origin and degraded aqueous plant material. It has buoyancy than palynomaceral 2.

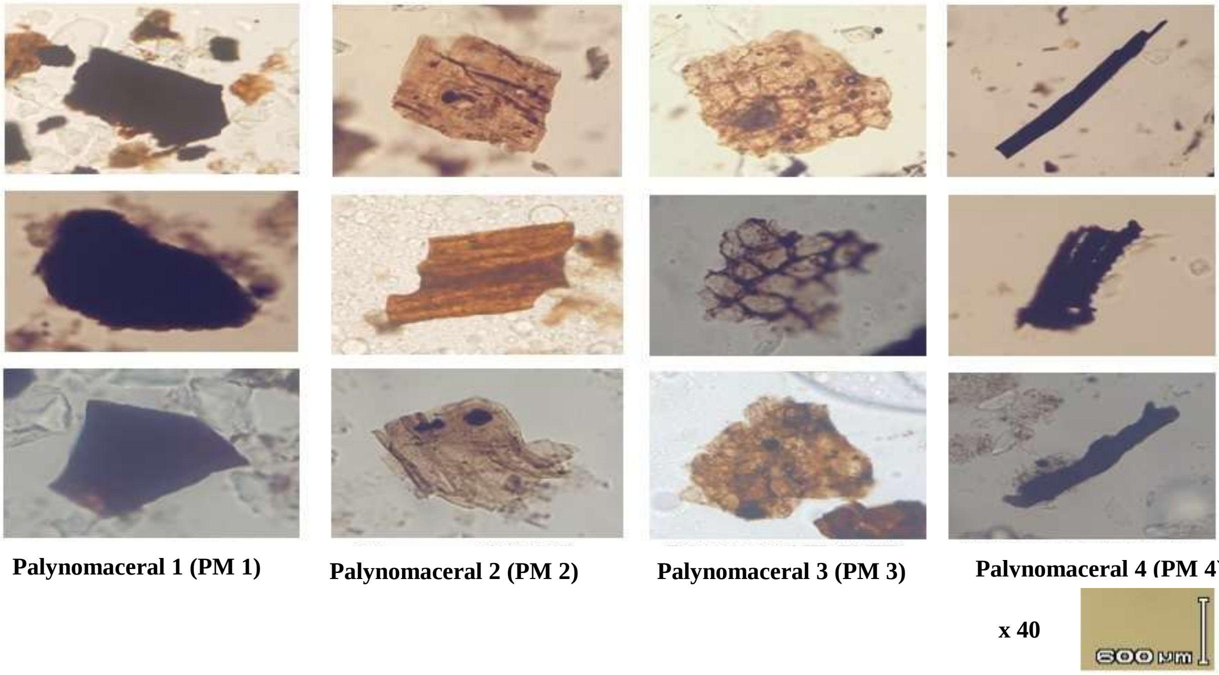


Plate I: Palynomaceral types recovered from HA-001, HB-001 and HD-001 wells

4.2.4 Palynomaceral 4 (PM 4)

The palynomaceral 4 (Inertnite) recovered from this study consist of black to dark brown coloured, equidimensional or blade-shaped materials which are generally opague and structureless. It is made up of compressed humic gels, charcoals and geothermally fusinized material. It has blade or needle shaped material. Blade shaped palynomaeceral 4 is highly buoyant and shows resistance to degradation. Therefore, they are usually transported over long distances. PM 4 are dominant in high energy environment.

4.3 Organic Maturation Levels for Palynofacies in the Studied Wells

(i) HA-001 WELL

Thermal Alteration Scale: Range between 4/5 – 5/6 (Batten, 1982).

Palynomorph colours: Range from light -medium brown to medium-dark brown (Pearson, 1984).

Degree of Maturation: Ranges from optimum petroleum generation to early gas generation (Figure 4.6).

(ii) HB-001 WELL

Thermal Alteration Scale: Ranging between 4/5 – 5/6 (Batten, 1982)

Palynomorph colours: Range from light-medium brown to medium-dark brown. (Pearson, 1984)

Degree of Maturation: Range from optimum petroleum generation to early gas generation (Figure 4.7).

(iii) HD-001WELL

Thermal Alteration Scale: Ranging from 3/4 – 5/6 (Batten, 1982)

Palynomorph colours: Range from orange-orange brown to medium to dark brown (Pearson 1984).

Degree of Maturation: Range from optimum petroleum generation to early gas generation (Figure 4.8).

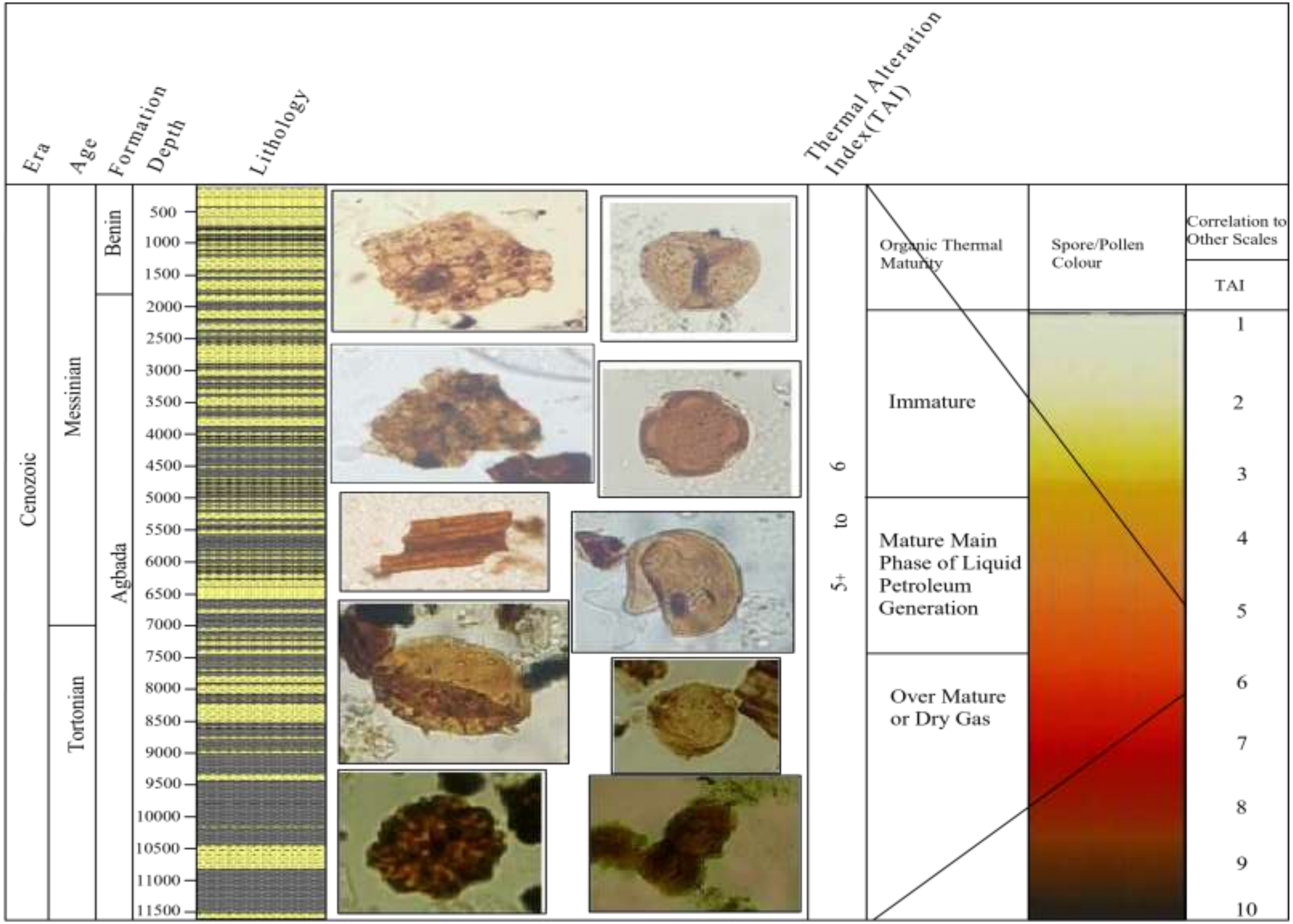


Figure 4.6: Palynofacies and organic thermal maturation of HA-001well

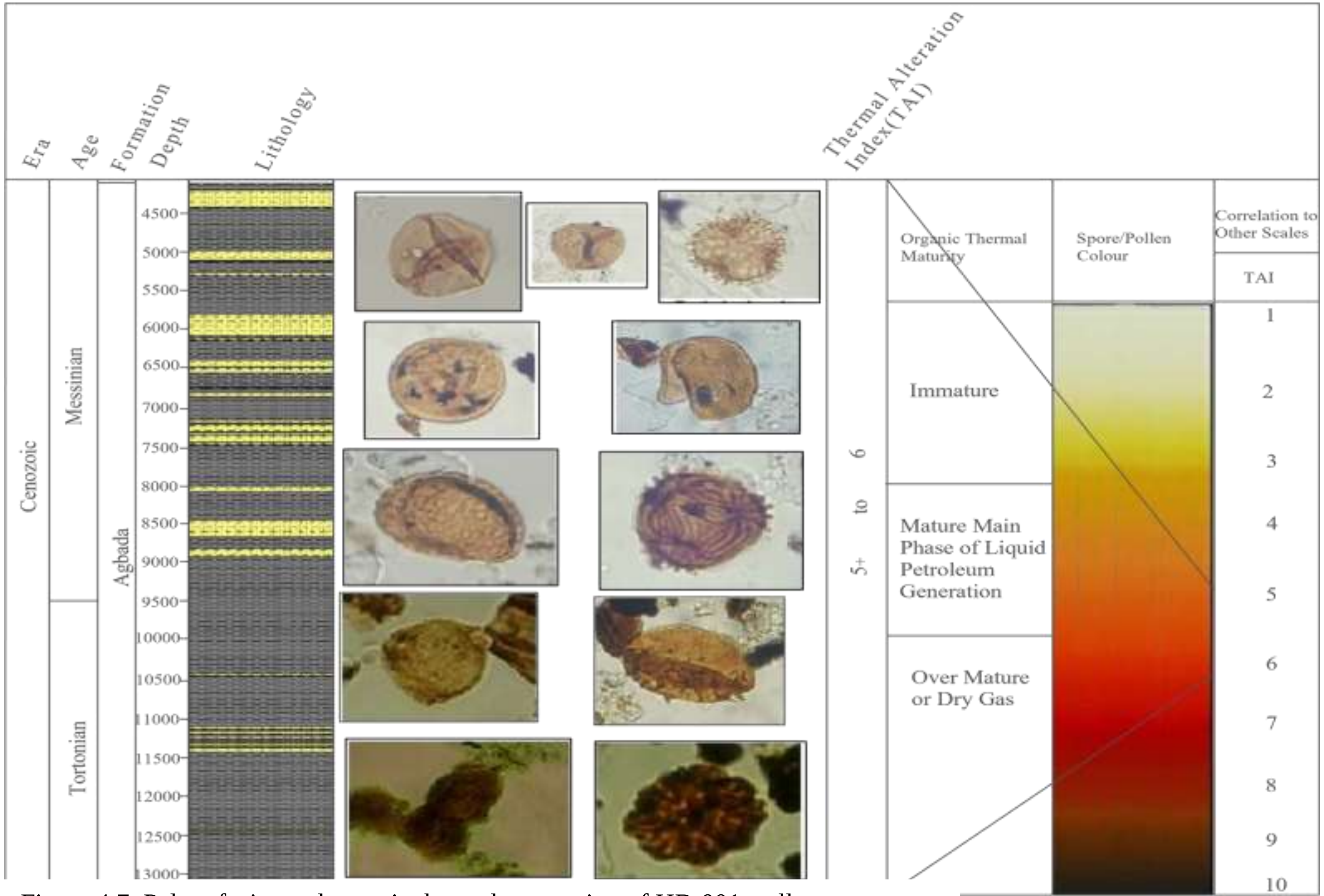


Figure 4.7: Palynofacies and organic thermal maturation of HB-001 well

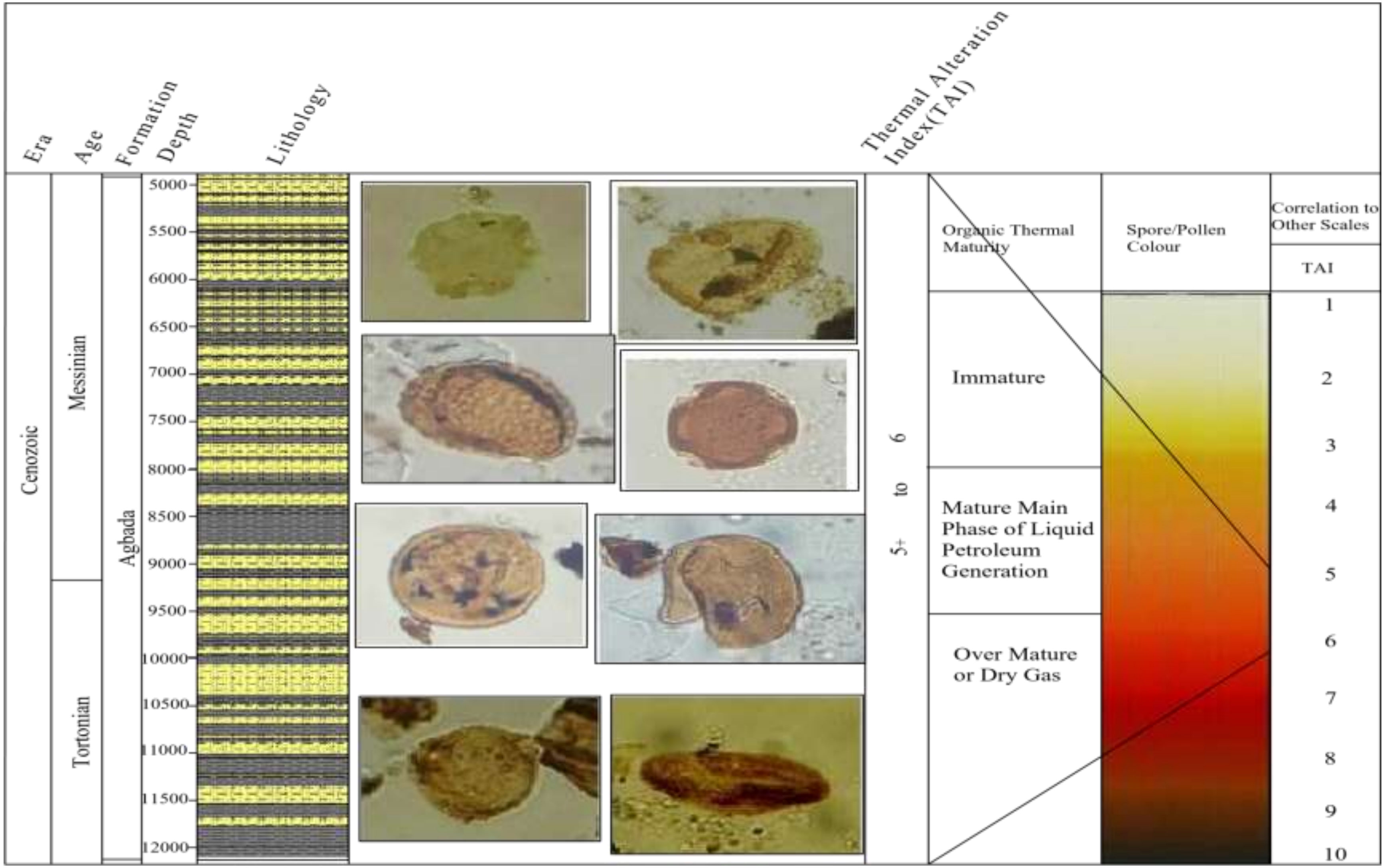


Figure 4.8: Palynofacies and organic thermal maturation of HD-001 well

4.4 Lithologic Description and Sedimentological Results

Detailed lithologic and sedimentological analyses result of HA, HB and HD-001 wells are presented in Figures 4.9 to 4.11. Sedimentological attributes are derived from the integrations of wire line log motifs and textural/lithologic attributes, the distribution of index accessories as well as our knowledge of the mutual juxtaposition of Niger Delta Basin sub-environments.

Detailed lithologic descriptions of the studied wells are presented in appendices A, B, and C. Textural characteristics and the distribution of index accessory minerals, according to Selley (1978); Durugbo and Uzodinma (2013), allowed the division of the entire intervals within the three wells into Agbada Formation, except the top depths of HA-001 well which is penetrated by continental Benin Formation. The lithologic subdivision of the three wells are shown in the Tables 4.1 to 4.3. The recognised lithofacies sequences were subdivided into subcycles of sedimentation. The Gamma Ray Log stacking pattern were used to delineate the subcycles which are interpreted to show authocyclicity.

4.4.1 Marine Paralic/Paralic Lithofacies Sequence of HA-001 Well (11500 – 3750 ft)

This interval is essentially a heterogeneous sequence of alternating sand and shale/ siltstone units. The regular pattern of sand and shale/siltstone intercalations permits easy recognition (on logs) of six hallocycles (third-order cycles) or subcycles of sedimentation within the marine paralic and paralic sequences. Each of these subcycles commences with a relatively thick marine shale/silt and progressively shallows into fluviomarine /fluviatile sands, based on the signatures of the gamma ray log and sand to shale ratio (Appendix D) (Selley, 1978; Durugbo and Uzodinma, 2013).

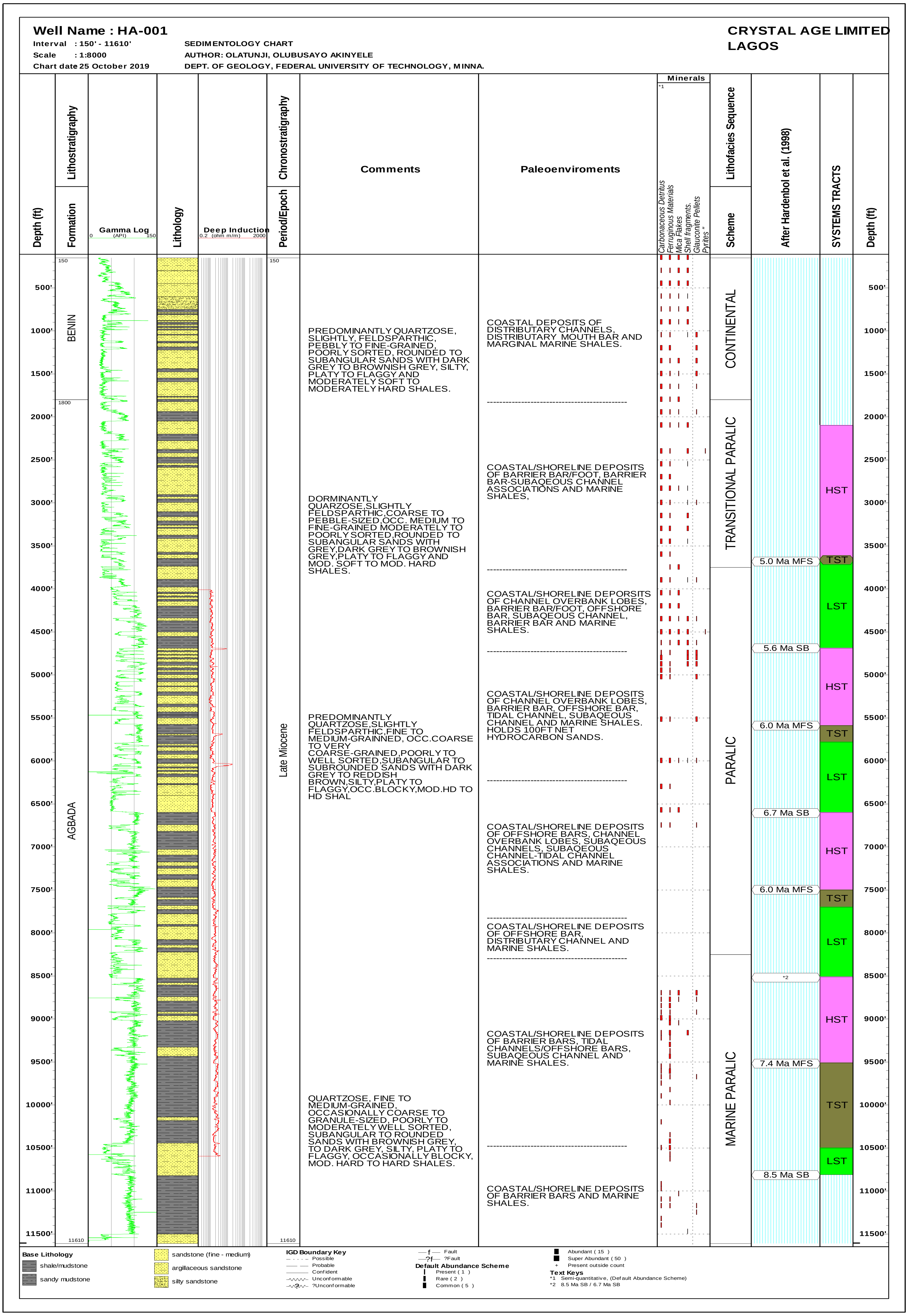


Figure 4.9: Lithologic and sedimentological chart of HA-001 well

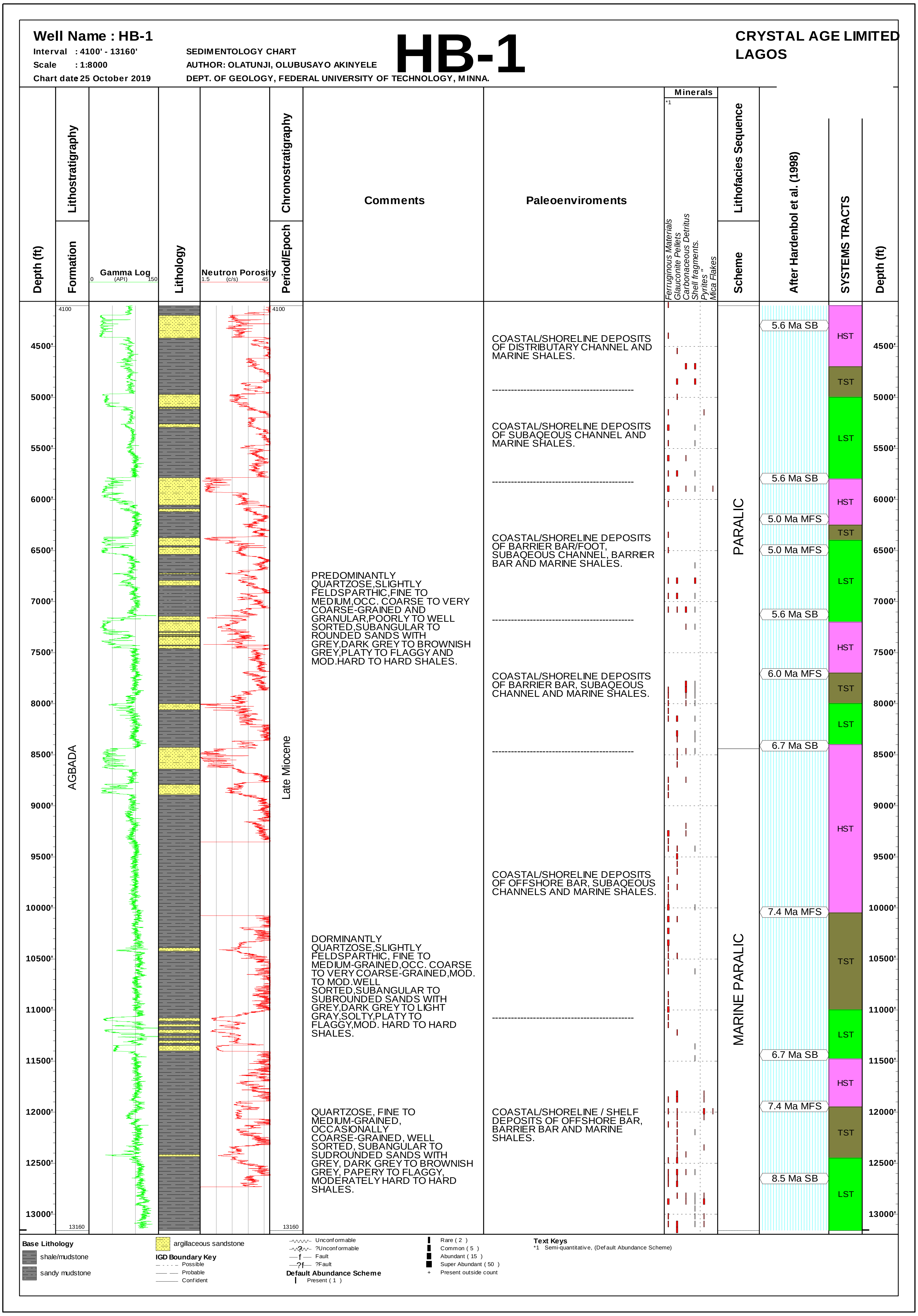


Figure 4.10: Lithologic and sedimentological chart of HB-001 well

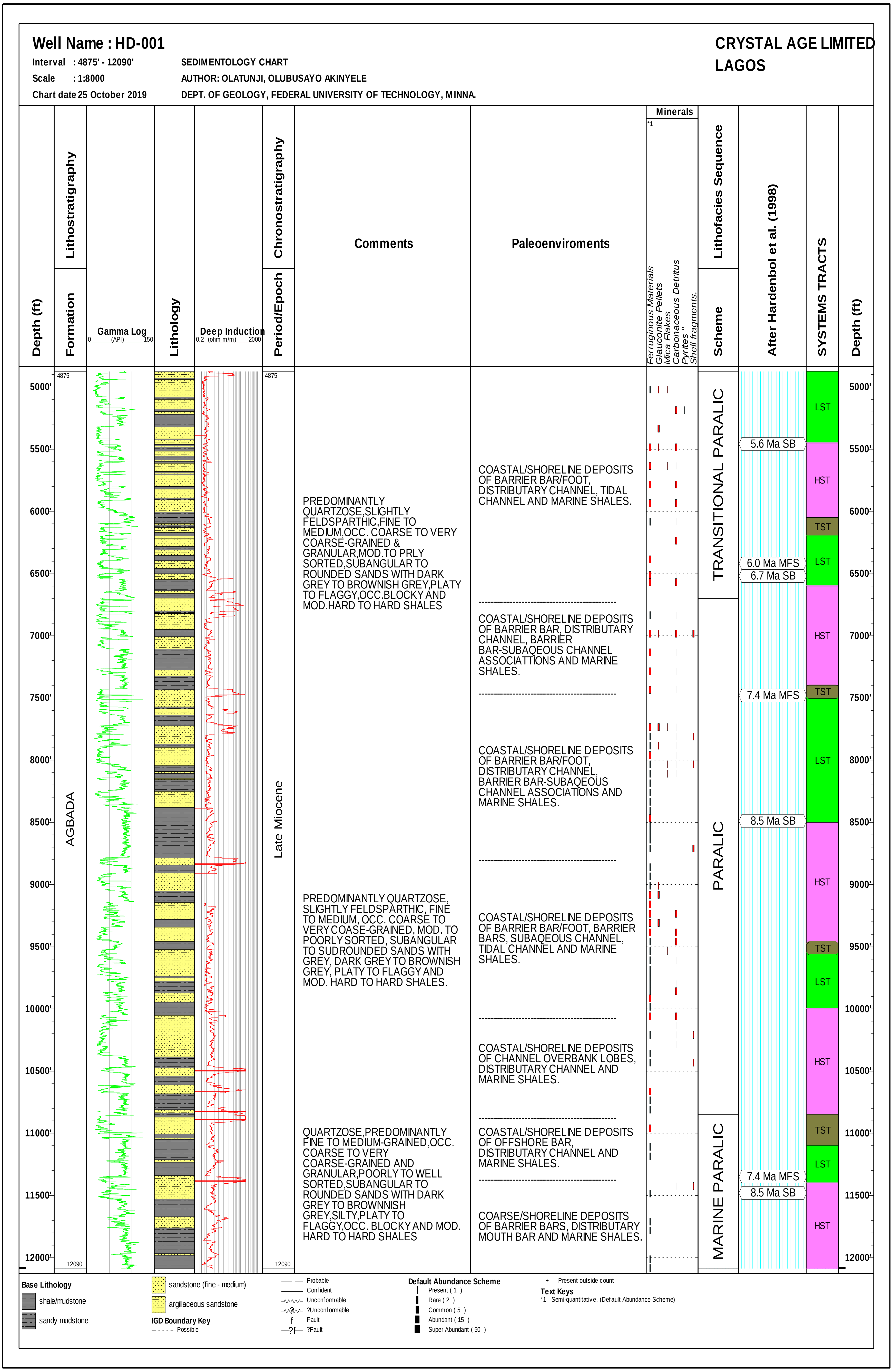


Figure 4.11: Lithologic and sedimentological chart of HD-001 well

Table 4.1: Lithostratigraphic Subdivision of HA-001 Well

Interval (ft)	Lithofacies Sequence	Lithological Characteristic	Inferred Formation
150– 1,800	CONTINENTAL	-Predominantly sands with minor shale intercalations. -Sands are predominantly quartzose, slightly feldsparthic, pebbly to fine-grained. -Sands are generally poorly-sorted. -Sand/Shale ratio of approximately 90:10.	BENIN
1,800– 3,750	TRANSITIONAL PARALIC	-Predominantly sands with occasional shale intercalations -Sands are predominantly quartzose, slightly feldsparthic, fine to granule-sized with occasional pebbles. -Sands are generally moderately to poorly sorted -Sand/ Shale ratio of 80:20.	AGBADA
3,750- 8,250	PARALIC	-Heterogenous sequence of alternating sand and shale/ silt units. -Sands are predominantly quartzose, slightly feldsparthic, fine to medium, occasionally coarse to very coarse-grained. -Sands are generally poorly to well sorted. -Sand/ Shale ratio of approximately 60:40.	
8,250- 11,500	MARINE PARALIC	-Predominantly shale with relatively thin sands. -Sands are quartzose, fine to medium-grained, occasionally coarse to granule-sized. -Sands are poorly to moderately well sorted. Sand/ Shale ratio of approximately 25:75.	

Table 4.2: Lithostratigraphic Subdivision of HB-001 Well

Interval (ft)	Lithofacies Sequence	Lithological Characteristic	Inferred Formation
4,100– 8,440	PARALIC	-Predominantly shales with relatively thick sand intercalations. - Sands are predominantly quartzose, slightly feldsparthic, fine to medium, occasionally coarse to very coarse-grained and granular. -Sands are generally poorly to well-sorted -Sand/shale ratio of approximately 40:60.	AGBADA
8,440– 13,160	MARINE PARALIC	-Predominantly shales with relatively thin sand intercalations. From 8440 – 11675 ft Sands are predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and moderately to well sorted Below 11675 ft Sands are quartzose, fine to medium, occasionally coarse-grained and well sorted, -Sand/shale ratio of approximately 20:80.	

Table 4.3: Lithostratigraphic Subdivision of HD-001 Well

Interval (ft)	Lithofacies Sequence	Lithological Characteristic	Inferred Formation
4,875– 6,700	TRANSITIONAL PARALIC	-Predominantly sands with relatively thick shale intercalations. -Sands are predominantly quartzose, slightly feldsparthic, fine to medium – grained, occasionally coarse to very coarse – grained and granular. -Sands are moderately to poorly sorted -Sand/ Shale ratio of approximately 70:30.	AGBADA
6,700– 10,850	PARALIC	-Predominantly sands with relatively thick shale intercalations. -Sands are predominantly quartzose, slightly feldsparthic, fine to medium, occasionally coarse to very coarse –grained. -Sands are moderately to poorly sorted -Sand/ Shale ratio of approximately 60:40.	
10,850- 12090	MARINE PARALIC	-Predominantly shale with relatively thick sand intercalations. -Sands are quartzose, fine to medium, occasionally coarse to very coarse-grained and granular. Sands are poorly to well sorted. -Sand/ Shale ratio of approximately 30:70.	

The recognized subcycles are as summarized in Table 4.4 and discussed as follows:

Table 4.4: Lithofacies Subcycles of HA–001 Well Marine Paralic/Paralic Sequence

Lithofacies sequence	Subcycles	Depth interval (FT DF)	Thickness (ft)
Paralic	F	4700 – 3750	950
	E	6200 – 4700	1500
	D	7800 – 6200	1600
Marine Paralic	C	8250 – 7800	450
	B	10450 – 8250	2200
	A	11500 – 10450	1050

4.4.1.1: The marine paralic lithofacies sequence (11500 – 8250 ft)

The marine paralic lithofacies sequence has thick shale units. The sand/ shale ratio is approximately 25:75 (Appendix D) (Selley, 1978; Durugbo and Uzodinma, 2013), two (2) Depositional hallocycles (subcycles A and B, Table 4.4) were identified based on the signature of the Gamma Ray Log. Each hallocycle consists of underlying predominantly shaly (transgressive) phase, overlain by a thick sandy (regressive) phase. These hallocycles are:

(i) Subcycle A: (11500 – 10450 ft)

This is the lowermost section of the analysed interval and it is composed of a monotonously shaly lower section (11,500 – 10,850 ft), overlain by a stack of sands (10,850 – 10,450 ft). The shale is brownish grey to grey, silty, platy to flaggy, occasionally blocky and moderately hard to hard. The sands are quartzose, very fine to medium- grained, occasionally coarse to very coarse–grained and granular; angular to rounded, and moderately to poorly-sorted. Ferruginous materials, carbonaceous detritus, mica flakes, shell fragments and glauconite pellets characterized the sequence. The monotonously shaly character of the lower section and the presence of shell fragment and glauconite pellets are consistent with low energy, shallow marine settings.

The amplified sand unit of the upper section of the subcycle (10850 – 10450 ft) consisting of a stack of sands exhibiting upward coarsening profile indicative of a barrier bar build-up, probably deposited during progradational episode. This is further confirmed by the mixture of carbonaceous detritus, mica flakes and glauconite pellets (Selley, 1976).

(ii) Subcycle B: (10450 – 8250 ft)

This 2200ft thick subcycle is composed of hemipelagic shale with silty sand intercalations (10450 – 8500 ft), overlain by a sandy section (8500 – 8350ft). It constitutes the top of the marine paralic lithofacies sequences. The shale/ siltstone is brownish grey to dark grey, silty, platy to flaggy, occasionally blocky and moderately hard to hard. Lithologically, the sands are quartzose, fine to medium – grained, occasionally coarse to very coarse –grained, sub angular to surrounded and moderately sorted. Ferruginous materials, carbonaceous detritus, glauconite pellets and mica flakes occurring in varying abundances constitute the accessory minerals suite of this subcycle. Also, one spot occurrence of shell fragments was recorded at sample interval 9150 ft. The predominantly shaly/ silty character of the lower part of the subcycle and the presence of glauconite pellets, ferruginous materials and shell fragments suggest deposition in a low energy, oxygenated, shallow marine settings (Selley, 1976). The stack of sands over intervals 10300 – 10160 ft and 9450 – 9340 ft exhibiting upward coarsening grain-size profiles are probably of barrier bar origins. Elsewhere within the shales are fining upward and symmetrical sands interpreted as tidal channels and offshore bars -respectively.

The typical multiserrate cylinder-shaped log character coupled with the regular carbonaceous detritus and glauconite pellets may suggest subaqeous channel deposits of the lower deltaic plain for the sandy upper part (8500 – 8250 ft).

4.4.1.2: The paralic lithofacies sequence (8250 – 7800 ft)

This Lithofacies sequence directly overlies the marine paralic sequence. This interval is essentially a heterogenous sequence of alternating sand and shale/ mudstone units. (See table 4.4 and appendix D) (Selley, 1978; Durugbo and Uzodinma, 2013). The sand/ shale ratio is approximately 60:40. Four (4) depositional subcycles were differentiated within this sequence, based on the signature of Gamma Ray Log. These are:

(i) Subcycle C (8250 – 7800 ft)

This interval is made up of a thin shaly base (8250 – 8100 ft) with minor sand intercalations, overlain by a more sandy section (8100 – 7800 ft). Non-availability of ditch cutting samples for this interval restricted interpretation only on the wire-line log evidence. The subtle symmetrical sands occurring over interval 8200 – 8150 ft are most likely to be of offshore bar origin (Sneider *et al.,* 1978). The amplified sand unit of the upper section (8100 – 7800 ft) of this subcycle consisting of multiple stacks of well-developed sands exhibiting cylinder - shaped grain-size profile is interpreted as distributary channel deposits.

(ii) Subcycle D: (7800 – 6200 ft)

This subcycle is composed of a thick shale unit (7800 – 6400 ft) with several silty sand intercalations, overlain by a sandy interval (6400 – 6200 ft). Like subcycle C discussed above, the ditch cutting samples were not recovered, except for intervals 6750 – 6200 ft. The shale is grey, brownish grey to dark grey, platy to flaggy and moderately hard. The sands are milky white to smoky, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse/ very coarse grained, moderately to moderately well-sorted and sub-angular to sub-rounded. Rare to common carbonaceous detritus, mica flakes, rare ferruginous materials glauconite pellets were recorded. The log character of the sands within the shale unit vary from symmetrical, cresentric and cylinder-shaped motifs, probably interpreted as offshore bars, channel overbank lobes and subaqeous channels. The Gamma Ray Log motifs of the upper section (6400 – 6200 ft) is a hybrid sand unit of multiserrate cylinder with minor bells and are most probably subaqeous channel-tidal channel associations (Sneider *et al.*, 1978). This is corroborated by the presence of carbonaceous detritus and glauconite pellets. The gradual absence of shell fragments shows that the depositional environment probably deepened from base to top (Selley, 1976).

(iii) Subcycle E (6200 – 4700 ft)

This interval is composed of alternating sand and shale interbeds. The basal section (6200 – 5570 ft) is essentially shaly with few sand breaks, grading upwards into a predominantly sandy sequence (5570 – 4770 ft). The shale is grey, brownish grey to brown, platy to flaggy, occasionally blocky and moderately soft to hard. The sands are milky white, predominantly quartzose, slightly feldsparthic, fine to medium- grained, occasionally coarse to very coarse-grained, moderately to poorly sorted and sub-angular to sub-rounded. This subcycle recorded an increase in the abundance of accessory minerals carbonaceous detritus, shell fragments, glauconite pellets and ferruginous materials. They occur regularly in rare to common quantities.

The cresentric, funnel and symmetrical-shaped log motifs of the sands within the shaly lower section, coupled with the present of glauconite pellets and shell fragments may suggest these are channel overbank lobes, barrier bar and offshore bar deposits. These criteria indicate marine deposition in close proximity to the ancient shoreline (Selley, 1978).

The bell, serrate/ slightly serrate cylinder-shaped log motifs by the sands occurring over the upper section (5570 – 4700 ft), are interpreted as tidal channel and subaqeous channel deposits. Supportive of this deduction is the occurrence of carbonaceous detritus and glauconite pellets. The appearance of shell fragments may also suggest an infilling of the channel to shallower depth. This subcycle holds a total of 100 ft net hydrocarbon sands at intervals 6070 – 6030 ft, 5710 – 5680 ft and 4730 – 4700 ft.

(iv) Subcycle F (4700 – 3750 ft)

This is composed of alternating beds of sands and shales with a lower thick shale section (4700 – 4200 ft) with few sand breaks, overlain by a more sandy sequence (4200 – 3750 ft). It constitutes the top of the paralic lithofacies sequence. Lithologically, the sands are milky white to smoky, predominantly quartzose, slightly feldsparthic, fine to medium – grained, occasionally coarse to very coarse –grained, moderately to poorly sorted and sub-angular to sub-rounded. The shale is grey, dark grey to brown coloured, silty, platy to flaggy, occasionally blocky and moderately hard to hard. The accessory mineral suites are mostly shell fragments, mica flakes, carbonaceous detritus ferruginous materials and glauconite pellets in decreasing order of abundance. These criteria indicate deposition in the lower deltaic plain environment. The cresentric-shaped motif occurring over interval (4560 – 4500 ft) is interpreted as channel overbank lobes. The amplified sand unit occurring over the interval 4420 – 4350 ft exhibiting a subtle upward coarsening grain-size profile is most likely to be of barrier bar origin. The underlying high gamma shale bed is interpreted as a barrier foot (Weber, 1971). Elsewhere in the shale lower section, symmetrical-shaped sands occur and are most probably offshore bar deposits.

The serrate cylindrical with overall coarsening upward Gamma Ray log motifs of the upper section (4200 – 3750 ft) may suggest subaqeous channel and barrier bar deposits respectively. This is corroborated by the present of glauconite pellets and carbonaceous detritus (Selley, 1978). Sediments of this subcycle are believed to have been laid down in an inner shelf to coastal deltaic settings. Also, the trend of increasing abundance of shell fragments from the bottom to the top of this subcycle could be attributed to progressive shallowing of the environment.

4.4.1.3: The transitional paralic lithofacies sequence (3750 – 1800 ft)

This is composed of alternating sequence of sands (20 – 150 ft thick) and relatively thinner shales (10 – 100 ft thick). The sequence exhibits a sand/ shale ratio of approximately 80:20. The sands are predominantly quartzose, slightly feldspathic; fine to medium; occasionally coarse to granule-sized and pebbles, moderately to poorly sorted and sub-angular to rounded. The shale is grey, dark grey to reddish brown, platy to flaggy and moderately soft to moderately hard. Index accessories are dominated by carbonaceous detritus, shell fragments and ferruginous materials. Rare glauconite pellets and mica flakes are recorded with one spot occurrence of pyrites at interval 2400 ft. This suggests deposition in a high energy, subwave, suboxic to anoxic, deltaic environment (Selley, 1976).

The sand/ shale alternation of the sequence suggests frequent interchanging high and low depositional energy regimes which might have resulted from a frequently shifting depositional axis on a gently subsiding passive continental margin. However, the higher proportion of sand and the ubiquitous occurrence of carbonaceous detritus suggest that it was deposited under a generally higher energy regime than the underlying paralic Sequence and definitely represent an environment proximal to the underlying paralic/marine paralic sequence within a general deltaic environment.

The sand bodies exhibiting the funnel-shaped motifs over this sequence are proposed to be of barrier bar origin. The other sand bodies showing cylinder and cylinder on funnel-shaped motifs are suggested to be of subaqeous channel and subaqeous channel-barrier bar association origin. The shales interbedded with the sands are suspected to be of interdistributary/ prodelta origin (Selley, 1978).

The alternation of high and low energy regime is probably related to the well documented frequent shift of depositional axis in the Niger Delta Basin.

4.4.1.4: The continental lithofacies sequence (1800 – 750 ft)

This consists predominantly of poorly sorted pebbly to fine-grained sands with minor shale intercalations. The sequence exhibits a sand/ shale ratio of approximately of 90:10. The base is always defined by a major shift of resistivity to the left, probably marking the bottom of fresh water. (Resistivity log for this sequence is unavailable).

On gamma ray log the sands (10 – 250 ft thick) exhibit cylinder and funnel-shaped motifs. The sequence is very rich in accessory minerals dominated by shell fragments, carbonaceous detritus, mica flakes and ferruginous materials with glauconite pellets restricted to intervals 1800 – 1050 ft. The aforementioned criteria suggest that the sediments of this sequence are probably distributary channel and distributary mouth bar deposits of the upper deltaic plain in close proximity to the lower deltaic plain (Selley, 1978). The increase in sand- percentage suggests relative shallowing or tremendous shallow water clastic influx. The depositional environment probably shallowed from base to top.

4.4.2 Marine Paralic/Paralic Lithofacies Sequence of HB-001 Well (13160 – 8440 ft)

This interval is essentially a heterogeneous sequence of alternating sand and shale/ siltstone units. The regular pattern of sand and shale/siltstone intercalations permits easy recognition (on gamma ray logs) of six hallocycles (third-order cycles) or subcycles of sedimentation within the Marine paralic and paralic sequences. Each of these subcycles commences with a relatively thick marine shale/silt and progressively shallows into fluviomarine /fluviatile sands. The recognized subcycles are as summarized in Table 4.5 and discussed as follows:

Table 4.5: Lithofacies Subcycles of HB–001 Well Marine Paralic/ Paralic Sequence

Lithofacies sequence	Subcycles	Depth interval (FT DF)	Thickness (ft)
Paralic	F	4100 – 4900	700
	E	4900 – 5800	900
	D	5800 – 7150	1350
	C	7150 – 8440	1290
Marine Paralic	B	8440 – 11050	2610
	A	11050 – 13160	1110

4.4.2.1: The marine paralic lithofacies sequence (13160 – 8400 ft)

Two (2) Depositional hallocycles (Subcycles A and B, Table 4.5) were identified. Each hallocycles consists of underlying predominantly shaly (transgressive) phase, overlain by a sandy sequence. These hallocycles are:

(i) Subcycle A: (11590 – 11020 ft)

This is the lowermost section of the analysed interval and is composed of anomalously silty shale sequence (13160 – 11400ft) with occasional sand/silt intercalations, overlain by a stack of sand (11400 – 11050 ft). This subcycle correlates well with subcycle A of HA-001 and HD-001.

The shale is grey, dark grey to brownish grey, papery to flaggy, moderately hard to hard and is characterized by low resistivity. Index minerals present in the shale include glauconite pellets, pyrites, ferruginous materials, carbonaceous detritus, shell fragments and spotty occurrences of mica flakes. These criteria indicate slow deposition in an overall low energy, marine settings with irregular bottom conditions (Selley, 1976).

Over the interval 12420 – 12400 ft, a genetic sand unit occur, exhibiting a thin symmetrical-shaped motif probably of offshore bar origin.

The upper sandy section (11400 – 11050 ft) is characteristically milky white, quartzose, fine to medium; occasionally coarse-grained and moderately to well sorted. The coarsening upward grain size profiles of the stack of sands coupled with the presence of glauconite pellets, shell fragments and carbonaceous detritus is interpreted as barrier bar deposits (Selley, 1978).

(ii) Subcycle B (11050 – 8440 ft)

This subcycle commences with a 2170 ft thick hemipelagic shaly section (11050 – 8440 ft) with thin sand intercalations, overlain by a relatively short sandy sequence (8880 – 8440 ft). It constitutes the top of marine paralic lithofacies sequence.

The shale is homogenous, light grey, dark grey to brownish grey, silty, platy to flaggy, moderately hard and is characterised by low resistivity. The sands are milky white, fine to medium-grained, occasionally coarse to very coarse-grained, sub-angular to sub-rounded and moderately to well sorted. Rare to few ferruginous materials and rare to common glauconite pellets are noted almost throughout the subcycle. Carbonaceous detritus and shell fragments are rare and fairly regular.

The predominantly shaly/silty character of the lower section and the persistence of glauconite pellets and ferruginous materials suggest deposition in a low energy, oxic, shallow marine settings. The symmetrical-shaped sand profile occurring over interval 10420 – 10400ft within the shale, is interpreted as offshore bar deposits (Sneider *et al.*, 1978).

The sand bodies occurring over the upper section of the subcycle, intervals 8900 – 8800 ft and 8650 – 8440 ft characterized by slightly serrate to multiserrate cylinder-shaped motifs interpreted as subaqeous channel deposits, suggest intermittent high energy clastic influx into the depositional basin. This may explain the presence of ferruginous materials and carbonaceous detritus in the subcycle. The foregoing inferences suggest a lower deltaic plain environment of deposition for the subcycle.

4.4.2.2: The paralic lithofacies sequence (8440 – 4100 ft)

This Lithofacies sequence directly overlies the Marine Paralic sequence. These consist of predominantly well-developed shale with relatively thick sand intercalations. (See Table 4.5 and Appendix E). Four (4) depositional subcycles were differentiated within this sequence. These are:

(i) Subcycle C (8440 – 7150 ft)

Just as in HA-001 and HD-001, this subcycle is composed of shaly lower section (8440 – 7460 ft) with a silty sand intercalation at the base, overlain by a sandy sequence (7460 – 7150 ft). The shale is dark grey to grey, platy to flaggy and moderately hard to hard. Lithologically, the sands are predominantly quartzose, slightly feldspathic, fine to medium – grained, occasionally coarse/ very coarse – grained, moderately well sorted and sub-angular to sub-rounded.

Glauconite pellets, carbonaceous detritus, shell fragments and ferruginous materials characterised the subcycle. The predominantly shaly character of the lower part of the subcycle, presence of glauconite pellets and shell fragments suggest deposition in low energy, shallow marine settings (Selley, 1978). The subtle upward coarsening sands occurring over interval 8080 – 8000 ft is most likely to be of barrier bar origin. This is corroborated by the presence of glauconite pellets, shell fragments and carbonaceous detritus. The slightly serrate to multiserrate cylinder-shaped motifs exhibited by the sands occurring over the upper section (7460-7150 ft) of this subcycle are interpreted as subaqeous channels and indicate prograding shorelines. Presence of carbonaceous detritus, shell fragments and glauconite pellets lends credence to this interpretation (Appendix E). Also, the appearance of shell fragments suggests an infilling of the channel to shallower depth.

(ii) Subcycle D: (7150 – 5800 ft)

This subcycle starts with a thick silty shale unit (7150 – 6540 ft), followed by a predominantly sandy sequence (6540 – 5800 ft) with a 270 ft shale inter-bed.

The shale is grey, dark grey to grey, platy to flaggy and moderately hard to hard. The sands are milky white to buff, predominantly fine to medium-grained, occasionally coarse to very coarse-grained, moderately to well sorted and sub-angular to sub-rounded Index minerals and accessories are dominated by ferruginous materials, shell fragments, glauconite pellets and carbonaceous detritus with rare mica flakes.The predominantly shaly character of the lower section and the persistence of ferruginous materials, shell fragments and glauconite pellets are consistent with low energy, sub-wave, sub-oxic, shallow marine settings. The amplified sand unit occurring over interval 6860 – 6710 ft within the shale exhibiting a subtle upward coarsening grainsize profile is most likely to be of barrier bar origin. The underlying high gamma shale bed is interpreted as a barrier foot (Weber, 1971).

The multiserrate cylinder and funnel-shaped log character of the upper section (6540 – 5800 ft) and the mixture of carbonaceous detritus glauconite pellets may suggest a subaqeous channel and barrier bar deposits respectively for the sands. The trend of increasing abundance of shell fragment from the bottom to the top of this subcycle could be attributable to progressive shallowing of the environments.

Presence of shell fragments, carbonaceous detritus and pyrites lends credence to this interpretation. Sediments of this subcycle are interpreted to have been laid down in inner shelf to coastal deltaic environments.

(iii) Subcycle E (5800 – 4900 ft)

This relatively short subcycle starts with a monotonously shaly lower section (5800 – 5100 ft), overlain by a genetic sand interval (5100 – 4900 ft)

The shale is grey, brownish grey to dark grey, blocky to platy and hard to moderately hard. The sands are typically milky white to buff, fine to medium- grained, occasionally coarse to granular and pebbles, sub-angular to rounded and moderately to poorly- sorted. The accessory mineral suites are mostly shell fragments, ferruginous materials, glauconite pellets and carbonaceous detritus in decreasing order of abundance. Mica flakes pyrites are spotty. These criteria indicate deposition in lower deltaic plain environments. The monotonously shaly character coupled with the presence of glauconite pellets and shell fragments indicate deposition in a low energy, shallow marine settings in close proximity to the ancient shoreline. The aforementioned evidence coupled with the GR log character suggests that the slightly serrate/ smooth cylinder/ cylinder-shaped sands are most likely subaqeous channel deposits. Further supporting these deductions, is the presence of carbonaceous detritus and glauconite pellets (Selley, 1978).

(iv) Subcycle F (4900 – 4100 ft)

Just as in subcycle E discussed above, this short subcycle commences with a monotonously shale unit (4900 – 4410 ft), overlain by a sandy interval (4410 – 4100 ft) which was not fully analyzed at the top. The gamma ray log character suggests a good shale development within the lower section of the subcycle. Complementary evidence from ditch descriptions indicates an overall sandiness. These seemingly contradictory observations may be attributable to down-hole cavings or lag time errors.

The sands are fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly-sorted and sub-angular to rounded. The shale is grey, brownish grey to dark grey and platy to flaggy, occasionally blocky and hard to moderately hard. Index accessories are dominated by glauconite pellets, shell fragments and carbonaceous detritus but restricted to the lower section of the subcycle. Ferruginous materials are rare and occur sparingly (Selley, 1978).

On the gamma ray log, the amplified sand of the upper part of the subcycle exhibits a multiserrate cylinder-shaped motif interpreted as distributary channel deposits.

Compared with HA-001 and HD-001, this subcycle is better developed.

4.4.3 Marine Paralic/Paralic Lithofacies Sequence of HD-001 Well (12090–6700 ft)

This interval is mainly a heterogeneous sequence of alternating sand and shale/ siltstone units. The regular pattern of sand and shale/siltstone intercalations allows easy recognition on gamma ray logs of six hallocycles (third-order cycles) or subcycles of sedimentation within the marine paralic and paralic sequences. Each of these subcycles commences with a relatively thick marine shale/silt and progressively shallows into fluviomarine /fluviatile sands. The recognised subcycles are as summarised in Table 4.6 and discussed as follows.

4.4.3.1: The marine paralic lithofacies sequence (12090 – 10850 ft)

The marine paralic lithofacies sequence is characterised by thinner shale units compared to those found in HA -001 and HB-001 (Table 4.3). The sand/ shale ratio is approximately.

Table 4.6: Lithofacies Subcycles of HD–001 Well Marine Paralic/ Paralic Sequence

Lithofaciessequence	Subcycles	Depth interval (ft)	Thickness (ft)
Paralic	F	6700 – 7440	740
	E	7440 – 8780	1340
	D	8780 – 10050	1270
	C	10050 – 10850	800
Marine Paralic	B	10850 – 11350	500
	A	11350 – 12090	740

30:70. Compared with HA -001 and HB -001, two (2) depositional hallocycles (subcycles A and B, Table 4.6) were identified. Each hallocycles consists of underlying predominantly shaly (transgressive) phase, overlain by a thick sandy (regressive) phase. These hallocycles are:

(i) Subcycle A: (12090 – 11350 ft)

Just as in HA-001 and HB-001, this is the lowermost section of the analysed interval and is composed of a thick shale unit (12090–11550ft) with silty sand intercalations, overlain by a stack of sands (11550 – 11350 ft). The shale is dark grey to brownish grey, silty, platy to flaggy, occasionally blocky and moderately hard to hard. The sands are milky white, quartzose, fine to medium- grained, occasionally coarse-grained to very coarse-grained and granular, poorly to well sorted and sub-angular to rounded rare ferruginous materials occur almost throughout the subcycle with spotty records of mica flakes and shell fragments at sample interval 11415 ft.

The predominantly shaly/silty character of the lower part of the subcycle and the presence of ferruginous materials suggest deposition in a low energy, oxic, shallow marine settings (Selley, 1978). The subtle upward coarsening grainsizes profiles occurring over intervals 12010 – 11980 and 11800 – 11700 ft are most likely to be of barrier bar origin.

At the upper section of the subcycle (11550 – 11350 ft) consisting of stack of sands characterised by coarsening upward profiles interpreted as distributary mouth bar build-ups, indicate prograding shoreline. Supporting these deductions are the co-occurrence of mica flakes, shell fragments and absence of glauconite pellets.

(ii) Subcycle B (11350 – 10850 ft)

This subcycle commences with a silty shale (11350 – 11000 ft) with thin sand intercalations, overlain by a sandy section (11000 – 10850ft). It constitutes the top of the marine paralic lithofacies sequence.

The shale is dark grey to brownish grey, silty, platy to flaggy and moderately hard to hard. The sands are milky white, predominantly fine to medium – grained, occasionally coarse/ very coarse –grained, sub-angular to sub-rounded and moderately to well sorted.

Rare/ few ferruginous materials occur almost throughout the subcycle. The predominantly shaly/ silty character of the lower section of the subcycle and the occurrence of ferruginous materials are consistent with low energy, oxic, shallow marine settings. The symmetrical sands occurring over intervals 11240 – 11230 ft within the shale is most probably an offshore bar deposit (Sneider *et al*., 1978)

The sand units of the upper section (11000 – 10850 ft) characterised by multiserrate cylinder-shaped motifs are most probably distributary channel deposits of the lower deltaic plain. It suggests intermittent high energy burst into the depositional basin. This may also explain the presence of ferruginous materials in the subcycle.

4.4.3.2: The paralic lithofacies sequence (10850 – 6700 ft)

This lithofacies unit directly overlies the marine paralic sequence. These consist predominantly of well-developed thick sands with relatively thick shaly intervals. (Table 4.6 and Appendix F). Four (4) depositional subcycles were differentiated within this sequence. These are:

(i) Subcycle C (10050 – 10850 ft)

Just as HA-001, this subcycle is composed of shaly section (10850 – 10380 ft) with silty sand intercalations at the base, overlain by a sandy interval (10380 – 10050 ft).

The shale is grey, dark grey to brownish grey, silty, platy to flaggy and moderately hard to hard. The sands are quartzose, fine to medium – grained, occasionally coarse to very coarse –grained, moderately sorted and sub-angular to sub-rounded. Ferruginous materials, carbonaceous detritus and shell fragments characterized the sequence. Two genetic sand units exhibit cresentric –shaped profile over the intervals 10680 – 10620 ft and 10510 – 10470 ft and are most probably channel overbank lobes.

While the upper section of the subcycle (10380 – 10050 ft) consisting of sands characterised by multiserrate cylinder character is interpreted as distributary channel deposits. This is further confirmed by the mixture of carbonaceous detritus, shell fragments and absence of glauconite pellets (Selley, 1976).

(ii) Subcycle D: (10050 – 8780 ft)

This subcycle is composed of a thin shale unit (10050 – 9800 ft) with minor sand intercalations, overlain by a predominantly sandy section (9800 – 8780 ft). The sands are milky white, fine to medium-grained, occasionally coarse to very coarse to very coarse-grained, moderately to well sorted and sub-angular to sub -rounded. The shale is dark grey to grey, silty, platy to flaggy and moderately hard to hard.

Index minerals are dominated by ferruginous materials, carbonaceous detritus and glauconite pellets. The coarsening upward sand occurring over interval 9950 – 9900 ft within the shale is most probably a barrier bar/ foot origin.

The aforementioned evidence coupled with the log character of the sand at the upper section (9800 – 8780 ft) suggest that the multiserrate upward coarsening, cylinder and fining upward profiles are most likely barrier bars, subaqeous channel and tidal channel deposits (prograding complex). Sediments of this subcycle are believed to have been laid down in coastal deltaic to inner shelf environments (Sneider *et al.*, 1978).

(iii) Subcycle E (8780 – 7440 ft)

This interval is composed of alternating beds of sand and shale with a shaly lower section (8780 – 8370 ft), overlain by a predominantly sandy sequence (8370 – 7440 ft).

The shale is grey, dark grey to brownish grey, platy to flaggy and moderately hard to hard. The sands are predominantly quartzose, slightly feldsparthic, fine to medium – grained, occasionally coarse to very coarse –grained and granular, moderately to poorly sorted and sub-angular to round.

Mica flakes and glauconite pellets are spotty while ferruginous materials and carbonaceous detritus occur in rare to few quantities. Rare shell fragments are noted over the upper section of the subcycle (8080 – 7440 ft). The predominantly shaly character of the lower section coupled with presence of glauconite pellets indicate deposition in low energy marine settings in close proximity to the ancient shoreline (Selley, 1978).

The gamma ray log motifs of the upper section of this subcycle (8370 – 7440 ft) are essentially coarsening upwards, cylinders and coarsening upwards on cylinder -shaped profiles interpreted as barrier bar/ foot, distributary channel and barrier bar- subaqeous channel associations. This suggest intermittent high energy clastic burst into the depositional basin. The appearance of shell fragments may also suggest an in-filling of the channel to shallower depth.

(iv) Subcycle F (7440 – 6700 ft)

This short subcycle have striking resemblance in log motifs and lithologic attributes with the subcycle E discussed above. Characteristically, it is composed of alternating beds of sands and shales with a shaly lower section (7440 – 7110 ft) with minor sand breaks, overlain by a predominantly sandy sequence (7110 – 6700 ft). This sandy section is less pronounced in HB-001 or some part probably eroded.

Index minerals and accessories are mostly ferruginous materials, carbonaceous detritus with spot occurrences of shell fragments and glauconite pellets noted at depth interval 6990 ft. These criteria indicate deposition in the lower deltaic plain environment. As in HA-001, the amplified sand unit occurring over the interval 7330 – 7260 ft exhibiting a subtle upward coarsening grain size profile is most probably of barrier bar origin.

The typical cylinder, funnel-cylinder shaped log character coupled with the persistence of ferruginous materials, carbonaceous detritus shell fragment and glauconite pellets in the upper part of the subcycle may suggest a distributary channel, barrier bar-subaqeous channel associations for these sands. The appearance of shell fragments towards the top of this subcycle could be attributed to shallowing of the environment from bottom to the top (Selley, 1978).

4.4.3.3: The transitional paralic lithofacies sequence (6700 – 4875 ft)

This lithofacies sequence is characterised by frequent sand/ shale alternations with the sand bodies being generally thicker than the shale units. The thickness of the sands range from 10 – 180 ft and the shale intercalation less than 100 ft. The sequence exhibits a sand/ shale ratio of approximately of 70:30. Over the upper section of the sequence (4875 – 5940 ft), the sands are predominantly quartzose, slightly feldsparthic; fine to medium; occasionally coarse to granule-sized and moderately to poorly sorted. The lower interval (5940 – 6700 ft) is dominated by fine to medium, occasionally coarse to very coarse-grained sands. The shale is grey, dark grey to brownish grey, platy to flaggy, occasionally blocky and moderately hard to hard. Rare to abundant carbonaceous detritus, rare to common ferruginous materials are noted throughout the sequence (Appendix F). Glauconite pellets occur in rare to few quantities over the interval 5490 - 4875 ft with occasional occurrences of mica flakes and pyrites. The sand/ shale alternation of the sequence suggests frequent interchanging high and low depositional energy regimes which might have resulted from a frequently shifting depositional axis on a gently subsiding passive continental margin. However, the higher proportion of sand and the ubiquitous occurrence of carbonaceous detritus suggest that it was deposited under a generally higher energy regime than the underlying paralic sequence and definitely represent an environment proximal to the underlying paralic/ marine paralic Sequence within a general deltaic environment (Selley, 1978).

The log characters of the sands are essentially funnel, cylinder and minor bell-shaped motifs. This coupled with the presence of carbonaceous detritus and glauconite pellets suggest deposition in the lower deltaic sub-environment varying from barrier bars/ foot, distributary channels and tidal channel. The shale interbeds represent backswamp deposits (interdistributary prodelta deposits). Also, the absence of shell fragment and the spot occurrence of pyrite may indicate that the depositional environment slightly deepens from base to top.

4.4.4 Correlation of Lithofacies in HA-001, HB-001 and HD-001 Wells

The integration of sedimentologic description with wire-line logs allowed correlation of the sequences based on similar lithogies in the three studied wells. The similarities in the Gamma Ray Log signatures permitted the lithofacies correlation. The different lithofacies subcycles in HA – 001, HB -001 and HD – 001 displayed correlation within their sequences.

A good correlation exists between the most subcycles in the three wells (Figure 4.12) though penetrated sections of HA – 001 are far shallower than their equivalent settings in HB – 001and HD – 001which are further updip of the area (Tables 4.4 to 4.6). Sedimentation rate in the three wells is rapid as inferred on the basis of the thick marine paralic, paralic, transitional paralic section and short stratigraphic age of Late Miocene encountered. Sedimentation within the marine paralic/paralic and transitional paralic sequences are episodic and in various lobes not at different times. The correlation indicates the presence of lateral continuity of the lithofacies sequences in the studied area. This is significant in the exploration of hydrocarbon.

4.5 Paleoenvironment of Deposition

The periodic changes in the depositional environment over geologic time are inferred from paleoenvironment of deposition. Interpretation of paleodepositional environment is necessary for understanding various depositional environments and their reservoirs' attributes such as porosity, permeability and architectecture.

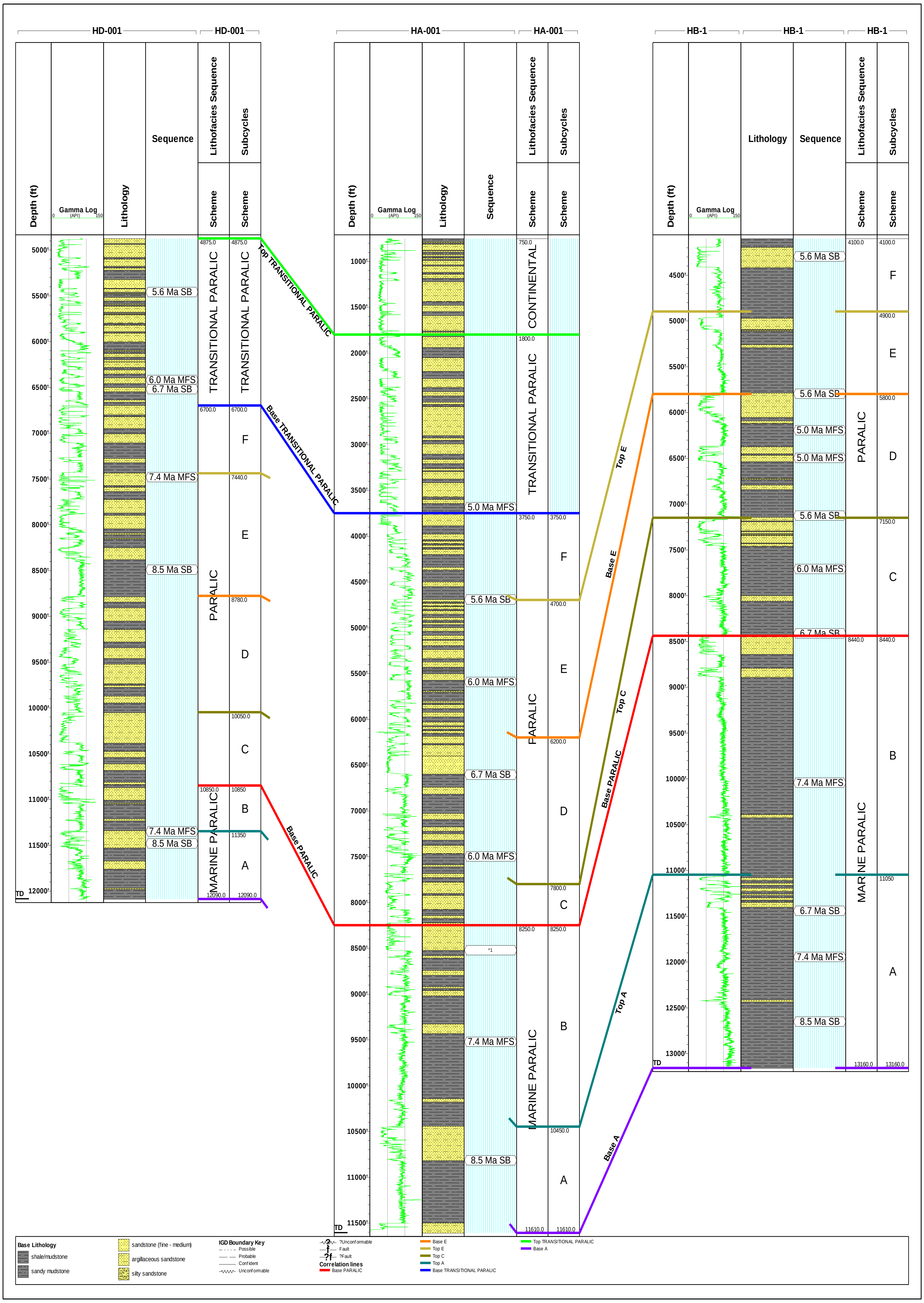


Figure 4.12: Correlation chart for Lithofacies sequences of HA-001, HB-001 and HD-001 wells

Quantitative variations of the palyno-ecological groups of the studied palynomorphs (Appendices G to I) such *Zonocostites ramonae, Psilatricolporites crassus, Monoporites annulatus, Cyperaceaepollis* sp., *Pachydermites diederixi* and *Botryococuss braunii*. The three studied wells showed that the palynomorphs taxa have freshwater swamp taxa with the highest representation of the total recovered palynomorphs, followed by mangrove and Savanah taxa in the three wells (Figures 4.13 to 4.15) Rainforest swamp and montane taxa have the lower representation in the three wells. During sea level fall, erosion and incision take place along coastal plain. The mangrove swamp taxa will be of reduced extent as well as freshwater swamps. Therefore, the early stage of sea level fall is expected to have low abundance of coastal swamp species and increased pollen resulting from well-drained fluvial settings (Morley, 1995; Adojoh *et al.*, 2015). Savanah and montane taxa become widespread. When sea level rises, upper delta plain develops and it is controlled by freshwater and alluvial wetland (Poutmot, 1989). The presence of mangrove pollen will increase while the freshwater and rainforest swamps become expanded until the sea level falls (Figures 3.8 and 3.9) (Morley, 1995; Rull, 2002). The coastal environments are distinguished by poorly sorted palynomacerals 1 and 2, common to rich occurences of fungal spores and absence of dinocysts.

The marine environment is recognized by small to medium organic matter that are well sorted, common to abundant palynomaceral 1 and 2, some needle-shaped to lath-shapedpalynomaceral 4 and presence of foraminiferal linings and dinocysts (Oyede, 1992).

The index minerals common in shallow water environments are ferruginous materials, shellfragments and carbonaceous detritus. Mica flakes pyrites and gluaconites pellets are index mineral found in deeper water conditions (Selley, 1978).

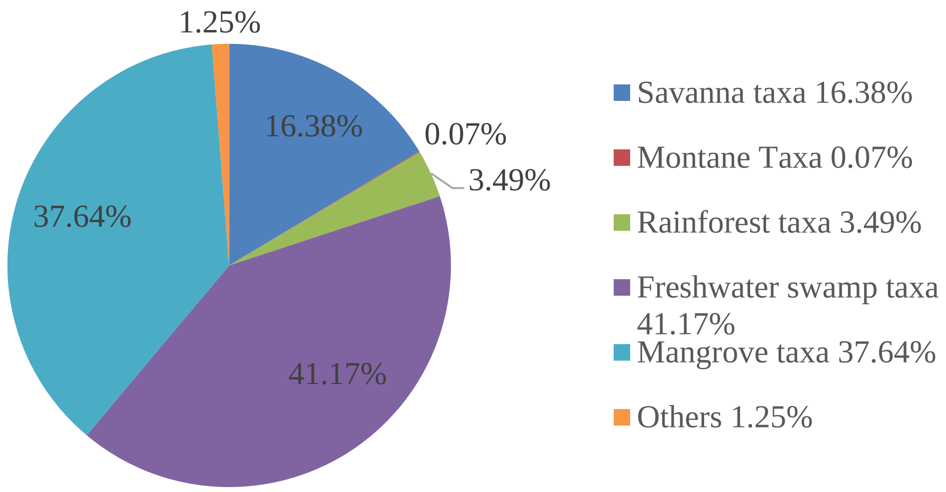


Figure 4.13: Palyno-ecological groups of palynomorphs from HA-001 well

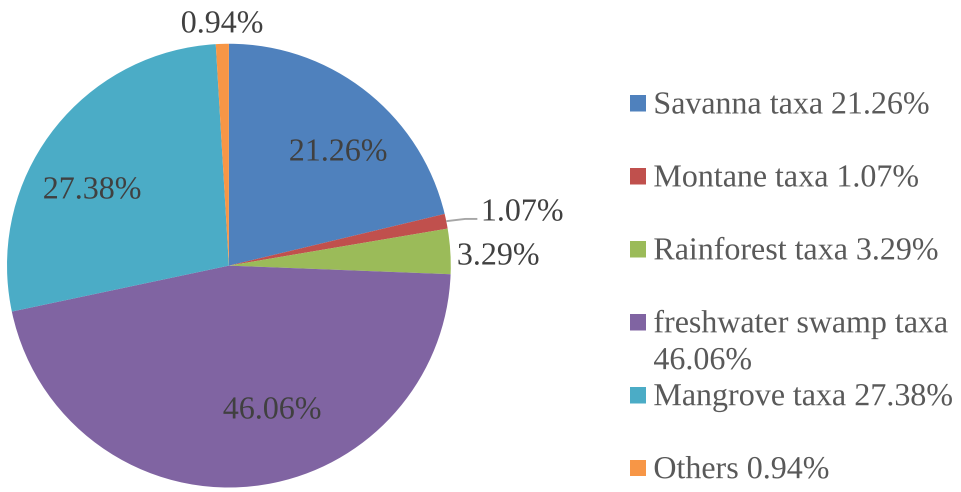


Figure 4.14: Palyno-ecological groups of palynomorphs from HB-001 well

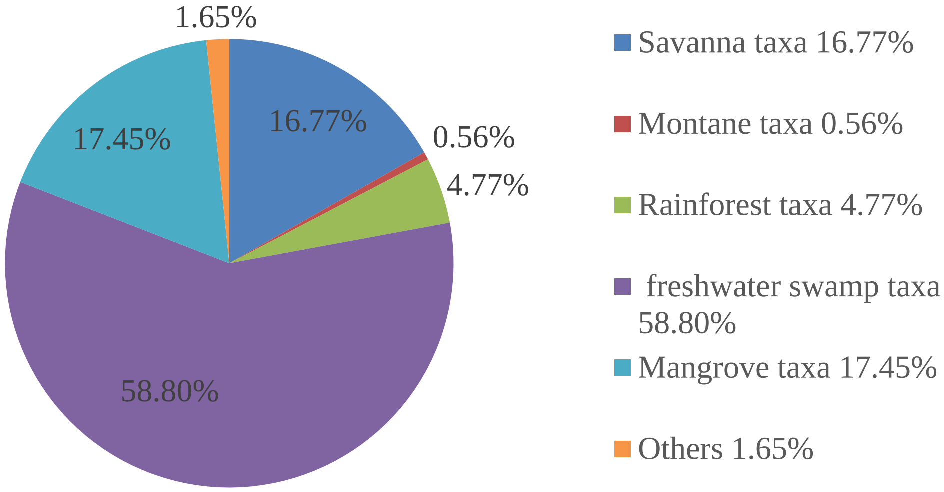


Figure 4.15: Palyno-ecological groups of palynomorphs from HD-001 well

Lower delta plain to delta front and prodelta environment within coastal deltaic to shallow marine environment of deposition were inferred for the studied intervals of HA-001, HB-001 and HD-001 wells (Figures 3.8, 3.9 and Table 4.7)

The intervals 150 – 5000 ft, 4100 – 5800 ft and 4875 – 5940 ft in HA-001, HB-001 and HD-001 wells respectively were interpreted to be deposited in the lower delta plain environment which is equivalent to foreshore environment (Figures 3.8, 3.9 and Table 4.7). The criteria for interpretation are:

Table 4.7: Environment of Deposition in HA-001, HB-001 AND HD-001 Wells

HA-001 well intervals (ft)	HB-001 well intervals (ft)	HD-001 well intervals (ft)	Inferred environment of deposition
750 – 5000	4,100 – 5800	4875 – 5940	Delta plain (lower delta plain/foreshore
5000 – 8800	5800 – 8440	5940 – 9915	Subaqueous delta plain (delta front/upper shoreface
8800 – 11610	8440 – 13160	9915 – 12090	Subaqueous delta plain (delta front to prodelta/lower shoreface to proximal offshore

i. The intervals are characterised by high occurrence of freshwater swamp taxa, followed by mangrove, savanna and rainforest swamp taxa with minimal presence of montane taxa (Adojoh *et. al*., 2015; Olayiwola and Bamford, 2016). *Zonocostites ramonae*, *Retitricolporites irregularis, Sapotaceoidaepollenites* sp., *Psilatricolporites crassus, Laevigatosporites* sp., *Verrucatosporites* sp., and *Acrostichum ahereum* are the examples of the taxa recorded. Abundant freshwater algae *Botryococcus braunii* was also recorded within these intervals which is indicative of high influx of freshwater.

ii. Common to abundant occurrences of poorly sorted, small to large palynomacerals I and II with small to common occurrences of poorly sorted, small to medium sized PM III and IV (Figures 3.8, 3.9 and 4.15) (Oyede, 1992) and

iii. The sands exhibit cylinder and funnel-shaped Gamma ray log motifs suggesting distributary channel and distributary mouth bar deposits of the lower deltaic plain (Sneider *et al*., 1978). The lithology consists predominantly of poorly sorted pebbly to fine-grained. Sands with minor shale intercalations. The sequence is very rich in accessory minerals dominated by shell fragments, carbonaceous detritus, mica flakes and ferruginous materials with glauconite pellets indicating shallow water clastic influx (Selley, 1978).

The intervals 5000 – 8800 ft, 5800 – 8440 ft and 5940 – 9915 ft in HA-001, HB-001 and HD-001 wells respectively were interpreted to have been deposited in delta front environment of deposition. This is equivalent to upper shoreface (Figure 3.8). The reasons for this deduction are:

i. The intervals consist of abundant freshwater swamp and mangrove swamp taxa with increased occurrence of savanna taxa. There is a little representation of rainforest swamp and montane taxa. Examples of taxa recovered in the intervals are *Zonocostites ramonae, Monoporites annulatus, Psilatrocolporites crassus, Retribrevitricolporites protrudens, Sapotaceoidaepollenites* and abundant freshwater algae *Botryococcus braunii*.

ii. Common to moderate occurrences of poorly sorted, small to large palynomacerals I and II with few palynomacerals III and IV (Oyede, 1992); and

iii. The log characters of the intervals are essentially funnel, cylinder and minor bell-shaped motifs suggesting deposition in the delta front varying from barrier bars, distributary channels and tidal channel (Sneider *et al*., 1978; Beka and Oti, 1995). The shale is grey, dark grey to brownish grey, platy to flaggy, occasionally blacky and moderately hard. Rare to abundant carbonaceous detritus, rare to common ferruginous materials suggest shoreface deposition (Selley, 1978).

The intervals 8800 – 11610 ft, 8440 – 13160 ft and 9915 – 12090 ft are the lowermost parts of the HA-001, HB-001 and HD-001 wells respectively were delineated to be deposited in delta front to prodelta environment of deposition. The lower shoreface to proximal offshore (Figure 3.8) is equivalent to this environment. The criteria for this inference are:

i. There is a high dominance of freshwater swamp and mangrove swamp taxa in the intervals with increased occurrence of rainforest swamp taxa. There is a reduction in the presence of savanna and montane taxa indicating proximal offshore. (Adojoh *et al*., 2015; Olayiwola and Bamford, 2016).

ii. Common to abundant moderately sorted, small to large, palynomacerals I and II with common palynomacerals IV (Oyede, 1992).

iii. The sands are milky white, fine to medium-grained, occasionally coarse to very coarse-grained, moderately to well sorted and sub-angular to sub-rounded. The shale is dark grey to grey, silty, platy to flaggy and moderately hard. Index minerals are dominated by ferruginous materials carbonaceous detritus and glauconite pellets indicating barrier bar/foor origin (Selley, 1978). Log characters of the sand suggest that the multiserrate upward coarsening, cylinder and fining upward profiles are barrier bars, subaqueous channel and tidal channel deposits. The sediments of those intervals are laid down in coastal deltaic to inner shelf environments.

4.6 Paleoclimate

Paleoclimate variations are interpreted by pollen and spores because palyno-ecological groups (Appendices D to G) display similar responses to changes in climate through time. Rainforest and Savanah (hinterland) are more directly influenced by climatic factors, while mangrove and freshwater swamp taxa are less influenced sea-level changes have direct influence on mangrove and freshwater taxa changes in paleoclimate from the studied wells are determined from the relative abundance of the microfloral elements of palyno-ecological groups that thrive only under wet climates against groups which develop only under dry climates. Climatic fluctuations and sea level changes have been used to infer wet and dry climatic zones during the Late Miocene. The wet cycles suggest highstand transgressive systems tracts, while the dry cycles indicate lowstand systems tracts (Adojoh *et al*., 2015).

4.6.1 Wet Climatic Zones

The intervals 750 – 3450 ft, 4650 – 6300 ft and 9075 – 9675 ft in HA-001 wells have been inferred to be deposited under wet climatic conditions (Figures 3.8 and 3.9). In HB-001 well, the intervals 4100 – 5000 ft, 6500 – 7925 ft, 8700 – 9350 ft, 9950 – 10775 ft and 11600 – 12650 ft were inferred to be deposited under wet climatic conditions (Figures 3.8 and 4.16). In HD-001 well, the intervals 5490 – 6240 ft, 6840 – 7590 ft, 8415 – 9540 ft, 10215 – 11115 ft and 11490 – 12090 ft were similarly inferred to be deposited under wet climate (Figures 3.8 and 4.16). These intervals recorded high and increased representations of freshwater swamp taxa (*Laevigatosporites* sp., *Acrostichum aureum, Botrycoccus braunii and Retitricolporites irregularis*), Mangrove taxa (*Zonocostites ramonae* and *Psilatricolporites crassuss*) and Rainforest taxa (*Pachydermites diederixi, Sapotacea and Ctenolophonidites costatus*). There are low and reduced occurrences of Savanah and Montane taxa within the intervals such as *Monoporites annulatus, Steriesporites* sp., *Corylus* sp. and *Cyperaceapollis* sp. Increased occurrence of Freshwater, Mangrove and Rainforest taxa and reduced Savanah and Montane taxa are indicative of deposition during sea level rise and wet climatic conditions. The presence of a regular representation of Savanah and Montane and reduced representation of coastal miospores (Freshwater, Mangrove and Rainforest taxa) indicate sea level fall and dry climatic conditions (Ige, 2011; Adojoh *et al.*, 2015; Olayiwola and Bramford, 2016). The works of Durugbo *et al.* 2010, Ige, 2011 and Bankole *et al*. 2014 in the Niger Delta Basin is in accordance with the wet climatic zones of this study.

4.6.2 Dry Climatic Zones

The intervals 3450 – 4650 ft, 6300 – 9075 ft and 9675 – 11600 ft in HA-001 were inferred to be deposited under dry climatic conditions (Figures 3.8, 3.9, 4.16 and 4.17). Intervals

5000 – 6500 ft, 7925 – 8760 ft, 9350 – 9950 ft, 10775 – 11600 ft and 12650 – 13160 ft in HB-001 were also inferred to be deposited under similar dry conditions (Figures 4.16, 4.17 and 4.18). Lastly, in HD-001 wells, intervals 4875 – 5490 ft, 6240 – 6840 ft, 7590 – 8415 ft, 9540 – 10215 ft and 11115 – 11490 ft were inferred to be deposited under dry climatic conditions. There are significant reductions of freshwater, mangrove and rainforest taxa with high representations of savanah and montane taxa within these intervals inferring dry climate and sea level fall (Figure 3.8). Ige (2011), Durugbo *et al.* (2010) and Bankole *et al.* (2014) employed this method to study the paleoclimate of the Niger Delta Basin.

4.7 Sequence Stratigraphy of HA-001, HB-001 and HD-001 Wells

The sequence stratigraphic results of the three wells are presented in Figures 4.19 to 4.21 respectively. In this study, four Maximum Flooding Surfaces and three Sequence Boundaries were identified within the studied intervals in the three wells. System tracts were also identified within the depositional sequences bounded by the Maximum Flooding Surfaces of Catuneanu *et al*. (2011).

Palyno-ecological groupings of palynomorphs of Adojoh *et al*. (2015) (Figure 3.9) show that increase in mangrove, freshwater and rainforest taxa with decrease in savannah and Montane taxa indicate well climate and Highstand System Tract (HST) while increase in savannah and montane taxa with decrease in mangrove, freshwater and rainforest taxa indicate dry climate and Lowstand System Tracts (LST).

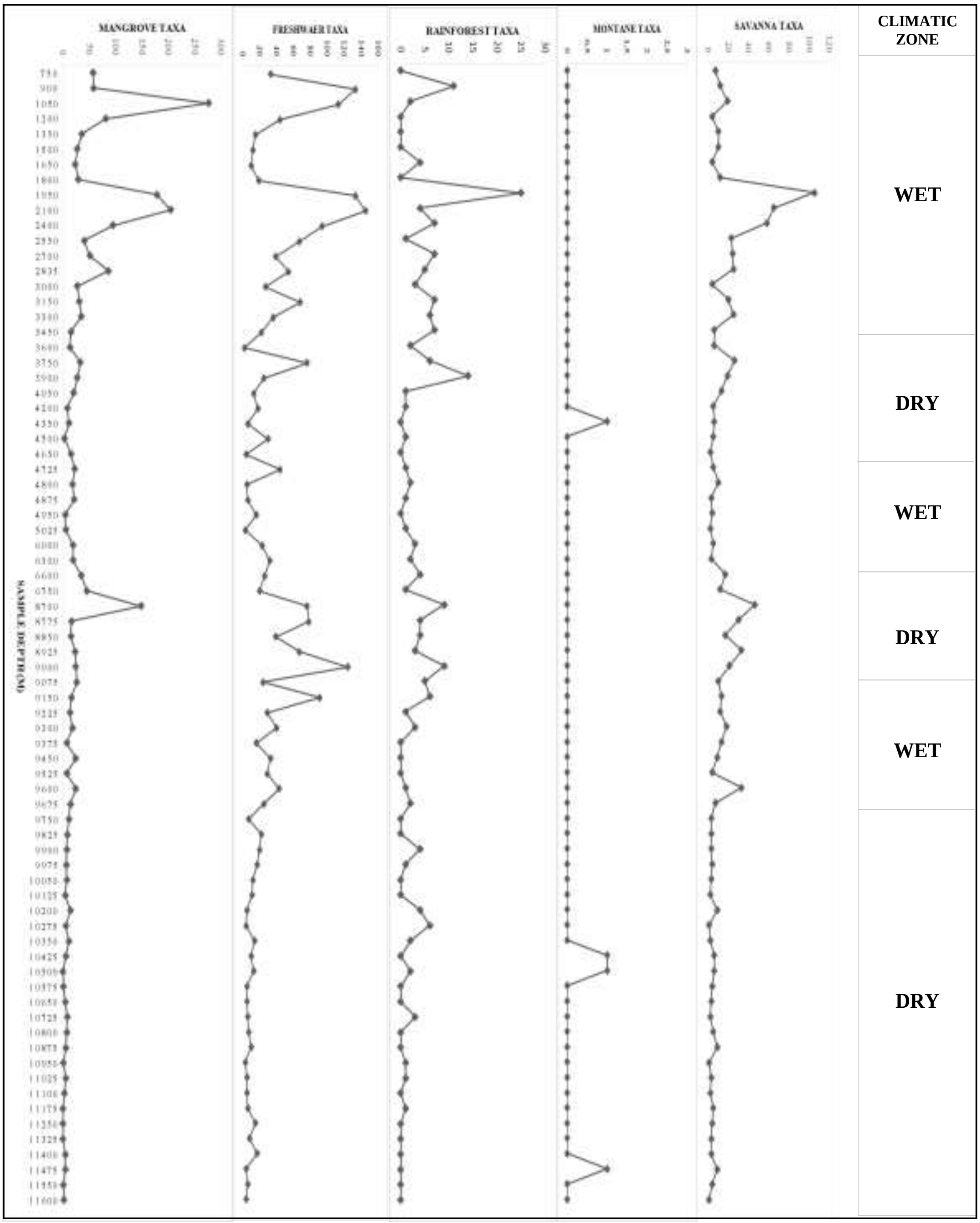


Figure 4.16: The Abundance (Population Count) of the Palyno-ecological Groups and Paleoclimate Zones of HA-001 well

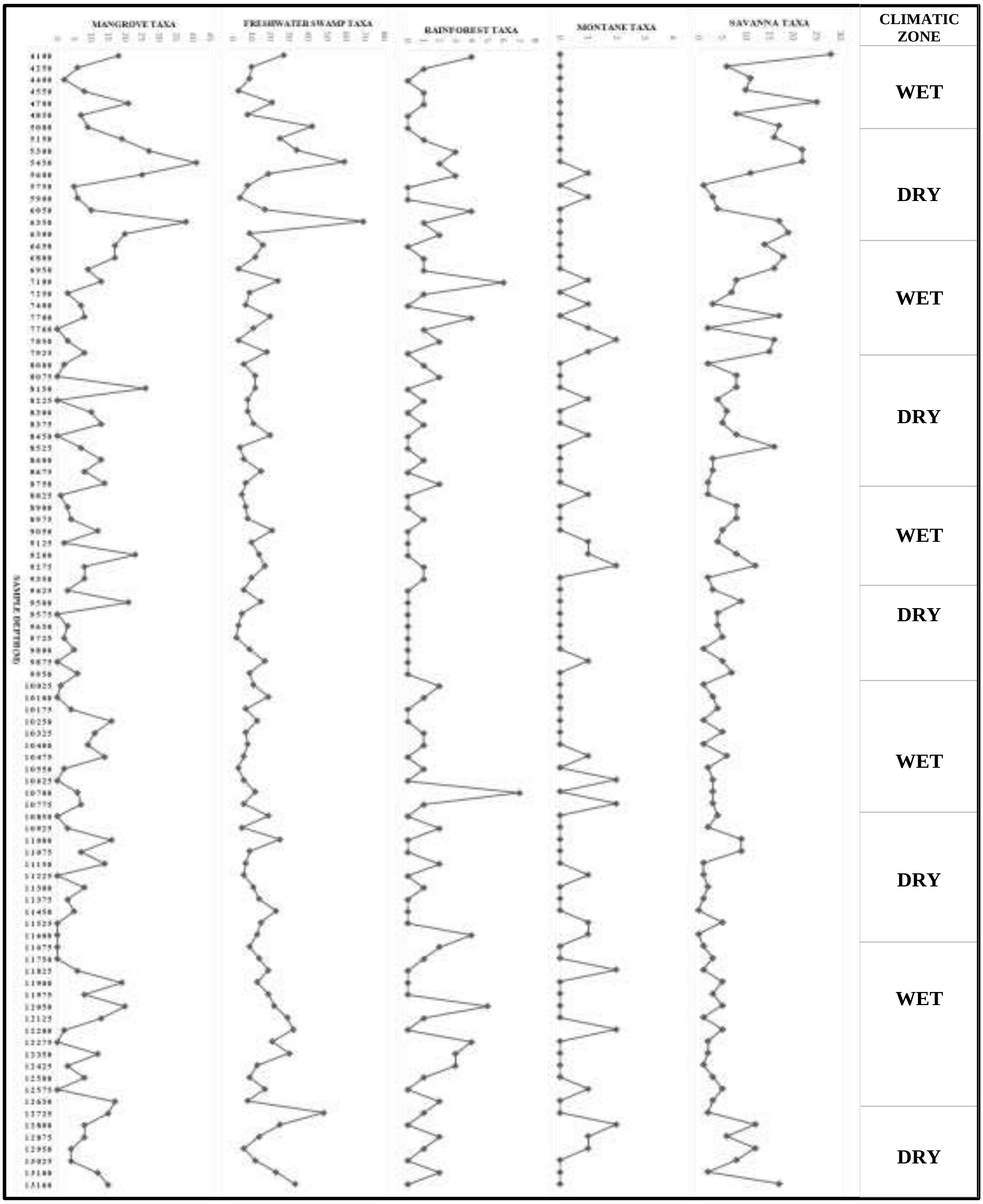


Figure 4.17: The Abundance (Population Count) of the Palyno-ecological Groups and Paleoclimate Zones of HB-001 Well

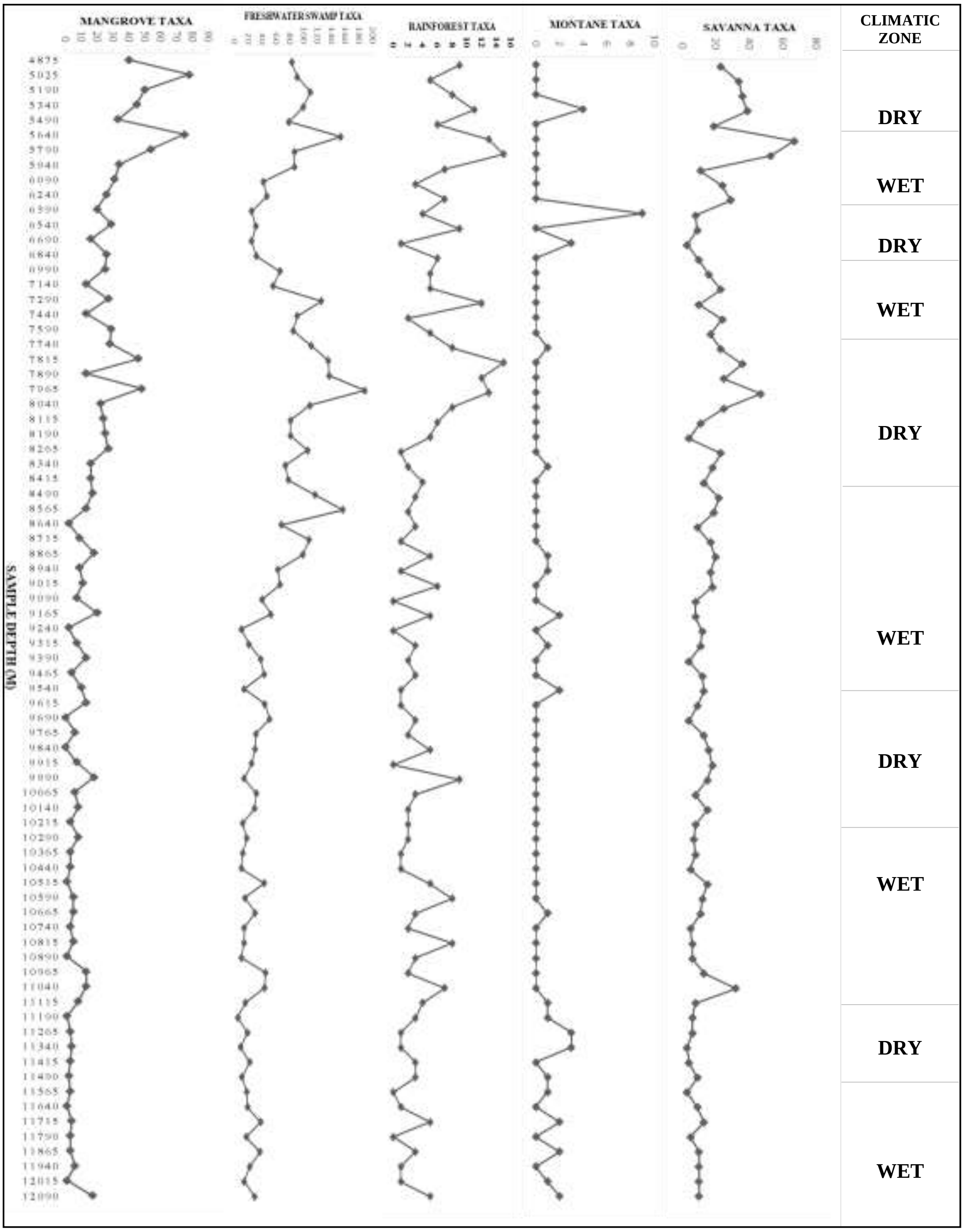


Figure 4.18: The Abundance (Population Count) of the Palyno-ecological Groups and Paleoclimate Zones of HD-001 Well

Potential hydrocarbon reservoirs and cap rocks can be found within the sandstone and shale units of the depositional sequences. The Maximum Flooding Surfaces are the shaliest points as implied by Gamma Ray Log for the studied wells. There is high delivery and abundance of pollen and spores with abundance small and medium sized palynomaceral 1 and 2 in the Maximum Flooding Surface (MFS). There is low recovery of pollen, spores and palynomacerals at the Sequence Boundaries. The surfaces are dated based on their stratigraphic positions in the sequence.

4.7.1 Stratigraphic Surfaces in HA-001 Well

Four **(**4) Sequence Boundaries and 4 Maximum Flooding Surfaces were identified. Thus, three depositional sequences following the model-independent method of Catuneanu *et al*. (2011) the Sequence Boundaries were identified as the sharp vertical facies shift, which correspond to a non-gradational change in of gamma signature within a relatively low overall fossil count. SB1 (8.5 Ma), SB2 (8.5/6.7 Ma), SB3 (6.7 Ma) and SB4 (5.6 Ma) are found to occur at approximate depths of 10815, 8520, 6605, 4690 feet respectively. There is decrease in pollen, spores and palynomacerals recoveries at this depth (Figure 4.19). The Maximum Flooding Surfaces were recognised as the interval between an overall fining upward unit underlying an overall coarsening upward unit. These are identified on the data as the maximum gamma reading within a sequence, corresponding to high relative abundance and diversity of palynomorphs. MFS1 (7.4 Ma), MFS2, MFS3 (6.0 Ma) and MFS4 (5.0 Ma) were found to occur at approximate depths of 9520, 7498, 5520, 3682 feet respectively. The surfaces are correlated to the Niger Delta Cenozoic Chronostratigraphic Chart (Figure 4.22).

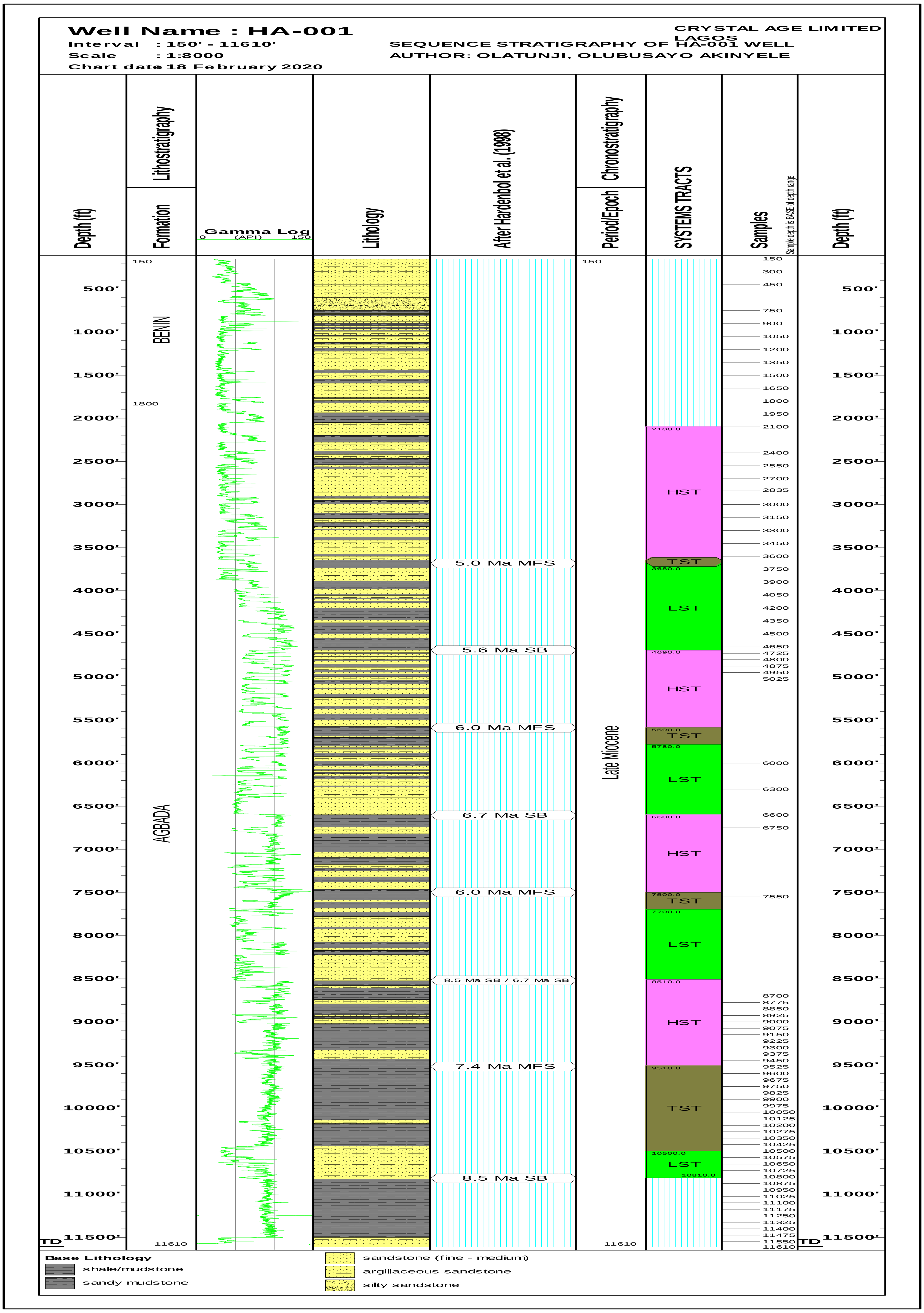


Figure 4.19: Sequence stratigraphic chart of HA-001 well

4.7.1.1 Depositional sequences of HA-001 well

Based on the identified stratigraphic surfaces, 3 depositional sequences were identified. These are Sequence1 (bounded by SB1 and SB2), Sequence2 (bounded by SB2 and SB3) and Sequence3 (bounded by SB3 and SB4).

(i) **Sequence 1:** This sequence was deposited in a coastal deltaic environment with a high fresh water influx in most part except toward the top where there is a reduction in the freshwater being fed into the systems. This is evident by the presence of *Laevigatosporites* sp. Lying on SB1 is a lowstand prograding wedge which displays a coarsening upward (progradational) pattern that is truncated by an overlying transgressive surface (at about 10450 ft). At the SB1, there is a marked decrease in palynomacerals I and II.

On the other hand, the amount of pollen and spores increases. Above the lowstand unit is a shaling upwards unit with an occasional sandy streak. This unit grades up to the overlying MFS1 to make the transgressive systems tract, indicating a reversal of the erstwhile relative sea level rise. This reversal is preserved in the sequence as the overall coarsening upward unit which forms the highstand systems tract of the sequence. This HST is characterised by the dominance of aggrading shales (shale build-up) and prograding sands that are truncate beneath the overlying SB2. There are few to zero occurrence of savanna and montane taxa with relatively increase in freshwater and mangrove taxa (Appendices D to F)

(ii) **Sequence 2:** This coastal deltaic sequence is characterised by a high proportion of sand as seen by the characteristic high gamma ray readings. Overlying the SB2 are the blocky lowstand systems tracts sand units which are predictive of fluvial channels that cut through the delta. Their vertical limit is the transgressive surface (at about 7700 ft) which marks the onset of transgression. The thin unit between these transgressive surfaces and the MFS2 a transgressive systems tracts unit by a fining upwards sequence. This followed by the observed overall prograding unit characterised by the aggrading shales that show internal progradation at their upper limits. This forms the highstand systems tract of the Sequence2, bounded above by the SB3. The palynomaceral present are not degraded and there are good recoveries of small and medium sized PM 1.

(iii) **Sequence 3**: The lowstand system tracts unit of this sequence is bounded below by the SB3 and above by a transgressive surface which occurs at an approximate depth of 5780 ft. This lowstand system tracts is made up of lowstand fan indicated by an overall fining upwards sandy unit deposited in a coastal deltaic environment with low influence of freshwater incursion. This sand grows upwards to be terminated by the overlying transgressive sandswhich begins the relative sea level rise that results in the deposition of the relatively thin transgressive systems tracts shale which is bounded above by the MFS3. Above the MFS3 were deposited are aggrading sands of the highstand system tracts which are characterised by intercalated shales that are indicative of high frequency relative sea level fluctuation.

4.7.2 Stratigraphic Surfaces in HB-001 Well

Six candidate Sequence Boundaries and four Maximum Flooding Surfaces were identified. The Sequence Boundaries SB1 (8.5 Ma), SB2, SB3 (6.7 Ma), SB4 (5.6 Ma) and SB5 were delineated at approximate depths of 12650,11440,8410,7125,5793, and 4295 ft respectively while the maximum flooding surfaces MSF1, MFS2 (7.4 MA), MFS3 (6.0 MA) and MFS4 (5.0 MA) were delineated at approximate depths of about

11945,10040, 7708,6192 and 6495 ft respectively (Figure 4. 20). The associated palynomacerals consist of diverse and abundant pollen, spore, abundant medium sized PM 1 and 2 and few occurrence of large sized PM 1 and 2. The surfaces are correlated to the Niger Delta Cenozoic Chronostratigraphic Chart (Fig. 4.22).

4.7.2.1 Depositional sequences in HB-001 well:

Based on the identified stratigraphic surfaces, 5 depositional sequences were identified. These are Sequence1 (bounded by SB1 and SB2), Sequence2 (bounded by SB2 and SB3), Sequence3 (bounded by SB3 and SB4), Sequence 4 (bounded by SB4 and SB5) and Sequence6 (bounded by SB5 and SB6).

(i) **Sequence 1**: The lowstand system tract unit of this sequence is relatively thin with an upward coarsening stacking pattern that is characteristic of lowstand prograding wedge; bounded above by the transgressive surface occurring at approximately 12395 ft. overlying the transgressive sand is the fining upward shaly transgressive system tract unit which is capped beneath the MFS1. The highstand system tract unit overlying the MFS1 is characterised by a shale buid-up that is suggestive of a period of relative sea level standstill that ended in the rapid of fall that resulted in the SB2.

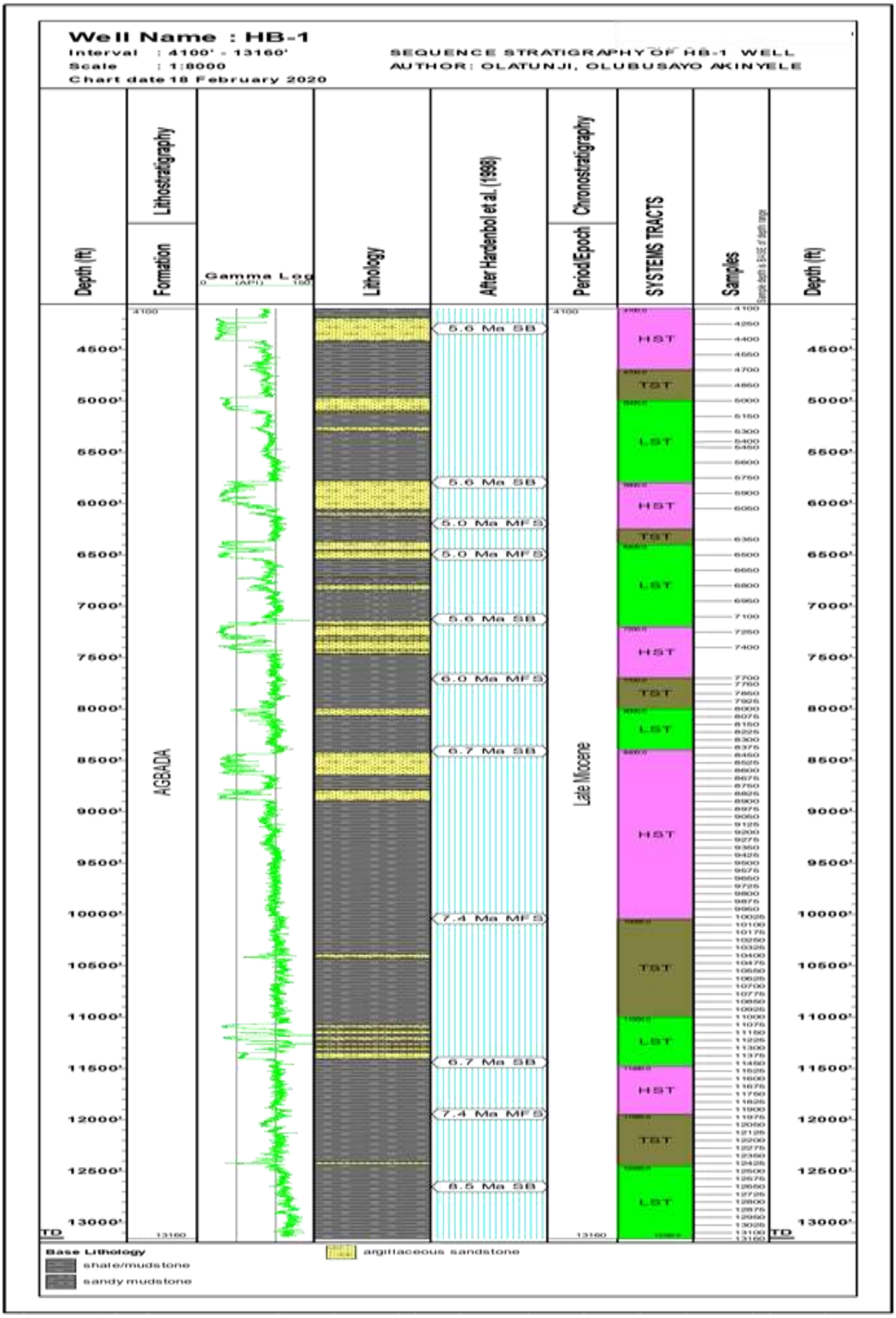


Figure 4.20: Sequence stratigraphic chart of HB-001 well

(ii) **Sequence 2**: Overlying the SB2 is the lowstand system tract unit also characterised as lowstand prograding wedge due to its log signature and stacking pattern. It is bounded above by the transgressive surface at approximately 11040 ft. The transgressive system tract overlying (bounded above by MFS2) the transgressive sand is predominantly shaly with an observable streak of sand. The highstand system tract unit overlying the MFS2 and capped above by the SB3 is composed of an aggrading shale that grades upwards in prograding sands.

(iii) **Sequence 3**: Overlying SB3 is the LST unit that is characterised by overall upward coarsening indicative of a lowstand prograding wedge. At the onset of transgression (TS) the transgressive system tract unit was deposited, culminating in the overlying MFS3. Overlying the MFS3 is the highstand system tract unit comprising an aggrading shale overlain by prograding sands. Sequence4 and 5 are same as sequence 3, differences are only in the surfaces and their depths.

4.7.3 Stratigraphic Surfaces in HD-001 Well

Based on the wireline logs, abundance and diversity of palynomorphs and palynofacies provided for the study. Five (5) Sequence Boundaries and 4 Maximum Flooding Surfaces were identified in the well. The recognition of these surfaces was done using similar techniques as in the HA1 and HB1 wells. The Sequence Boundaries SB1 (8.5 Ma), SB2, SB3, (6.7 Ma), SB4 (5.6 Ma) and SB5 were found to occur at approximate depths of about 11350, 10040, 8470, 6550 and 5220 ft respectively while the Maximum Flooding Surfaces MFS1, MFS2 (7.4 Ma), MFS3 (6.0 Ma) and MFS4 were delineated at 10710, 9450, 7350 and 6040 ft respectively (Figure 4. 21). These MFS depths are associated with major pollen, spores, PM 1 and 2 abundance and diversity peaks. The vertical sections penetrated by the

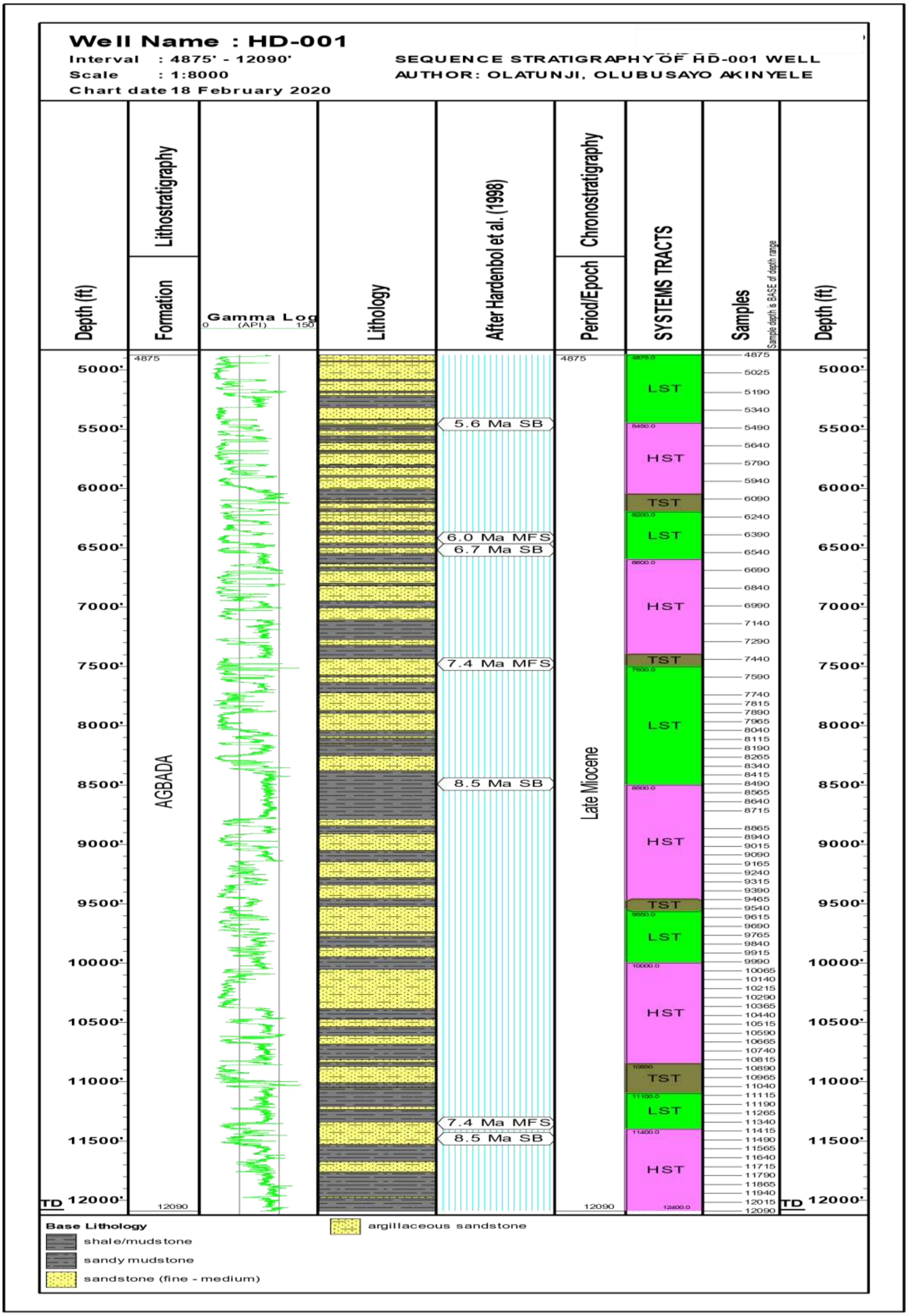


Figure 4.21: Sequence stratigraphic chart of HD-001 well

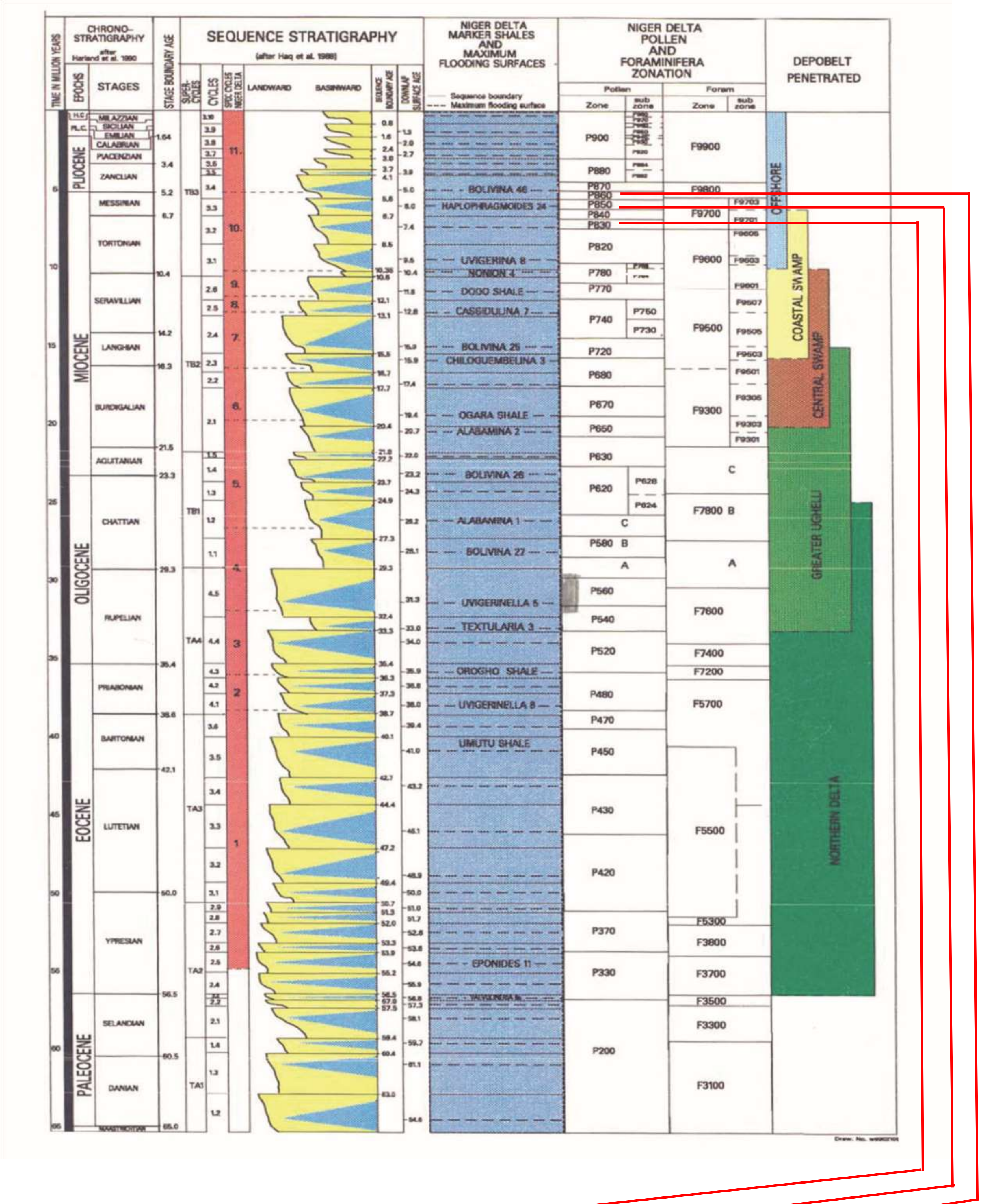
well were subdivided into sequences and their associated systems tracts on the basis of these surfaces. The surfaces are correlated to the Niger Delta Cenozoic Chronostratigraphic Chart (Fig. 4.22).

4.7.3.1 Depositional sequences in HD-001 well

Four sequences were delineated within the HD-001 well. These are Sequence 1 (bounded below by SB1 and above by SB2), Sequence 2 (bounded below by SB2 and above by SB3), Sequence 3 (bounded below by SB3 and above by SB4) and Sequence 4 (bounded below by SB4 and above by SB5).

(i) **Sequence 1**: Directly overlying the SB1 is the lowstand system tract unit characterised by a basal internal retrogradation but an overall progradation, which is diagnostic of the lowstand prograding wedge. The palynofacies association consists of low abundance of mangrove, freshwater, and rainforest taxa and increased occurrence of montane and savanna taxa. Large sized PM 1 and 2 are also common. The upper part of the lowstand systems tract shows a blocky to crescentic log motif that is suggestive of fluvial channel deposits that forms to the maximum limit of relative sea level fall of a transgressive surface at 10820 ft). Overlying the TS is a thin transgressive system tract unit shale that is bounded above by the MFS1.

(ii) Above the MFS1 are the relatively blocky sandy units of the highstand system tract which are characterised by thin internal shale build-ups. The unit is bounded by the SB2,



P830	P840/P850	P860	Pzones Evamy *et al.* (1978)	This Study 2020
	Cyperaceaepollis sp. - *Elaeis guineensis*	*Nympheaepollis clarus* - *Echitriletes pliocenicus*	Subzones	
Stereisporites sp.	*Cyperaceaepollis* sp. - *Nympheaepollis clarus*		HA-001 Well	
Stereisporites sp.	*Cyperaceaepollis* sp. - *Nympheaepollis clarus*		HB-001 Well	
Stereisporites sp.	*Cyperaceaepollis* sp. - *Nympheaepollis clarus*		HD-001 Well	
LATE MIOCENE				Period/Epoch

Figure 4.22: Age correlation of the established Palynostratigraphic zones in HA-001, HB-001 and HD-001 wells with the Niger Delta Cenozoic chronostratigraphic chart.

(iii) **Sequence 2**: The LST unit is a lowstand prograding which characterised by a coarsening up unit indicating a transition from shale-rich to shale-free system. The lowstand system tract is bounded above by a transgressive surface (at a depth of about 90540 ft). Above the TS and the overlying MFS2 is a thin transgressive system tract shale that shows a fining upward motif. Overlying the MFS2 is the highstand systems tract unit which is characterised by alternating fining up and coarsening up units that indicate fluctuation in relative sea level positions. The unit is bounded above by the SB3.

(iv) **Sequence 3**: The lowstand systems tract unit of this sequence is characterised by an overall coarsening up unit with intermittent shale intercalations, bounded above by a transgressive surface at a depth of about 7410 ft. Overlying the TS is a thin transgressive system tracts shale bounded at the top by the MFS3. The highstand system tracts is predominantly sandy with intermittent shale presence.

(v) **Sequence 4**: Bounded below by the SB4 and above by a TS (at a depth of about 6100 ft), the LST unit is blocky sand characteristic of fluvial channel deposits, with shale intercalations at intervals. The TST is relatively thin and bounded above by the MFS4. Above the MFS4 are the highstand system tracts deposits that show initial progradation and a later aggradation.

4.8 Systematic Description of some Selected Palynomorph Species

4.8.1 Taxonomic Criteria

The Palynomorph species were identified using the works of Germeraad *et al.* (1968), Salard – Cheboldaeff (1975, 1976, 1978), Jan du Chene *et al.* (1978), Haseldonckx (1977), Anderson and Muller (1975) and Kumar (1981).

The classification scheme adopted for the microfloras encountered in this study was based on morphological forms. The morphological characteristics used are:

(i) types of apertures and their numbers

(ii) types of sculptural elements or ornamentation

4.8.2 Apertures

The primary criteria in morphological classification are based on the characteristics of the apertures. The apertural types for spores are either:

(i) Monelete – possess by spores having a laesura (one slit) mark.

(ii) Triletes – possess by spores having three laesurae (three-star slits) marks.

Pollen apertural types are more complex than in the spores.

They include:

(i) Inaperturate pollen – Pollen without an aperture

(ii) Colpate – those with slits as apertures

(iii) Porate pollen – Pollen with pores as apertures

(iv) Colporate pollen – Pollen with combination of slits and pores as apertures

(v) Sulcate pollen – Pollen with reduced slits as apertures

(vi) Saccate pollen - pollen with air sacs as apertures

The numbers of these apertural types present in pollen and their position form the secondary criteria in morphological classification of miospores. They vary in number for instance, there could be one colpus (monocolpate), two colpi (diporate), three colpi (tricolpate) in colpate pollen; one pore (monoporate), two pores (diporate), three pores (triporate), more than three pores (stephanoporate) in porate pollen.

4.8.3 Sculptural Elements

The pollen and spores' ornamentations have been discussed in the literature (Erdtman, 1952; Kremp, 1968). The ornamentation forms recognised in this study are Psilate, Echinate, Spinose, Verrucate, Bacculate, Striate, Reticulate and Gemmate.

The advantage of this concept of morphological group classification is that fossil pollen and spores are classified without any particular reference to their botanical affinities. However, this mode of classification has the disadvantage of putting pollen and spores belonging to different families under the same morphological group.

DIVISION I	SPORITES H. POTONIÉ, 1893
CLASS A:	Triletes (REINSCH, 1884) POTONIÉ et KREMP, 1954
GENUS:	*Crassoretitriletes* GERMERAAD, HOPPING and MULLER, 1968
	Crassoretitriletes vanraadshooveni GERMERAAD *et al.*1968
	Plate II, Figure 1
Description:	Single grain, radiallysymmetrical, anisopolar, with rounded distal pole and slightly pointed proximal pole, in polar view almost circular, Laesura trilete, indistinct, often covered by sculpture. Reticulate over entire surface
Dimensions:	58-101 µm (equatorial diameter)
Location:	Slide HB7700ft, well HB-001, Nigeria
Remarks:	Rare occurrence in the intervals of wells HA-001, HB-001 and HD-001
Genus:	*Acrostichum* KAR, 1992
	Acrostichumaureum KAR, 1992
	Plate II, Figure 2
Description:	Trilete spore, anisopolar, single grain, radially symmetrical with triangular amb. The trilete mark can be indistinct depending on view position. Exine thickness range

	between 1 and 2 µm. Verrucae which may be as high as 2 µm and are irregularly arranged on the surface. Folding is a common feature of the surface of the exine
Dimensions:	Diameter 57-70 µm
Location:	Slide HD10740ft, well HD-001, Nigeria
Remarks:	This form occurs frequently in wells HA-001, HB-001 and HD-001. Rare to abundant specimens of this species were recovered in the studied intervals.
Genus:	*Magnastriatites* GERMERAAD, HOPPING and MULLER, 1968
	Magnastriatites howardi GERMERAAD *et al.*, 1968
	Plate II, Figure 3
Description:	Single grain, radially symmetrical, anisopolar, with rounded distal pole and more pointed proximal pole, in polar view nearly circular; shape suboblate spherical. Laesura trilete, costae 2 in wide. Contact area of proximal face psilate, surrounded by a circular ridge, which make contact with the striate ridge pattern at the points of the laesura. Remainder of the wall coarsely straite.
Dimension:	77-132 µm (equatorial diameter)
Location:	Slide HA 1950ft, well HA-001, Nigeria
Remarks:	Rare to few occurrences of the species found in the three studied wells.
GENUS:	*Polypodiaceiosporites* POTONIÉ, 1951
	Polypodiaceiosporites sp. (*Pteris* sp.)
	Plate II, Figure 4
Desciption:	Triangular, rounded and thickened corners, smooth outline, trilete marks long, narrow nearly extending to the cingulum, smooth cingulum, central body gemmate
Dimension:	42.5-42.5 µm
Location:	Slide HD 4875ft, well HD-001, Nigeria
Remarks:	Few to common occurrence of the specie were recovered in the three studied wells
CLASS B:	Moneletes IBRAHIM, 1933

Genus:	*Laevigatosporites* IBRAHIM, 1933
	Laevigatosporites sp.
	Plate II, Figure 5
Description:	Spherical to elliptical monelete microspore, exine thickened, psilate to scabrate, monolete mark distinct and long
Dimensions:	65-35 µm
Location:	Slide HD7440ft, well HD-001, Nigeria
Remarks:	This form occurs frequently in wells HA-001, HB-001 and HD-001. Rare to abundant specimens were recovered in the studied intervals

GENUS:	*Verrucatosporites* (PFLUG, 1952) ex R. POTONIÉ, 1956
	Verrucatosporites sp.
	Plate II, Figure 6
Description:	Single grain, ellipsoidal in polar view, bilaterally symmetrical, anisopolar, distal side convex, straight proximal, monolete microspore, monolete mark distinct and as long as spore length, verrucate to gemmate sculptured
Dimensions:	39-61 µm, including gemmae
Location:	Slide HB 8000ft, well HB-001, Nigeria
Remarks:	Few to common recovery from the studied intervals of the three wells

DIVISION II	POLLENITES R, POTONIÉ, 1931
ANGIOSPERMAE	
Class:	Monocolpatae INVERSEN et TROELS SMITH, 1950
	Echinate pollen
	Plate III, Figure 1
Description:	Single grain, radially symmetrical, colpus indistinct pollen, ellipsoidal to spherical in outline, echinate with regularly distributed long spines
Dimensions:	55-42.5 µm

Location:	Slide HD 7140ft, well HD-001, Nigeria
Remarks:	Rare grains of this specie were recovered in well HD-001

Genus:	*Proxapertites* VAN DER HAMMEN, 1956
	Proxapertites cursus VAN HOLKEN – KLINKENBERG, 1966
	Plate III, Figure 2
Description:	Single grain radially symmetrical, slightly anisopolar, since the grains are separated by ectexinous equatorial colpus into two, slightly unequal pores; oblate, in polar view, colpus ectexinous, somewhat irregularly bordered by narrow, indistinct margins of thinning ectexine
Dimensions:	35-69 µm
Location:	Slide HB 5150ft, well HB-001, Nigeria
Remarks:	Rare grains of the specimens were recovered from wells HB-001 and HD-001

Class:	Monoporatae IVERSEN et TROELS SMITH, 1950
Genus:	*Monoporites* (COOKSON, 1947) ex VAN DER HAMMEN, 1954. *Monosporites annulatus* VAN DER HAMMEN, 1954
	Plate III, Figure 3
Description:	Single grain, radially symmetrical, anisopolar, almost spherical. Single aperture small, circular, penetrating entire wall, costate, costa slightly protruding. Endexine, columellae indistinct and thick, tectum psilate, very finely perforate or scabrate
Dimensions:	38-43 µm
Location:	Slide HA 9900ft, well HA-001, Nigeria
Remarks:	Abundant and frequently occurring in wells HA-001, HB-001 and HD-001

Class:	Stephanoporatae IVERSEN et TROELS SMITH, 1950
Genus:	*Alnipollenites* R. POTONIÉ, 1931

Alnipollenites verus R. POTONIÉ, 1934 ex R. POTONIE, 1934

Plate III, Figure 4

Description: Single grain, radially symmetrical, isopolar, oblate; outline in polar view subangular, 3-6 ectexinous and endexinous pores, 3-4n wide, slightly vestibulate; columellae indistinct, tectum smooth or finely granulate

Dimensions: 30-34 µm

Location: Slide HB 7925ft, well HB-001, Nigeria

Remarks: Rare to few occurrences of the specimens recovered in wells HA-001, HB-001 and HD-001

Genus: *Pachydermites* GERMERAAD, HOPPING and MULLER, 1968

Pachydermites diederixi GERMERAAD, HOPPING and MULLER, 1968

Plate III, Figure 5

Description: Single grain, oblate, stephanoporate pollen, radially symmetrical, isopolar, tetraporate to hexaporate, pore unidentical in shape with two pores facing each other in opposite sides, interior surface psilate

Dimensions: 48×48 µm

Location: Slide HA 900ft, well HA-001, Nigeria

Remarks: Few to moderate recovery of species from the three wells

Class: Tricolpatae IVERSEN et TROELS SMITH, 1950

Genus: *Straitricolpites catatumbus* GONZALEZ, 1967

Plate III, Figure 6

Description: Single grain, radially symmetrical, isopolar, prolate; outline in polar view trilobite to spherical. Tricolpate, colpi ectexinous, long, intruding with straight simple borders and pointed ends. Pores absent or indistinct.

Dimensions: 35-50 µm

Location: Slide HD 5025ft, well HD-001, Nigeria

Remarks: Few species are present in the studied intervals of wells HB-001 and HD-001

Class: Periporatae IVERSEN et TROELS SMITH, 1950

Genus: *Echiperiporites* VAN DER HAMMEN et WYMSTRA, 1964

Echiperiporites estelae GERMERAAD, HOPPING and MULLER, 1968

Plate III, Figure 7

Description: Single grain, spherical, isopolar, centro-symmetrical, wide annuli, smooth, tectate, periporate, long spine on the exine

Dimensions: 40×40 µm

Location: Slide HD8190ft, well HD-001, Nigeria

Remarks: Rare few specimens of this species are present HB-001 and HD-001 wells

Class: Stephanocolpatae IVERSEN et TROELS SMITH, 1950

Genus: *Ctenolophonidites* VAN HOEKEN-KLINKENBERG, 1966

Ctenolophonidites costatus (VAN HOEKEN-KLINKENBERG, 1964) ex VAN HOEKEN-KLINKENBERG, 1966

Plate III, Figure 8

Description: Single grain, radially symmetrical, isopolar, spherical oblate; 6-colpate; long and ectexinous colpi slightly costate equatorially. Ectexine locally thickened into a pattern of radial costae, meeting near the poles and forming ring-like ridges, occasionally with extra ridges inside these rings. Columellae and tectum not differentiated, wall psilate and thick at the equator.

Dimensions: 37×50 µm

Location: Slide HA 1650ft, well HA-001, Nigeria

Remarks: A single grain of this form is present in HA-001 well.

Class: Tricolporatae IVERSEN et TROELS SMITH, 1950

Genus:	*Zonocostites* GERMERAAD, HOPPING and MULLER, 1968
	Zonocostites ramonae GERMERAAD, HOPPING and MULLER, 1968
	Plate III, Figure 9
Description:	Single grain, spherical in outline, isopolar, radially symmetrical, tricolporate, rather short colpi, large pores, distinctly costate exine wall thin, tectate and psilate to finely perforate
Dimensions:	17.5×15 µm
Location:	Slide HA 750ft, well HA-001, Nigeria
Remarks:	It occurs abundantly throughout the studied intervals in HA-001, HB-001and HD-001 wells except for very few intervals where rare specimens were recovered. The sparsity of this species at these horizons might be as a result of unfavourable preservational conditions.

Genus:	*Psilatricolporites* (VAN DER HAMMEN, 1956) ex VAN DER HAMMEN et WYMSTRA, 1964.
	Psilatricolporites crassus VAN DER HAMMEN, 1964.
	Plate III, Figure 10
Description:	Single grain, radially symmetrical, isopolar, spherical to subprolate; outline in polar view circular. Tricolporate; colpi medium long, ectexinous, straight with pointed ends; pore endexinous, equatorially elongated, oval perforate-foveolate
Dimensions:	42×65 µm
Location:	Slide HB 4250ft, well HB-001, Ngeria
Remarks:	Rare to common occurrence in the studied intervals of the three wells

Genus:	*Retitricolporites* (VAN DER HAMMEN, 1956) ex VAN DER HAMMEN et WYMSTRA, 1964.
	Retitricolporites sp.
	Plate III, Figure 11

Description:	Small grain, circular to spherical in shape, tricolporate pollen, colpi short, reticulate, bilaterally symmetrical.
Dimensions:	35 µm×37 µm
Location:	Slide HD 8865ft, well HD-001, Nigeria
Remarks:	A single grain was found in well HD-001

Retitricolporites irregularis VAN DER HAMMEN et WYMSTRA, 1964

Plate III, Figure 12

Description:	Single grain, radially symmetrical, isopolar, spherical; outline in polar view circular. Tricolporate; colpi ectexinous, long, strongly intruding with straight costate borders and pointed ends; pores endexinous, oval and equatorially elongated
Dimensions:	29 µm×50 µm
Location:	Slide HB 4250ft, well HB-001, Nigeria
Remarks:	Few to common occurrence in the three studied wells

Genus: *Verrutricolporites* VAN DER HAMMEN et WYMSTRA, 1964

Verrutricolporites rotundiporis VAN DER HAMMEN et WYMSTRA, 1964

Plate III, Figure 13

Description:	Single grain, radially symmetrical, isopolar, spherical to sub-prolate; outline in polar view lobate. Tricolporate, apertures interlobate; colpi ectexinous, indistinct, medium long, intruding; pores endexinous, circular, sharply outlined. Tectum psilate or covered by low, irregularly shaped verrucae.
Dimensions:	15 µm×24 µm
Location:	Slide HD 5025ft, well HD-001, Nigeria
Remarks:	Rare specimens found in few intervals within the studied intervals in HD-001 well.

Genus: *Retibrevitricolporites*, LEGOUX, 1978

Retibrevitricolporites protrudens, LEGOUX, 1978

Plate III, Figure 14

Description:	Single grain, radially symmetrical, isopolar, oblate; outline in polar view protruding. Tricolporate; colpi long, ectexinous with thickened tectum. Wall finely reticulale
Dimensions:	26 µm×32 µm
Location:	Slide HA 900ft, well HA-001, Nigeria
Remarks:	Rare to common occurrence of species found in the three studied wells

GYMNOSPERMAE

Genus:	*Podocarpidites* (COOKSON, 1947) COUPER, 1953
	Podocarpidites sp.

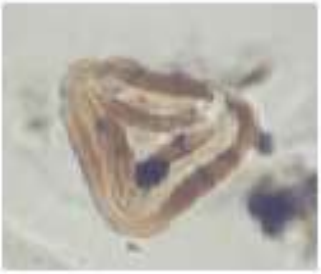
Plate III, Figure 15

Description:	Bisaccate pollen grain, subspherical to elongate body divided nearly equally by a narrow furrow running vertically across the whole length of the granulate body. The sacci are firmly attached to the body, they are sub-rounded and of different sizes. The sacci are finely reticulate, the reticula are of different shapes and sizes.
Dimensions:	60 µm×44 µm
Location:	Slide HD 12090ft, well HD-001, Nigeria
Remarks:	Rare few specimens of this species were found in studied intervals of the three wells

1. ***Crassoretitriletes vanraadshooveni***

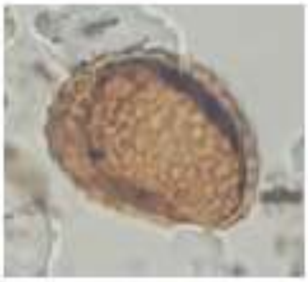
2. ***Acrostichum aureum***

3. ***Magnastriatites howardi***



4. ***Polypodiaceiosporites* sp.**

5. ***Laevigatosporites* sp.**



6. ***Verrucatospotites* sp. x 25**

Plate II: Palynomorphs sporites recovered from the studied wells

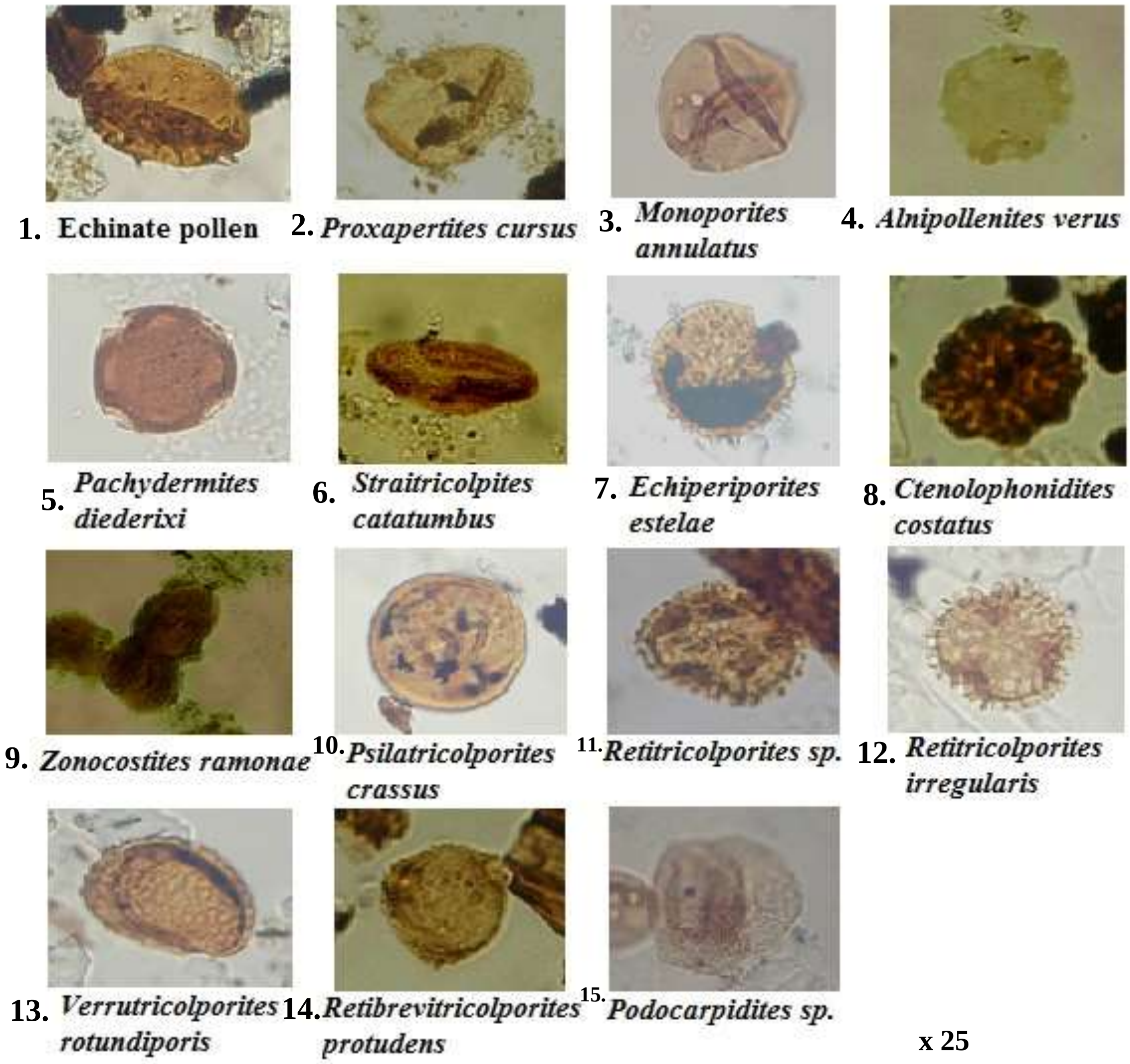


Plate III: Palynomorphs pollenites recovered from the studied wells

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Palynofacies, lithofacies and sequence stratigraphy analyses were carried out within sedimentary section penetrated in HA-001, HB-001 and HD-001 wells, using ditch cutting samples and wireline logs provided by Shell Production and Development Company. Seventy-six, Seventy-seven and Ninety-six ditch cutting samples within the depth intervals of 750 – 11610 ft, 4100 – 13160 ft and 4875 – 12090 ft in HA-001, HB-001 and HD-001 wells respectively were analysed. Moderate to abundant freshwater, mangrove and rainforest taxa were recovered while moderate savanah and montane taxa were recovered. Large sizes of palynomacerals 1 and 2, with few to common occurrences of palynomacerals 3 and 4 were also recovered.

Observed lithological altenation of sand and shale units which reveals rapid shoreline progradation. The grain size increases from essentially fine to medium-grained, occasionally coarse-grained at the basal part of the wells, to dominantly fine to medium-grained, occasionally coarse to granule sizes at the upper part. The sands are mostly sub-angular to sub-rounded and generally poorly to well sorted. Index minerals and accessories are dominated by ferruginous materials, glauconite pellets, carbonaceous detritus, shell fragments and pyrites with irregular occurrences of micaflakes. The lithologic, textural and Gamma Ray Log data indicate that the entire interval studied in the HA-001 well essentially shows the Benin and Agbada Formations. The entire studied intervals in HB-001 and HD-001 wells belong to the Agbada Formation.

The stratigraphic age range of the recovered diagnostic marker species indicates Late Miocene age for the studied intervals. *Nympheaepollis clarus* has been assigned Late Miocene age in Nigeria (Evamy *et al*., 1978) *Cyperaceaepollis* sp. and *Elaeis guineensis* have not been reported earlier than Late Miocene age (Evamy *et al*., 1978 and Germeerad *et al*., 1968) and they are Late Miocene marker. The presence of *Nympheaepollis clarus, Cyperaceaepollis* sp. and *Stereisporites*sp. has been used to infer Late Miocene age (Morley and Richard, 1993 and Olayiwola and Bamford 2016). The recovery of the diagnostic marker species from the intervals of the studied wells gave the indication that the stratigraphic interval was deposited during the Late Miocene.

Two palynostratigraphic zones each were established in the three wells using the international stratigraphic guide. *Cyperaceaepollis* sp. – *Nympheaepollis clarus* and *Stereisporites* sp. zones were established in HA-001, HB-001 and HD-001 wells. *Nympheaepollis clarus* – *Echitriletes pliocenicus* and *Cyperaceaepollis* sp. – *Elaeis guineensis* subzones were established for the *Cyperaceaepollis* sp. – *Nympheaepollis clarus* zone in the three wells. The two zones are assemblage zones. The subzones and the zone erected in the studied wells are equivalent to P860, P840 – P850 and P830 of Evamy *et al*. (1978).

Thermal maturity of miospores and palynomacerals encountered in the three wells using the thermal alteration scale of Batten (1982) and spores colour index chart of Pearson (1984) indicated optimum petroleum generation to early gas generation.

The upper intervals in the three wells showed optimum petroleum generation for the miospores and palynomacerals while the lowest interval displayed early gas generation. The composition of palynomacerals and the degree of thermal alteration of sedimentary rocks based upon change in colour of miospores have been used in the oil industries in determining the level of organic maturation and hydrocarbon source rock potential.

Lower delta plain, delta front and prodelta environments of deposition have been interpreted for the three wells using the palyno-ecological groupings, palynofacies association and sedimentological attributes. Sand bodies which represent sub-environments within these settings are deposited in sequences. Each sequence commences with a trangressive phase followed by significant regressions. The palyno-ecological groupings of the recovered palynomorph taxa showed that the studied well intervals were deposited under alternating dry and wet paleoclimatic conditions. The dry climatic zones showed high representation of savanah and montane taxa and low occurrence of freshwater, mangrove and rainforest taxa. The wet climatic zones indicated increased representation of freshwater, mangrove, and rainforest taxa and reduced occurrences of savanah and montane taxa.

There were good correlations of the palynostratigraphic zones, lithostratigraphic intervals and systems tracts in the three wells which are useful in guiding well trajectory horizontal drilling activities. The lithological units of sandstone and shale of the systems tracts are good targets for hydrocarbon reservoirs and caprocks respectively. The geometry, areal extent and calculation of total accumulated hydrocarbon are established by the lateral continuity of sandstone units interpreted in the lithofacies subcycles and systems tracts correlation.

Lowstand Systems Tracts, Trangressive Systems Tracts and Highstand Systems Tracts were recognized on the basis of Gamma Ray Logs signatures, lithology and abundance and diversity of palynomorphs and palynofacies. Chronostratigraphic surfaces such as Sequence Boundary, Maximum Flooding Surface and Transgressive Surface were also identified. The Sequence Boundaries and Maximum Flooding Surfaces were dated 8.5 Ma, 6.7 Ma, 5.6 Ma and 7.4 Ma, 6.0 Ma, 5.0 Ma respectively by correlation to Niger

Delta Cenozoic chronostratigraphic chart and the global sequence chart of Haq *et al.* (1988).

5.2 RECOMMENDATIONS

Core samples should be preferentially analysed for this type of study instead of ditch cuttings. A prominent feature in cores are sedimentary structures which are factors that can be used to facilitate a better understanding of the depositional environment. This will increase the accuracy of biostratigraphic data currently operated only from the ditch cutting samples. Even though costly, core samples are less affected, by side wall caving, drilling rod and sample mix-up.

Data from exploration wells should be made readily available for academic purposes. Hitherto, such data are regarded as the private property of the companies which funded the exploration. The companies have the total right of ownership of the data but they can be made available to the academia with a confidential code. The concept of cyclicity is better understand when seismic approach is employed because shale markers are easily delineated.

Well control is needed for the specific and major aims of this study. Such well control includes provision of complete suite of logs for the wells. For instance, provision of both Gamma Ray/Resistivity and Litho-Density/Compensated Neutron Log tools for the three wells in order to identify the pay zones and also differentiate hydrocarbon types over gross hydrocarbon sand intervals.

5.3 The Contribution of this Research Work to Knowledge

This research work has been able to establish two assemblage palynostratigraphic biozones; *Cyperaceaepollis* sp. – *Nympheaepollis clarus* and *Stereisporites* sp. zones that conform to international stratigraphic guide and successfully utilize stratigraphic range of recovered pollen and spores' marker species in dating the strata penetrated by the three wells. This will no doubt enhance the application of biostratigraphy in exploration activities which have drifted into offshore region. The work has also integrated palynofacies data, sedimentologic data and Gamma Ray Log data; using these to delineate paleoenvironment of deposition. The sequence stratigraphic results of the penetrated stratigraphic sequences were achieved using the integration of Gamma Ray Log into palynofacies data.

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APPENDIX

APPENDIX A

Lithologic Description of HA-001 Well

750ft	SILTSTONE/ SAND	**Sand (90%):** Milky white buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to pebbles, poorly sorted, sub-angular to rounded **Shale (5%):** As above. **Siltstone (5%):** Whitish, blocky, gritty, hard. **Accessories:** Few shell fragments, rare carbonaceous detritus, ferruginous materials and mica flakes.
900ft	SAND	**Sand (90%):** Milky white to buff and smoky, predominantly quartzose, slightly feldsparthic, pebble-sized to fine-grained, poorly sorted, rounded to sub-angular **Shale (10%):** Brownish grey to dark grey, platy to flaggy, moderately soft to moderately hard. **Accessories:** Abundant carbonaceous detritus, few shell fragments, ferruginous materials and rare mica flakes.
1050ft	SAND	**Sand (95%):** Milky white, predominantly quartzose, slightly feldsparthic, coarse to very coarse-grained and pebbles, occasionally medium to fine-grained, poorly sorted, rounded to sub-angular **Shale (5%):** Dark grey to brownish grey, platy, moderately soft to moderately hard. **Accessories:** Abundant glauconite pellets, few ferruginous materials, rare mica flakes, carbonaceous detritus and shell fragments.
1200ft	SAND	**Sand (95%):** As above. **Shale (5%):** As above. **Accessories:** Few ferruginous materials, carbonaceous detritus and glauconite pellets.
1350ft	SAND	**Sand (100%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained,

		occasionally coarse to pebbles, poorly sorted, sub-angular to rounded **Accessories:** Few glauconite pellets, mica flakes, carbonaceous detritus and rare ferruginous materials.
1500ft	SAND	**Sand (100%):** Milky white, predominantly quartzose, slightly feldsparthic, coarse to very coarse-grained and granular, occasionally medium to fine-grained, poorly sorted, rounded to sub-angular. **Accessories:** Few glauconite pellets, carbonaceous detritus, rare ferruginous materials and mica flakes.
1650ft	SAND	**Sand (90%):** Milky white to smoky and buff, predominantly quartzose, slightly feldsparthic, pebble to fine-grained, poorly sorted, rounded to sub-angular **Shale (10%):** Dark grey to brownish grey, platy, moderately soft to moderately hard, **Accessories:** Abundant carbonaceous detritus, rare ferruginous materials, mica flakes and glauconite pellets.
1800ft	SAND	**Sand (90%):** As above. **Shale (10%):** As above. **Accessories:** Abundant carbonaceous detritus, few mica flakes and rare ferruginous materials.
1950ft	SAND	**Sand (95%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (5%):** Dark grey to brownish grey, platy to flaggy, moderately soft to moderately hard. **Accessories:** Common carbonaceous detritus, rare ferruginous materials, mica flakes and glauconite pellets.
2100ft	SAND	**Sand (90%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to pebble-sized, poorly sorted, sub-angular to rounded **Shale (10%):** As above.

		Accessories: Abundant carbonaceous detritus, common shell fragments, rare ferruginous materials and mica flakes.
2400ft	SAND	**Sand (90%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, poorly sorted, sub-angular to rounded **Shale (10%):** As above. **Accessories.** Commoncarbonaceous detritus, few shell fragments, rare ferruginous materials and pyrites.
2550ft	SAND	**Sand (90%):** Milky white to smoky, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, poorly sorted, sub-angular to rounded **Shale (10%):** Dark grey to brownish grey, platy to flaggy, occasionally blocky, moderately hard. **Accessories:** Common carbonaceous detritus, rare ferruginous materials and shell fragments.
2700ft	SAND	**Sand (90%):** Milky white to buff and smoky, predominantly quartzose, slightly feldsparthic, coarse to pebbles, occasionally medium to fine-grained, poorly sorted, rounded to sub-angular **Shale (10%):** Dark grey, platy, moderately hard. **Accessories:** Abundant carbonaceous detritus, and few ferruginous materials.
2835ft	SHALY SAND	**Sand (85%):** As above. **Shale (15%):** Dark grey to reddish brown, platy to blocky. moderately hard. **Accessories:** Abundant carbonaceous detritus, few ferruginous materials, mica flakes and shell fragments.
3000ft	SAND	**Sand (95%):** Milky white, predominantly quartsoze, slightly feldsparthic, fine to pebble-sized, poorly sorted, sub-angular to rounded **Shale (5%):** Asabove.

		Accessories: Few carbonaceous detritus, rare ferruginous materials, shell fragments and glauconite pellets.
3150ft	SAND	**Sand (95%):** Milky white to smoky and buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, poorly sorted, sub-angular to rounded **Shale (5%):** Dark grey to reddish brown, platy to flaggy, moderately hard. **Accessories:** Common shell fragments, few carbonaceous detritus and rare ferruginous materials.
3300ft	SAND	**Sand (90%):** Milky white to smoky and buff colour, predominantly quartzose, slightly feldsparthic, coarse to pebble-sized, occasionally medium to fine-grained, poorly sorted, rounded to sub-angular **Shale (10%):** Dark grey to reddish brown, platy to flaggy, occasionally blocky, moderately hard. **Accessories:** Common carbonaceous detritus, few ferruginous materials and shell fragments.
3450ft	SAND	**Sand (90%):** Milky white to buff and smoky, predominantly quartzose, slightly feldsparthic, coarse to pebble-sized, occasionally medium to fine-grained, poorly sorted, rounded to sub-angular **Shale (10%):** Dark grey to reddish brown, platy to flaggy, moderately hard. **Accessories:** Few ferruginous materials, carbonaceous detritus and shell fragments.
3600ft	SAND	**Sand (95%):** As above. **Shale (5%):** As above. **Accessories:** Common carbonaceous detritus and rare ferruginous materials.
3750ft	SAND	**Sand (90%):** Milky white to smoky and buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, poorly sorted, sub-angular to rounded

		Shale (10%): Dark grey to brown, platy, occasionally blocky, moderately hard to hard. **Accessories:** Few carbonaceous detritus and rare ferruginous materials.
3900ft	SHALY SAND	**Sand (80%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, sub-angular to sub-rounded **Shale (20%):** As above. **Accessories:** Few carbonaceous detritus, rare ferruginous materials, glauconite pellets and shell fragments.
4050ft	SHALY SAND	**Sand (85%):** As abovebut moderately sorted. **Shale (10%):** Dark grey to brown, platy to flaggy, occasionally blocky, moderately hard to hard. **Siltstone (5%):** Whitish grey, blocky, gritty, hard. **Accessories:** Few carbonaceous detritus, mica flakes and rare ferruginous materials.
4200ft	SHALY SAND	**Sand (80%):** Milky white to smoky, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, sub-angular to sub-rounded **Shale (20%):** Reddish brown to grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Common mica flakes, few ferruginous materials and carbonaceous detritus.
4350ft	SHALY SAND	**Sand 55%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (45%):** Dark grey to reddish brown, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Abundant shell fragments, few ferruginous materials,

		carbonaceous detritus, rare mica flakes and glauconite pellets.
4500ft	SHALY SAND	**Sand (65%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to pebble-sized, poorly sorted, sub-angular to rounded **Shale (35%):** Reddish brown to grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Common mica flakes, few ferruginous materials, carbonaceous detritus, shell fragments and rare pyrites.
4650ft	SHALY SAND	**Sand (55%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse/ very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (45%):** Dark grey to brown, platy to flaggy, moderately soft to moderately hard. **Accessories:** Common mica flakes, few shell fragments, rare ferruginous materials, carbonaceous detritus and glauconite pellets.
4725ft	SHALY SAND	**Sand (65%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, sub-angular to sub-rounded **Shale (25%):** Dark grey to brown, platy to flaggy, occasionally blocky, moderately hard to hard. **Siltstone (10%):** Grey, gritty, hard. **Accessories**: Few glauconite pellets, shell fragments, rare ferruginous materials and carbonaceous detritus.
4800ft	SHALY SAND	**Sand (60%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (40%):** Dark grey to brown, platy to flaggy, occasionally blocky, moderately soft to hard.

		Accessories: Common ferruginous materials, carbonaceous detritus, shell fragments and glauconite pellets.
4875ft	SANDY SILTSTONE/ SHALE	**Sand (40%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, angular to sub-rounded **Shale (10%):** As above. **Siltstone (50%):** Whitish grey, blocky, gritty, hard. **Accessories:** Few carbonaceous detritus, shell fragments, glauconite pellets and rare ferruginous materials.
4950ft	SHALY SAND	**Sand (70%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (25%):** Dark grey to brown, platy to occasional blocky, moderately soft to hard. **Siltstone (5%):** Yellowish white, gritty, fairly hard. **Accessories:** Few glauconite pellets, carbonaceous detritus and rare ferruginous materials.
5025ft	SHALY SAND	**Sand (85%):** Milky white to smoky, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (15%):** Reddish brown to grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Few glauconite pellets, carbonaceous detritus and rare ferruginous materials.
6000ft	SHALY SAND	**Sand (60%):** Milky white to smoky, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, sub-angular to sub-rounded

		Shale (40%): Brown to grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Few ferruginous materials, carbonaceous detritus, rare mica flakes, shell fragments and glauconite pellets.
6300ft	SAND	**Sand (90%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (10%):** Brown to grey, platy, moderately hard. **Accessories:** Few carbonaceous detritus and rare ferruginous materials.
6600ft	SAND	**Sand (90%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse-grained, well sorted, angular to sub-angular **Shale (10%):** Brown to dark grey, platy, moderately hard. **Accessories**: Common mica flakes, carbonaceous detritus and rare ferruginous materials.
6750ft	SHALY SAND	**Sand (80%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, angular to sub-rounded **Shale (20%):** Brown to grey, platy to flaggy, moderately hard. **Accessories:** Rare ferruginous materials, carbonaceous detritus and glauconite pellets.
8700ft	SHALY SAND	**Sand (70%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (30%):** Brown to grey, flaggy to platy, moderately hard. **Accessories:** Few mica flakes, glauconite pellets, rare ferruginous materials and carbonaceous detritus.
8775ft	SHALY SAND	**Sand (55%):** Milky white, predominantly quartzose, slightly

		feldsparthic, very fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, angular to sub-rounded **Shale (45%):** Brownish grey to dark grey, platy to flaggy, occasionally blocky, moderately hard. **Accessories:** Fewferruginous materials, rare mica flakes, carbonaceous detritus and glauconite pellets.
8850ft	SANDY SILTSTONE/ SHALE	**Sand (40%):** As in 8700 ft. **Shale (45%):** Brownish grey to grey, platy to flaggy, moderately hard. **Siltstone (15%):** Creamy white, blocky, gritty, hard. **Accessories:** Common ferruginous materials and rare carbonaceous detritus.
8925ft	SHALY SAND	**Sand (60%):** Milky white, predominantly quartzose, slightly feldsparthic, coarse to very coarse-grained, occasionally medium to fine-grained, moderately sorted, sub-rounded to sub-angular **Shale (40%):** Brownish grey to dark grey, platy to flaggy, occasionally blocky, moderately hard. **Accessories:** Rare ferruginous materials, carbonaceous and glauconite pellets.
9000ft	SHALY SAND	**Sand (80%):** As above. **Shale (20%):** Brownish grey to grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Few ferruginous materials and mica flakes.
9075ft	SHALY SAND	**Sand (55%):** As above. **Shale (55%):** Brownish grey to grey, platy to flaggy, moderately hard. **Accessories:** Common ferruginous materials and rare mica flakes.
9150ft	SANDY SHALE	**Sand (40%):** Milky white to smoky and buff, predominantly quartzose, slightly feldsparthic, very fine to very coarse-grained and granular, poorly sorted, angular to rounded **Shale (60%):** Brownish grey to grey, blocky to platy, moderately hard to hard.

		Accessories: Few ferruginous materials, shell fragments and rare carbonaceous detritus.
9225ft	SANDY SHALE	**Sand (45%):** Milky white, quartzose, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, angular to rounded **Shale (55%):** Brownish grey to dark grey, platy to flaggy, occasionally blocky, moderately hard. **Accessories:** Rare ferruginous materials and carbonaceous detritus.
9300ft	SANDY SHALE	**Sand (35%):** Milky white, quartzose, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (65%):** Grey to dark grey, platy to flaggy, moderately hard. **Accessories:** Few ferruginous materials.
9375ft	SANDY SHALE	**Sand (30%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (70%):** Grey to dark grey, platy to flaggy, occasionally blocky, moderately hard **Accessories:** Rare ferruginous materials.
9450 ft	SANDY SHALE	**Sand (30%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (70%):** Grey to dark grey, platy to flaggy, occasionally blocky, moderately hard **Accessories:** Common ferruginous materials.
9525ft	SANDY SHALE	**Sand (25%):** As above. **Shale (75%):** As abovebut moderately hard to hard. **Accessories:** Rare ferruginous materials and carbonaceous detritus.
9600ft	SANDY SHALE	**Sand (30):** As above.

		Shale (70%): Brownish grey to dark grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Few ferruginous materials and rare carbonaceous detritus.
9675ft	SANDY SHALE	**Sand (45%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (55%):** Grey to brownish grey, platy to flaggy, occasionally blocky, moderately hard to hard **Accessories:** Rare ferruginous materials, carbonaceous detritus and glauconite pellets.
9750ft	SHALY SAND	**Sand (75%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (25%):** Brownish grey to dark grey, platy, moderately hard. **Accessories:** Rare carbonaceous detritus.
9825ft	SANDY SHALE	**Sand (40%):** As above. **Shale (60%):** Brownish grey to grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Rare ferruginous materials.
9900ft	SHALY SAND	**Sand (65%):** As above. **Shale (35%):** As above. **Accessories:** Rare carbonaceous detritus.
9975ft	SHALY SAND	**Sand (70%):** As above. **Shale (30%):** Brownish grey to grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare carbonaceous detritus.
10050ft	SANDY SHALE	**Sand (35%):** As above. **Shale (65%):** Grey, platy to flaggy, moderately hard to hard. **Accessories:** Nil.
10125ft	SHALY SAND	**Sand (60%):** As above.

		Shale (40%): Grey to dark grey, platy to flaggy, moderately hard to hard. **Accessories:** Nil.
10200ft	SHALY SAND	**Sand (55%):** As above. **Shale (45%):** Brownish grey to grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Rare carbonaceous detritus.
10275ft	SHALY SAND	**Sand (55%):** As above. **Shale (45%):** Grey to brownish grey, platy to flaggy, occasionally blocky, moderately hard to hard **Accessories:** Nil.
10350ft	SANDY SHALE	**Sand 40%):** Milky white, predominantlyquartzose, slightly felsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (60%):** As in 10200 ft. **Accessories:** Rare ferruginous materials and carbonaceous detritus.
10425ft	SANDY SHALE	**Sand 30%):** As above. **Shale (70%):** Grey to brownish grey, platy to flaggy, occasionally blocky, moderately hard to hard **Accessories:** Common ferruginous materials.
10500ft	SHALY SAND	**Sand (60%):** Milky white to smoky and buff, predominantlyquartzose, slightly felsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, sub-angular to sub-rounded **Shale (40%):** As above. **Accessories:** Few ferruginous materials and rare carbonaceous detritus.
10575ft	SANDY SHALE	**Sand (40%):** Milky white to smoky and buff, predominantlyquartzose, slightly felsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (60%):** As above. **Accessories:** Rare ferruginous materials.

10650ft	SHALY SAND	**Sand (70%):** Milky white, predominantlyquartzose, slightly feldsparthic, very fine to medium-grained, occasionally to very coarse-grained and granular, poorly sorted, angular to rounded **Shale (30%):** Grey to brownish grey, silty, platy to flaggy, occasionally blocky, moderately hard to hard **Accessories:** Rare ferruginous materials.
10725ft	SHALY SAND	**Sand (65%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, angular to sub-rounded **Shale (35%):** As above. **Accessories:** Nil,
10800ft	SHALY/SILTSTONE SAND	**Sand (55%):** As above. **Shale (35%):** Grey to brownish grey, platy to flaggy, moderately hard to hard. **Siltstone (10%):** Brownish white, blocky, gritty, hard. **Accessories**: Nil.
10875ft	SHALY/SILTSTONE SAND	**Sand (55%):** Milky white, predominantlyquartzose, slightly felsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (45%):** Grey to brownish grey, silty, platy to flaggy, moderately hard. **Accessories:** Rare carbonaceous detritus.
10950ft	SANDY SHALE	**Sand (45%):** As above. **Shale (55%):** Grey, platy to flaggy, moderately hard. **Accessories:** Rare carbonaceous detritus.
11025ft	SANDY SHALE	**Sand (30%):** Milky white, predominantlyquartzose, slightly feldsparthic, very fine to very coarse-grained, poorly sorted, angular to sub-rounded **Shale (70%):** Brownish grey to dark grey, silty, blocky to platy, moderately hard to hard. **Accessories:** Rare mica flakes.
11100ft	SHALY SAND	**Sand (75%):** Milky white, predominantlyquartzose, slightly feldsparthic, very fine to medium-

		grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (25%):** Brownish grey to grey, silty, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Rare ferruginous materials and carbonaceous detritus.
11175ft	SHALY SAND	**Sand (70%):** As above **Shale (30%):** Brownish grey to grey, silty, platy to flaggy, moderately hard. **Accessories:** Rare ferruginous materials, carbonaceous detritus and glauconite pellets.
11250ft	SANDY SHALE	**Sand (45%):** Milky white, predominantlyquartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, angular to sub-rounded **Shale (55%):** Brownish grey to grey, silty, platy to flaggy, moderately hard. **Accessories:** Rare glauconite pellets.
11325ft	SANDY SHALE	**Sand (40%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (60%):** Brownish grey to grey, silty, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Rare carbonaceous detritus.
11400ft	SANDY SHALE	**Sand (30%):** As above. **Shale (70%):** Brownish grey to dark grey, silty, platy to flaggy, moderately hard to hard. **Accessories:** Rare carbonaceous detritus.
11475ft	SANDY SHALE	**Sand (35%):** As above. **Shale 65%):** Brownish grey to grey, silty, platy to flaggy, moderately hard. **Accessories:** Rare shell fragments.
11550ft	SHALY SAND	**Sand (70%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, angular to sub-rounded

		Shale (30%): Brownish grey to grey, silty, platy, moderately hard. **Accessories:** Nil.
11610ft	SAND SHALE	**Sand (85%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (15%):** As above. **Accessories:** Rare pyrites and glauconite pellets.

APPENDIX B

Lithologic Description of HB-001 Well

4100ft	SAND	**Sand (95%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to pebbles, poorly sorted, sub-angular to rounded **Shale (5%):** Grey, platy, hard to moderately hard. **Accessories:** Rare ferruginous materials.
4250ft	SAND	**Sand (97%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (3%):** Grey, flaggy to platy, hard to moderately hard. **Accessories.**Nil.
4400ft	SAND	**Sand (95%):** As above. **Shale (5%):** Dark grey, platy to flaggy occasionally blocky, hard to moderately hard. **Accessories:** Rare ferruginous materials.
4550ft	SAND	**Sand (90%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (10%):** Grey, platy, moderately hard to hard. **Accessories:** Rare glauconite pellets.
4700ft	SHALY SAND	**Sand (65%):** Milky white buff and smoky, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, sub-angular to rounded **Shale (35%):** Brownish grey to grey, platy to flaggy, moderately hard to hard. **Accessories:** Few carbonaceous detritus and shell fragments.

4850ft	SHALY SAND	**Sand (55%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to pebble-sized, poorly sorted, sub-angular to rounded **Shale (45%):** Brownish grey to dark grey, platy to blocky, moderately to hard. **Accessories:** Common shell fragments and glauconite pellets.
5000ft	SAND	**Sand (90%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, sub-angular to sub-rounded **Shale (10%):** Brownish grey/ grey, platy, hard to moderately hard. **Accessories:** Rare glauconite pellets.
5150ft	SHALY SAND	**Sand (80%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to pebbles, poorly sorted, sub-angular to rounded **Shale (20%):** Dark grey to brownish grey, platy to flaggy, hard to moderately hard. **Accessories:** Rare ferruginous materials and pyrites.
5300ft	SHALY SAND	**Sand (60%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, poorly sorted, sub-angular to rounded **Shale (40%):** Reddish brownto grey, platy to flaggy, occasionally blocky, hard to moderately hard. **Accessories:** Few ferruginous materials and rare shell fragments.
5450ft	SANDY SHALE	**Sand (55%):** As above. **Shale (45%):** As above. **Accessories:** Rare ferruginous materials and shell fragments.
5600ft	SHALE	**Sand (10%):** Milky white, quartzose, fine to medium-grained, occasionally coarse-grained well sorted, mostly sub-angular.

		Shale (90%): Grey, blocky to platy, moderately hard to hard, **Accessories:** Common ferruginous materials and rare carbonaceous detritus.
5750ft	SHALE	**Sand (10%):** Milky white, quartzose, fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (90%):** Grey, platy, moderately hard to hard, **Accessories:** Common glauconite pellets, rare ferruginous materials and shell fragments.
5900ft	SHALY SAND	**Sand (55%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (45%):** Grey, platy, moderately hard to hard. **Accessories:** Rare ferruginous materials, carbonaceous detritus and shell fragments.
6050ft	SHALY SAND	**Sand (85%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular to sub-rounded **Shale (15%):** Asabove. **Accessories:** Rare ferruginous materials.
6350ft	SANDY SHALE	**Sand (45%):** As above. **Shale (55%):** Grey, platy, moderately hard to hard. **Accessories.** Rare ferruginous materials.
6500ft	SHALY SAND	**Sand (70%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular to sub-rounded **Shale (30%):** Grey, platy, moderately hard. **Accessories:** Rare ferruginous materials.
6650ft	SHALY SAND	**Sand (60%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained,

		occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (40%):** Grey, platy, moderately hard to hard. **Accessories:** Rare shell fragments.
6800ft	SANDY SHALE	**Sand (40%):** Milky white to smoky, predominantly quartzose, slightly feldsparthic, fine to medium-grained, coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (60%):** Grey, platy. moderately hard to hard **Accessories:** Few shell fragments, glauconite pellets and rare ferruginous materials.
6950ft	SANDY SHALE	**Sand (30%):** Milky white to buff, predominantly quartsoze, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (70%):** As above. **Accessories:** Few glauconite pellets, rare ferruginous materials and shell fragments.
7100ft	SANDY SHALE	**Sand (20%):** Milky white to boff, quartzose, fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (80%):** Dark grey to grey, platy to flaggy, moderately hard to hard. **Accessories:** Few carbonaceous detritus, rare ferruginous materials, shell fragments and glauconite pellets.
7250ft	SAND	**Sand (90%):** Milky white, predominantly quartsoze, slightly feldsparthic, fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular to sub-rounded **Shale (10%):** Dark grey to grey, platy, moderately hard to hard. **Accessories:** Rare carbonaceous detritus and shell fragments.
7400ft	SHALY	**Sand (80%):** Milky white, predominantly quartzose, slightly

		feldsparthic, fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (20%):** Grey, platy, moderately hard to hard. **Accessories:** Nil.
7700ft	SANDY SHALE	**Sand (30%):** As above. **Shale (70%):** Dark grey to grey, platy, moderately hard to hard. **Accessories:** Nil.
7760ft	SANDY SHALE	**Sand (30%):** As above. **Shale (30%):** Dark grey to grey, platy, moderately hard to hard. **Accessories:** Few carbonaceous detritus and rare shell fragments.
7850ft	SANDY SHALE	**Sand (25%):** Milky white, quartzose, fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (75%):** Dark grey to grey, platy, moderately hard to hard. **Accessories:** Rare ferruginous materials, carbonaceous detritus and shell fragments.
7925ft	SANDY SHALE	**Sand (15%):** Milky white, quartzose, fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular to sub-rounded **Shale (85%):** Dark grey to grey, platy, moderately hard. **Accessories:** Rare ferruginous materials, carbonaceous detritus and shell fragments.
8000ft	SANDY SHALE	**Sand (40%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (60%):** Dark grey to grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials, carbonaceous detritus and shell fragments.
8075ft	SHALY SAND	**Sand 60%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse/ very coarse-

		grained, moderately well sorted, sub-angular to sub-rounded **Shale (40%):** Grey, platy to flaggy, moderately hard. **Accessories:** Rare ferruginous materials.
8150ft	SHALY SAND	**Sand (75%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (25%):** Grey/brownish grey, platy, moderately hard to hard. **Accessories:** Few glauconite pellets, rare ferruginous materials and shell fragments.
8225ft	SHALY SAND	**Sand (80%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (20%):** Grey to grey, platy, moderately hard. **Accessories:** Nil.
8300ft	SHALY SAND	**Sand (55%):** As in 8150 ft. **Shale (45%):** Grey, platy to flaggy, moderately hard to hard. **Accessories**: Few glauconite pellets and rare shell fragments.
8375ft	SANDY SHALE	**Sand (30%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (70%):** As above. **Accessories:** Rare shell fragments and glauconite pellets.
8450ft	SHALY SAND	**Sand (65%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse/very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (35%):** Grey, platy to flaggy, occasionally blocky, moderately hard to hard.

		Accessories: Rare carbonaceous detritus, shell fragments and glauconite pellets.
8525ft	SHALY SAND	**Sand (75%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (25%):** Grey, platy to flaggy, moderately hard. **Accessories:** Rare glauconite pellets.
8600ft	SHALY SAND	**Sand (80%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (20%):** Grey, platy, moderately hard. **Accessories:** Rare glauconite pellets.
8750ft	SHALY SAND	**Sand (65%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse-grained, well sorted, mostly sub-angular **Shale (35%):** Grey, platy, moderately hard. **Accessories:** Rare ferruginous materials and carbonaceous detritus.
8825ft	SHALY SAND	**Sand (70%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular. **Shale (30%):** As above. **Accessories:** Rare ferruginous materials.
8900ft	SHALY SAND	**Sand (80%):** As above **Shale (20%):** Dark grey to grey, blocky to platy, moderately hard to hard. **Accessories**: Rare ferruginous materials.
8975ft	SHALY SAND	**Sand (80%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded

		Shale (20%): As above. **Accessories:** Nil.
9275ft	SANDY SHALE	**Sand (40%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (60%):** Dark grey to grey, platy to flaggy, moderately hard to hard **Accessories:** Few ferruginous materials and rare carbonaceous detritus.
9350ft	SANDY SHALE	**Sand (30%):** As above. **Shale (70%):** As above but platy. **Accessories:** Rareferruginous materials.
9425ft	SANDY SHALE	**Sand (25%):** As above. **Shale (75%):** Dark grey to grey, platy, moderately hard. **Accessories:** Rare ferruginous materials, shell fragments and glauconite pellets.
9500ft	SANDY SHALE	**Sand (35%):** As above. **Shale (65%):** As above. **Accessories:** Common glauconite pellets.
9575ft	SANDY SHALE	**Sand (45%):** As above. **Shale (55%):** Dark grey to grey, platy, moderately hard. **Accessories:** Rare glauconite pellets.
9650 ft	SANDY SHALE	**Sand (40%):** As above. **Shale (60%):** As above. **Accessories:** Rare glauconite pellets.
9725ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (90%):** Dark grey to light grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Rare ferruginous materials.
9800 ft	SANDY SHALE	**Sand (25%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (75%):** As above. **Accessories:** Rare ferruginous materials and glauconite pellets.
9875ft	SANDY SHALE	**Sand (25%):** Milky white, quartzose, very fine to medium-grained,

		occasionally coarse to very coarse-grained, moderately to poorly sorted, angular to sub-rounded **Shale (75%):** Dark grey/ grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials and glauconite pellets.
9950ft	SANDY SHALE	**Sand (30%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (70%):** Dark grey to grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials.
10025ft	SANDY SHALE	**Sand (15%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, angular to sub-rounded **Shale (85%):** Dark grey, platy, moderately hard to hard. **Accessories:** Few ferruginous materials and rare shell fragments.
10100ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular **Shale (85%):** Dark grey, platy to flaggy, moderately hard to hard. **Accessories:** Few ferruginous materials and rare glauconite pellets.
10175ft	SILTSTONE/SHALE	**Sand (traces):** As above. **Shale (90%):** Dark grey, platy to blocky, moderately hard to hard. **Siltstone (10%):** Light grey, blocky, gritty, hard. **Accessories:** Nil.
10250ft	SHALE	**Sand (5%):** As above. **Shale (95%):** Dark grey/ brownish grey, platy to flaggy, moderately hard to hard. **Accessories:** Few ferruginous materials.
10325ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, very well sorted, angular to sub-angular. **Shale (95%):** As above.

		Accessories: Few ferruginous materials.
10400ft	SILTSTONE/ SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular. **Shale (85%):** Dark grey to brownish grey, platy to flaggy, moderately hard to hard. **Siltstone (10%):** Light grey, blocky, gritty and hard. **Accessories:** Rare ferruginous materials.
10475ft	SILTSTONE/ SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular **Shale (85%):** Dark grey, platy to flaggy, moderately hard to hard. **Siltstone (10%):** As above. **Accessories:** Rare ferruginous materials and glauconite pellets.
10550ft	SHALE	**Sand (traces):** As above. **Shale (100%):** Dark grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials.
10625ft	SHALE	**Sand (traces):** As above. **Shale (100%):** Dark grey, platy, moderately hard to hard. **Accessories:** Rare ferruginous materials and shell fragments.
10700ft	SHALE	**Shale (100%):** Dark grey, platy, moderately hard to hard. **Accessories:** Nil.
10775ft	SHALE	**Sand (5%):** As in 10550 ft. **Shale (95%):** As above. **Accessories:** Nil.
10850ft	SHALE	**Sand (5%):** As above. **Shale (95%):** Dark grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials.
10925ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to very coarse-grained, poorly sorted, angular to sub-rounded **Shale (95%):** As above. **Accessories:** Rare ferruginous materials.
11000ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular

		Shale (95%): Dark grey, silty, papery to platy, moderately hard **Accessories:** Few ferruginous materials.
11075ft	SANDY SHALE	**Sand (15%):** As above. **Shale (85%):** Dark grey, silty, platy, moderately hard. **Accessories:** Rare ferruginous materials.
11150ft	SHALY SAND	**Sand (60%):** As above. **Shale (40%):** Dark grey to grey, silty, platy, moderately hard. **Accessories:** Rare ferruginous materials.
11225ft	SHALY SAND	**Sand (70%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse-grained, well sorted, angular to sub-angular **Shale (30%):** Dark grey to grey, silty, platy, moderately hard. **Accessories:** Rare glauconite pellets.
11300ft	SANDY SHALE	**Sand (40%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (60%):** Dark grey to grey, platy to flaggy, moderately hard. **Accessories:** Nil,
11375ft	SANDY SHALE	**Sand (55%):** As above. **Shale (45%):** As above. **Accessories**: Few ferruginous materials and rare mica flakes.
11450ft	SANDY SHALE	**Sand (35%):** Milky white, predominantly quartzose, slightly felsparthic, very fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, angular to sub-rounded **Shale (65%):** As above. **Accessories:** Rare shell fragments.
11525ft	SHALY SAND	**Sand (60%):** As above. **Shale (40%):** Grey, platy to flaggy, moderately hard. **Accessories:** Nil.
11600 ft	SANDY SHALE	**Sand (20%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse to very coarse-

		grained, moderately sorted, angular to sub-rounded **Shale (80%):** Dark grey to brownish grey, platy to flaggy, moderately hard. **Accessories:** Nil.
11675ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, angular to sub-rounded **Shale (90%):** Dark grey, silty, platy to flaggy, occasionally blocky, moderately hard. **Accessories:** Nil.
11750ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, angular to sub-angular **Shale (90%):** As above. **Accessories:** Nil.
11825ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, mostly sub-angular. **Shale (95%):** Dark grey, silty, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Few glauconite pellets and rare pyrites.
11900ft	SHALE	**Sand (5%):** As above. **Shale (80%):** Dark grey to brownish grey, silty, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Few glauconite pellets, rare ferruginous materials and pyrites.
11975ft	SANDY SHALE	**Sand (25%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, angular to sub-angular **Shale (75%):** As above. **Accessories:** Common pyrites, rare ferruginous materials, mica flakes and glauconite pellets.
12050ft	SHALE	**Sand (5%):** As above.

		Shale 95%): Dark grey, silty, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Rare ferruginous materials, pyrites and glauconite pellets.
12125ft	SHALE	**Sand (10%):** As above. **Shale (90%):** Dark grey, silty, platy to flaggy, moderately hard. **Accessories:** Rare ferruginous materials and glauconite pellets.
12200ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, mostly sub-angular **Shale (95%):** As above. **Accessories:** Rare pyrites and glauconite pellets.
12275ft	SHALE	**Sand (5%):** As above. **Shale (95%):** As above. **Accessories:** Rare glauconite pellets.
12350ft	SHALE	**Sand (5%):** As above. **Shale (95%):** As above. **Accessories:** Rare pyrites and glauconite pellets.
12425ft	SANDY SHALE	**Sand (15%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, angular to sub-angular **Shale (85%):** Dark grey, silty, platy to flaggy, occasionally blocky, moderately hard. **Accessories:** Rare carbonaceous detritus and glauconite pellets.
12500 ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, very well sorted, angular to sub-angular **Shale (95%):** Dark grey to brownish grey, silty, platy to flaggy, moderately hard. **Accessories:** Few glauconite pellets and rare ferruginous materials.
12575ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, angular to sub-angular **Shale (95%):** As above. **Accessories:** Few glauconite pellets, rare ferruginous materials,

		carbonaceous detritus and shell fragments.
12650ft	SHALE	**Sand (5%):** As above. **Shale (95%):** Dark grey to brownish grey, silty, platy to flaggy, occasionally blocky, moderately hard. **Accessories:** Rare ferruginous materials and glauconite pellets.
12725ft	SHALE	**Sand (5%):** As above. **Shale (95%):** As above. **Accessories:** Few glauconite pellets and rare ferruginous materials.
12800ft	SHALE	**Sand (traces):** As above. **Shale (100%):** As above. **Accessories:** Rare carbonaceous detritus, pyrites, shell fragment and glauconite pellets.
12875ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, mostly sub-angular **Shale (95%):** Dark grey to brownish grey, silty, platy to flaggy, moderately hard. **Accessories:** Few ferruginous materials, pyrites, rare carbonaceous detritus and shell fragments.
12950ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, very well sorted, angular to sub-angular **Shale (95%):** Dark grey to brownish grey, silty, platy, moderately hard. **Accessories:** Rare shell fragments.
13025ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, angular to sub-angular **Shale (90%):** Dark grey to brownish grey, silty, platy to flaggy, moderately hard. **Accessories:** Rare ferruginous materials, shell fragments and glauconite pellets.
13100ft	SHALE	**Sand (10%):** As above. **Shale (90%):** As above. **Accessories:** Few glauconite pellets, rare ferruginous materials,

		carbonaceous detritus and shell fragments.
13160ft	SHALE	**Sand (traces):** As above. **Shale (100%):** Dark grey, platy, moderately hard. **Accessories:** Few glauconite pellets.

APPENDIX C

Lithologic Description of HD-001 Well

4875ft	SHALY SAND	**Sand (60%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (40%):** Grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare carbonaceous detritus.
5190ft	SHALY SAND	**Sand (70%):** Milky white to smoky, predominantly quartzose, slightly feldsparthic, fine to very coarse-grained and granule-sized, poorly sorted, sub-angular to rounded **Shale (30%):** Grey, platy, moderately hard to hard. **Accessories.** Common carbonaceous detritus.
5390ft	SANDY SHALE	**Sand (40%):** As above but milky white to smoky. **Shale (60%):** Grey to brownish grey, platy to flaggy occasionally blocky, moderately hard to hard **Accessories:** Few glauconite pellets.
5490ft	SHALY SAND	**Sand (65%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (35%):** Grey to brownish grey, platy to flaggy, moderately hard to hard. **Accessories:** Few ferruginous materials, carbonaceous detritus, rare mica flakes and glauconite pellets.
5625ft	SANDY SHALE	**Sand (45%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, sub-angular to rounded

		Shale (55%): Grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials, mica flakes and glauconite pellets.
5790ft	SANDY SHALE	**Sand (35%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (65%):** As above. **Accessories:** Abundant carbonaceous materials and few ferruginous materials.
5940ft	SANDY SHALE	**Sand (25%):** Milky white, quartzose, fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, sub-angular to sub-rounded **Shale (75%):** Grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Few ferruginous materials and carbonaceous materials.
6090ft	SANDY SHALE	**Sand (30%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub- rounded **Shale (70%):** Dark grey to brownish grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials and carbonaceous detritus.
6290ft	SHALY SAND	**Sand (65%):** Milky white to buff, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, poorly sorted, sub-angular to rounded **Shale (35%):** As above but platy. **Accessories:** Common carbonaceous materials.
6390ft	SANDY SHALE	**Sand (40%):** As in 6090 ft. **Shale (60%):** As above.

		Accessories: Common ferruginous materials.
6540ft	SHALY SAND	**Sand (60%):** Milky white to smoky, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (40%):** Dark grey to brownish grey, platy, moderately hard to hard, **Accessories:** Few ferruginous materials and rare carbonaceous detritus.
6590ft	SANDY SHALE	**Sand (30%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (70%):** Brownish grey to grey, platy, moderately hard to hard, **Accessories:** Common ferruginous materials and few carbonaceous detritus.
6870ft	SHALY SAND	**Sand (75%):** Milky white to buff and smoky, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (25%):** Dark grey to brownish grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials and carbonaceous detritus.
6990ft	SANDY SHALE	**Sand (30%):** As in 6590 ft. **Shale (70%):** Asabove but platy to flaggy, occasionally blocky. **Accessories:** Few ferruginous materials, carbonaceous detritus, shell fragments and rare glauconite pellets.
7140ft	SANDY SHALE	**Sand (40%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to very coarse-grained, moderately to poorly sorted, sub-angular to sub-rounded **Shale (60%):** Dark grey to brownish grey, platy, moderately hard to hard.

		Accessories. Few ferruginous materials and rare carbonaceous detritus.
7290ft	SANDY SHALE	**Sand (35%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (65%):** Brownish grey to grey, platy to flaggy, moderately hard to hard. **Accessories:** Few ferruginous materials and rare carbonaceous detritus.
7440ft	SANDY SHALE	**Sand (25%):** As in 7140 ft. **Shale (75%):** Brownish grey to grey, platy, moderately hard to hard. **Accessories:** Few ferruginous materials and rare carbonaceous detritus.
7590ft	SHALY SAND	**Sand (65%):** Milky white to smoky, predominantly quartzose, slightly feldsparthic, fine to medium-grained, coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (35%):** Grey, platy. moderately hard to hard **Accessories:** Nil.
7740ft	SHALY SAND	**Sand (80%):** Milky white to smoky and buff coloured, predominantly quartsoze, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, poorly sorted, sub-angular to rounded **Shale (20%):** Brownish grey to grey, platy, moderately hard to hard. **Accessories:** Few ferruginous materials, glauconite pellets, rare mica flakes and carbonaceous detritus.
7815ft	SHALY SAND	**Sand (60%):** As above but moderately to poorly sorted **Shale (40%):** Brownish grey to grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials, carbonaceous detritus and shell fragments.
7890ft	SHALY SAND	**Sand (75%):** Milky white, predominantly quartsoze, slightly feldsparthic, fine to medium-grained,

		occasionally coarse to very coarse-grained, moderately to poorly sorted, sub-angular to sub-rounded **Shale (25%):** Brownish grey to grey, platy, moderately hard to hard. **Accessories:** Rare ferruginous materials, carbonaceous detritus and glauconite pellets.
7965ft	SANDY SHALE	**Sand (45%):** As above. **Shale (55%):** Brownish grey to grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Few ferruginous materials and rare carbonaceous detritus.
8080ft	SHALY SAND	**Sand (75%):** As above. **Shale (25%):** As above but platy to flaggy. **Accessories:** Rare carbonaceous detritus, ferruginous materials, mica flakes and shell fragments.
8115ft	SANDY SHALE	**Sand (45%):** As above. **Shale (55%):** Dark grey to grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials, mica flakes and carbonaceous detritus.
8190ft	SHALY SAND	**Sand (55%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to pebble-sized, poorly sorted, sub-angular to rounded **Shale (45%):** Brownish grey to grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials.
8265ft	SANDY SHALE	**Sand (40%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained, moderately to poorly sorted, sub-angular to sub-rounded **Shale (60%):** As above. **Accessories:** Rare ferruginous materials.
8340ft	SHALY SAND	**Sand (65%):** As above. **Shale (35%):** As above. **Accessories:** Rare ferruginous materials.
8415ft	SHALY SAND	**Sand (85%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained,

		occasionally coarse to very coarse-grained, poorly sorted, sub-angular to sub-rounded **Shale (15%):** Grey, platy, occasionally blocky, moderately hard to hard. **Accessories:** Rare ferruginous materials.
8490ft	SANDY SHALE	**Sand (35%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coase-grained, moderately to poorly sorted, sub-angular to sub-rounded **Shale (65%):** Grey, platy to flaggy, moderately hard to hard. **Accessories:** Few ferruginous materials.
8565ft	SANDY SHALE	**Sand (20%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coase-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (80%):** Dark grey to grey, platy, moderately hard to hard. **Accessories:** Rare ferruginous materials.
8640ft	SANDY SHALE	**Sand (25%):** As in 8415 ft. **Shale (75%):** Dark grey to brownish grey, platy, moderately hard to hard. **Accessories**: Rare ferruginous materials.
8715ft	SANDY SHALE	**Sand (30%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse-grained, mostly sub-angular **Shale (70%):** As above. **Accessories:** Few shell fragments and rare ferruginous materials.
8865ft	SANDY SHALE	**Sand (35%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse/very coase-grained, moderately well sorted, sub-angular to sub-rounded **Shale (65%):** Dark grey to brownish grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials.

8990ft	SANDY	**Sand (20%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (80%):** Dark grey to brownish grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Rare ferruginous materials and glauconite pellets.
9015ft	SANDY SHALE	**Sand (35%):** Milky white, predominantly quartzose, slightly feldsparthic, fine to medium-grained, occasionally coarse to very coarse-grained and granular, moderately to poorly sorted, sub-angular to rounded **Shale (65%):** Dark grey to grey, platy to flaggy, moderately hard to hard. **Accessories:** Few ferruginous materials and glauconite pellets.
9090ft	SANDY SHALE	**Sand (65%):** As above. **Shale (35%):** As above. **Accessories:** Common ferruginous materials.
9165ft	SHALE	**Sand (traces):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular **Shale (100%):** Dark grey to grey, blocky to platy, moderately hard to hard. **Accessories**: Common ferruginous materials.
9240ft	SHALE	**Sand (5%):** As above but moderately well sorted **Shale (95%):** As above. **Accessories:** Few ferruginous materials and carbonaceous detritus.
9315ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (90%):** Dark grey to grey, platy to flaggy, occasionally blocky, moderately hard to hard

		Accessories: Abundant ferruginous materials and few glauconite pellets.
9390ft	SHALE	**Sand (10%):** As above. **Shale (95%):** As above. **Accessories:** Common carbonaceous detritus and few ferruginous materials.
9465ft	SHALE	**Sand (5%):** As in 9240 ft. **Shale (95%):** Dark grey, platy to flaggy, moderately hard to hard. **Accessories:** Few carbonaceous detritus and rare ferruginous materials.
9540ft	SANDY SHALE	**Sand (25%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular **Shale (75%):** Same as above. **Accessories:** Rare ferruginous materials and carbonaceous detritus.
9615ft	SANDY SHALE	**Sand (30%):** As above. **Shale (70%):** Dark grey, platy, moderately hard to hard. **Accessories:** Rare ferruginous materials and carbonaceous detritus.
9630ft	SANDY SHALE	**Sand (15%):** Milky white, quartzose, very fine to medium-grained, very well sorted, angular **Shale (85%):** As above. **Accessories:** Rare ferruginous materials.
9765ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (90%):** As above. **Accessories:** Few carbonaceous detritus and rare ferruginous materials.
9840ft	SANDY SHALE	**Sand (15%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular **Shale (85%):** Dark grey, platy, moderately hard to hard. Accessories: Rare ferruginous materials and carbonaceous detritus.
9915ft	SANDY SHALE	**Sand (30%):** Milky white, predominantly quartzose, slightly

		feldsparthic, very fine to medium-grained, occasionally coarse/ very coarse-grained, moderately well sorted, sub-angular to sub-rounded **Shale (70%):** Dark grey/ grey, platy, moderately hard to hard. **Accessories:** Few ferruginous materials.
10065ft	SANDY SHALE	**Sand (25%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (75%):** Dark grey to brownish grey, platy to flaggy, moderately hard to hard. **Accessories:** Few ferruginous materials and carbonaceous detritus.
10090ft	SANDY SHALE	**Sand (40%):** As above. **Shale (60%):** As above. **Accessories:** Rare carbonaceous detritus.
10140ft	SANDY SHALE	**Sand (30%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (70%):** Dark grey to brownish grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare carbonaceous detritus.
10215ft	SANDY SHALE	**Sand (45%):** As above. **Shale (55%):** Dark grey to grey, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials, carbonaceous detritus and shell fragments.
10365ft	SANDY SHALE	**Sand (20%):** As above. **Shale (80%):** As above. **Accessories:** Rare carbonaceous detritus.
10440ft	SANDY SHALE	**Sand (30%):** Milky white, predominantly quartzose, slightly feldsparthic, very fine to medium-grained, occasionally coarse to very coarse-grained and glanular, moderately to poorly sorted, sub-angular to rounded

		Shale (70%): As above. **Accessories:** Rare ferruginous materials.
10515ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (90%):** Dark grey to grey, platy, moderately hard to hard. **Accessories:** Nil.
10590ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, sub-angular **Shale (90%):** As above. **Accessories:** Nil.
10665ft	SANDY SHALE	**Sand (25%):** Milky white to smoky, quartzose, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (75%):** Dark grey to grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Few ferruginous materials.
10740ft	SHALE	**Sand (10%):** As above. **Shale (90%):** Dark grey to brownish grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Rare ferruginous materials.
10890ft	SILTY SHALE	**Sand (10%):** As above. **Shale (90%):** Dark grey/ brownish grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Nil.
10965ft	SANDY SHALE	**Sand (15%):** As above. **Shale (85%):** Dark grey/ brownish grey, silty, platy to flaggy, moderately hard to hard. **Accessories:** Few ferruginous materials.
11040ft	SANDY SHALE	**Sand (15%):** As above. **Shale (85%):** Dark grey, silty, platy to flaggy, moderately hard to hard. **Accessories:** Nil.
11115ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained,

		occasionally coarse to very coarse-grained, moderately sorted, sub-angular to sub-rounded **Shale (90%):** As above. **Accessories:** Rare ferruginous materials.
11190ft	SILTSTONE/ SHALE	**Sand (5%):** As above. **Shale (80%):** Dark grey to brownish grey, platy to flaggy, occasionally blocky, moderately hard to hard. **Siltstone (15%):** Whitish grey to brownish grey, gritty, hard. **Accessories:** Rare ferruginous materials.
11265ft	SILTSTONE/SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, well sorted, sub-angular. **Shale (80%):** As above. **Siltstone (15%):** As above. **Accessories:** Nil.
11340ft	SHALE	**Sand (5%):** As above. **Shale (95%):** Dark grey, silty, platy to flaggy, moderately hard to hard. **Accessories:** Nil.
11415ft	SILTSTONE/SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (75%):** Dark grey to brownish grey, silty, platy to flaggy, occasionally blocky, moderately hard to hard. **Siltstone (15%):** As above. **Accessories:** Rare carbonaceous detritus and shell fragments.
11490ft	SHALE	**Sand (10%):** As above. **Shale (90%):** As above. **Accessories:** Rare ferruginous materials,
11515ft	SHALE	**Sand (5%):** Milky white to buff, quartzose, very fine to medium-grained, very well sorted, mostly sub-angular. **Shale (95%):** Dark grey to grey, silty, platy to flaggy, moderately hard to hard. **Accessories**: Nil.
11640ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, angular to sub-rounded

		Shale (90%): As above. **Accessories:** Nil.
11715ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to very coarse-grained and granule-sized, poorly sorted, angular to rounded **Shale (90%):** Dark grey, silty, platy to flaggy, occasionally blocky, moderately hard to hard. **Accessories:** Rare ferruginous materials.
11790ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, very well sorted, angular to sub-angular **Shale (95%):** As above but dark grey to brownish grey. **Accessories:** Rare ferruginous materials.
11865ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse-grained, well sorted, angular to sub-rounded **Shale (95%):** As above. **Accessories:** Nil.
11940ft	SHALE	**Sand (10%):** Milky white, quartzose, very fine to medium-grained, occasionally coarse to very coarse-grained, moderately sorted, angular to sub-rounded **Shale (90%):** As above. **Accessories:** Nil.
12015ft	SHALE	**Sand (5%):** Milky white, quartzose, very fine to medium-grained, very well sorted, sub-angular. **Shale (95%):** Dark grey, silty, platy to flaggy, moderately hard to hard. **Accessories:** Rare ferruginous materials.
12090ft	SILTSTONE/SHALE	**Sand (5%):** As above. **Shale (80%):** Dark grey, silty, platy to flaggy, occasionally blocky, moderately hard to hard. **Siltstone (15%):** Whitish grey to brownish grey, gritty, fairly hard. **Accessories:** Rare ferruginous materials.

APPENDIX D

Palyno-ecological Groups of Palynomorphs from HA-001 Well

HA - 001 WELL

SAVANNA TAXA

S/N	Sample depth (meter)/Taxa	Polypodiaceoporites sp/Pteris sp	Cyperaceapolis sp	Coryius sp	Numulipollis neogenious	Fungal spore	Chenopodipollis sp	Canthiumidites sp	Monoporites annulatus	Proteacidites sp	Steiresporites sp	Total Savanna taxa
1	750	3							3		1	7
2	900	8	1					3				12
3	1050	8						2	8		1	19
4	1200	2							1		1	4
5	1350	2							7	1		10
6	1500	3							7			10
7	1650								4			4
8	1800	1	1						9		1	12
9	1950	6	2		1				95		1	105
10	2100	9							55		1	65
11	2400	1							57			58
12	2550					1			22			23
13	2700	2							22			24
14	2835								25			25
15	3000	3					1					4
16	3150								19		1	20
17	3300	3							21		1	25
18	3450	2							3		1	6
19	3600	2				1			3			6
20	3750	2							23		1	26
21	3900	2							14		3	19
22	4050	2							11			13
23	4200	2							3			5
24	4350	2						2	2			6
25	4500	1	1						3			5
26	4650	1							1			2
27	4725	1		1					3			5
28	4800		1					2	7			10
29	4875								2		1	3
30	4950	1		1					2			4
31	5025			1					1			2
32	6000	2	1						1		1	5
33	6300								3			3
34	6600	1	1						12		3	17
35	6750		2			2			8			12
36	8700	5	2						38		1	46
37	8775	1	2						27			30
38	8850			1				1	15			17
39	8925	2	2						27		2	33

MONTANE TAXA / RAINFOREST SWAMP TAXA

S/N	Sample depth (meter)/Taxa	Alnipollenites verus	Podocarpidites sp	Total Montane Taxa	Retibrevitricolporites protrudens	Pachydermites diederixi	Sapotaceae	Retitricolporites irregularis	Ctenolophonidites costalus	Elaeis guineensis	Total Rainforest taxa
1	750										
2	900				1	1	9				11
3	1050						1	1			2
4	1200										
5	1350										
6	1500										
7	1650						2	1	1		4
8	1800										
9	1950				1		15	9			25
10	2100				1	1		2			4
11	2400				1	1		5			7
12	2550					1					1
13	2700					3	1	3			7
14	2835					2		3			5
15	3000				1	2					3
16	3150					4	3				7
17	3300					2	3	1			6
18	3450					1	6				7
19	3600					1		1			2
20	3750					2	3	1			6
21	3900				1	1		12			14
22	4050						1				1
23	4200					1					1
24	4350	1		1							
25	4500					1					1
26	4650										
27	4725							1			1
28	4800					2					2
29	4875					1					1
30	4950										
31	5025							1			1
32	6000						3				3
33	6300					1	1				2
34	6600					1		3			4
35	6750						1				1
36	8700				2	4	3				9
37	8775					1	2	1			4
38	8850							4			4
39	8925					3					3

FRESHWATER SWAMP TAXA / MANGROVE TAXA

S/N	Sample depth (meter)/Taxa	Gemmamonoporites sp	Crassoretitriletes venraadshooveni	Laevigatosporites sp	Botyococcus Braunii	Verrucatosporites sp	Magnastriatites howardi	Acrostichium aureum	Total freshwater swamp taxa	Zonocostites ramonae	Psilatricolporites crassus	Total Mangrove taxa
1	750		1	32					33	55	2	57
2	900			60	1	51	1	20	133	56	2	58
3	1050			51	6	46		10	113	275	1	276
4	1200			22	5	16		1	44	80	1	81
5	1350			5	3	7			15	36		36
6	1500			8		1		3	12	27		27
7	1650		1	8	1				10	23		23
8	1800			13	2	4			19	29		29
9	1950			75	34	23	1		133	171	7	178
10	2100			58	32	55			145	200	4	204
11	2400			58	27	1		8	94	95		95
12	2550			28	12	16		11	67	38	2	40
13	2700			35	2	2			39	50	1	51
14	2835			38	3	13			54	85	1	86
15	3000		1	22	4				27	26	1	27
16	3150		1	34	3	12		18	68	31		31
17	3300			20	2	7		7	36	35		35
18	3450			13	2	7			22	14	1	15
19	3600					2			2	13		13
20	3750			46	3	14		13	76	33		33
21	3900			18				7	25	27		27
22	4050			8	3	2			13	18	2	20
23	4200			7	6	2		3	18	7	1	8
24	4350			3	1	1		1	6	11		11
25	4500			27	2	1			30	3		3
26	4650			3		1			4	13	2	15
27	4725			33	4	4		3	44	22		22
28	4800			1		1		3	5	17	1	18
29	4875				3	1		2	6	17	4	21
30	4950			11	3	1		1	16	4		4
31	5025			1	2				3	4	1	5
32	6000			12	5	4		2	23	18	1	19
33	6300			1	24	7			32	18	1	19
34	6600			24		2			26	35		35
35	6750			13	4	3			20	45		45
36	8700			47	24	5			76	145	3	148
37	8775	1		13	57	7			78	16		16
38	8850			1	31	7			39	15		15
39	8925			45		16		6	67	20	3	23

OTHERS

S/N	Sample depth (meter)/Taxa	Concentricytes sp	Spore In det.	Aletisporites sp	Nympheaepollis clarus	Lycopodium sp	Psilamonocolpites sp	Rauwolfia vomitra	Charred graminae cuticle II	Echitrilete pliocenicus	Trilete spore	Total
1	750											
2	900	1				2		1				4
3	1050	1										1
4	1200								2			2
5	1350								3			3
6	1500								5			5
7	1650											
8	1800											
9	1950				4				1			5
10	2100									1		1
11	2400				1		1		2			4
12	2550				1	2				1	3	7
13	2700				1				1			2
14	2835								2			2
15	3000								1	1		2
16	3150					2				1		3
17	3300											
18	3450											
19	3600					2				1		3
20	3750				1							1
21	3900						1					1
22	4050											
23	4200											
24	4350											
25	4500											
26	4650											
27	4725	1							2		2	5
28	4800											
29	4875											
30	4950											
31	5025											
32	6000											
33	6300			1								1
34	6600											
35	6750											
36	8700											
37	8775											
38	8850				2	2						4
39	8925											

APPENDIX D

Palyno-ecological Groups of Palynomorphs from HA-001 Well Continued

HA - 001 WELL

		SAVANNA TAXA											MONTANE TAXA			RAINFOREST SWAMP TAXA							FRESHWATER SWAMP TAXA								MANGROVE TAXA			OTHERS										
S/N	Sample depth (meter)/Taxa	*Polypodiaceoporites sp/Pteris sp*	*Cyperaceapolis sp*	*Coryius sp*	*Numulipollis neogenious*	*Fungal spore*	*Chenopodipollis sp*	*Canthiumidites sp*	*Monoporites annulatus*	*Proteacidites sp*	*Steiresporites sp*	***Total Savanna taxa***	*Alnipollenites verus*	*Podocarpidites sp*	***Total Montane Taxa***	*Retibrevitricolporites protrudens*	*Pachydermites diederixi*	*Sapotaceae*	*Retitricolporites irregularis*	*Ctenolophonidites costatus*	*Elaeis guineensis*	***Total Rainforest taxa***	*Gemmamonoporites sp*	*Crassoretiriletes venraadshooveni*	*Laevigatosporites sp*	*Botyococcus Braunii*	*Verrucatosporites sp*	*Magnastriatites howardi*	*Acrostichium aureum*	***Total freshwater swamp taxa***	*Zonocostites ramonae*	*Psilatricolporites crassus*	***Total Mangrove taxa***	*Concentricytes sp*	*Spore In det.*	*Aletisporites sp*	*Nympheaepollis clarus*	*Lycopodium sp*	*Psilamonocolpites sp*	*Rauwolfia vomitra*	*Charred graminae cuticle II*	*Echitrilete pliocenicus*	*Trilete spore*	***Total***
40	9000	3							18			**21**				1	1	6	1			**9**			50	62	8		4	**124**	24		**24**		1							1		**2**
41	9075	3							7			**10**						4			1	**5**			8		9		7	**24**	26		**26**			1								**1**
42	9150	2	1	1					8	1		**13**				1	1	2	2			**6**			50	35			6	**91**	16		**16**	1										**1**
43	9225	1						1	8		2	**12**						1				**1**			8	13	8			**29**	12	1	**13**											
44	9300	1							16		1	**18**							2		1	**3**			21	8	8		3	**40**	18		**18**					1						**1**
45	9375								12		1	**13**													7	6	2		1	**16**	7		**7**											
46	9450	5	1						3			**9**													17	8	8			**33**	24		**24**											
47	9525								4			**4**													12	14	2		1	**29**	7		**7**											
48	9600	6	1	2					24			**33**					1					**1**			13	22	7		1	**43**	24		**24**											
49	9675	1							6			**7**							2			**2**			4	12	9			**25**	14		**14**											
50	9750		1						1		1	**3**													3		1		3	**7**	11		**11**	1										**1**
51	9825	2							1			**3**													12	1	3		6	**22**	8		**8**	1										**1**
52	9900								3			**3**						4				**4**			17	3				**20**	5	2	**7**											
53	9975	2							2			**4**					1					**1**			12	5				**17**	6		**6**											
54	10050								2		1	**3**													7	2	2		1	**12**	7		**7**											
55	10125	1							1			**2**													8	1	1		1	**11**	4		**4**											
56	10200	6							3			**9**						2	2			**4**			3				2	**5**	14		**14**											
57	10275								1			**1**						3	3			**6**			3				1	**4**	5		**5**											
58	10350	1							1			**2**						2				**2**			6		6		2	**14**	11		**11**											
59	10425	3							2		1	**6**	1		**1**										6	4				**10**	5		**5**											
60	10500	4									2	**6**	1		**1**			2				**2**			9	4				**13**								1						**1**
61	10575								3		1	**4**													1	2	2			**5**	1		**1**								1			**1**
62	10650		2						1			**3**													2	3				**5**	4		**4**					1				1		**2**
63	10725								2			**2**					1	1	1			**3**			2	3	1			**6**	8		**8**											
64	10800	2							3			**5**													1	3	2		1	**7**	7		**7**											
65	10875	3		2					3		1	**9**													7	3				**10**	4	1	**5**											
66	10950	1										**1**						1				**1**				2	1			**3**		1	**1**											
67	11025			1					2			**3**					1					**1**			4	1				**5**	5		**5**											
68	11100	1									1	**2**													2	3				**5**	3		**3**					1						**1**
69	11175					1			3		1	**5**					1					**1**			3	3				**6**													1	**1**
70	11250	2							1		1	**4**													7	6	2			**15**				1									1	**2**
71	11325	2							1			**3**													2	3	3			**8**														
72	11400	1							2			**3**													4	12	1			**17**	4		**4**											
73	11475	2		4					1		2	**9**		1	**1**											3		1		**4**	4		**4**								1			**1**
74	11550	1		2							1	**4**													3	1	2			**6**	1		**1**											
75	11600	1										**1**													2	2				**4**	2		**2**											

APPENDIX E

Palyno-ecological Groups of Palynomorphs from HB-001 Well

HB - 001 WELL

		SAVANNA TAXA													MONTANE TAXA			RAINFOREST SWAMP TAXA								FRESHWATER SWAMP TAXA										MANGROVE TAXA			OTHERS								
S/N	Sample depth (meter)/Taxa	*Polypodiaceoporites sp/Pteris sp*	*Cyperaceapolis sp*	*Coryius sp*	*Numulipollis neogenious*	*Podocarpus milanjianus*	*Fungal spore*	*Chenopodipollis sp*	*Canthiumidites sp*	*Monoporites annulatus*	*Echiperiporites estelae*	*Proteacidites sp*	*Steiresporites sp*	***Total Savanna taxa***	*Alnipollenites verus*	*Podocarpidites sp*	***Total Montane Taxa***	*Retibrevitricolporites protrudens*	*Pachydermites diederixi*	*Peregrinipollis nigericus*	*Sapotaceae*	*Retitricolporites irregularis*	*Elaeis guineensis*	*Praedapollis flexibilis*	***Total Rainforest taxa***	*Striatricolporites catatumbus*	*Gemmamonoporites hians*	*Crassoreturiletes venraadshooveni*	*Laevigatosporites sp*	*Pediastrum sp*	*Botyococcus Braunii*	*Verrucatosporites sp*	*Magnastriatites howardi*	*Acrostichium aureum*	***Total freshwater swamp taxa***	*Zonocostites ramonae*	*Psilatricolporites crassus*	***Total Mangrove taxa***	*Concentricytes sp*	*Nympheaepollis clarus*	*Pollen in det.*	*Lycopodium sp*	*Charred graminae cuticle II*	*Echinate pliocenicus*	*Trilete spore*	*Echistephanoporite echinatus*	***Total***
1	4100									28				**28**					1		3				**4**				20			7			**27**	18		**18**				2		1			**3**
2	4250									6				**6**								1			**1**				8			2			**10**	5	1	**6**							1		**1**
3	4400	1					1			9				**11**															4		3	1		1	**9**	2		**2**	1								**1**
4	4550	1								8			1	**10**							1				**1**									3	**3**	8		**8**		1							**1**
5	4700		1							22			2	**25**					1						**1**				13		5	3			**21**	21		**21**									
6	4850									8				**8**															6		1	1			**8**	7		**7**				1					**1**
7	5000	1								16				**17**															31		1	4		6	**42**	8	1	**9**									
8	5150	2								13		1		**16**				1							**1**				17		8				**25**	19		**19**					1				**1**
9	5300	2	1						1	18				**22**							2	1			**3**				27			6	1		**34**	27		**27**		1							**1**
10	5450	1		1					1	19				**22**								2			**2**				33		18	6	2		**59**	41		**41**									
11	5600			2						9				**11**		1	**1**		2					1	**3**				13		6				**19**	25		**25**									
12	5750									1				**1**															3		3	2			**8**	4	1	**5**									
13	5900									2			1	**3**		1	**1**												3		1				**4**	6		**6**									
14	6050	2								1			1	**4**							4				**4**			1	12			4			**17**	10		**10**									
15	6350									15			2	**17**							1				**1**		2		32		20	6	1	8	**69**	38		**38**		1							**1**
16	6500	3	1	3		1				11				**19**					1		1				**2**	1	3		2			3			**9**	19	1	**20**									
17	6650	1		1						12				**14**													2		11		2	1			**16**	17		**17**	1								**1**
18	6800	1	2							15				**18**					1						**1**				8			4			**12**	17		**17**									
19	6950	1	4	3	1					7				**16**					1						**1**				3						**3**	9		**9**									
20	7100	3								4			1	**8**		1	**1**		2		4				**6**				11		6	7			**24**	13		**13**		1							**1**
21	7250	1								6				**7**					1						**1**				2		4	2	1		**9**	3		**3**		2							**2**
22	7400					1				2				**3**		1	**1**										1		3		3				**7**	7		**7**									
23	7700	1	1	1						14				**17**				1	2				1		**4**			1	15		2			2	**20**	7	1	**8**		2							
24	7760	1								1				**2**		1	**1**				1				**1**				3		5	3			**11**												
25	7850	1		7						7			1	**16**		2	**2**		1				1		**2**						2	1			**3**	3		**3**									
26	7925	1		3						11				**15**	1		**1**												11			6		1	**18**	7	1	**8**									
27	8000					1				1				**2**							1				**1**				3		1	2			**6**	2		**2**							1		**1**
28	8075	2		2						4				**8**					1			1			**2**				11			1			**12**									1			**1**
29	8150	2								6				**8**															6		2	4			**12**	26		**26**						1			**1**
30	8225			1						3				**4**		1	**1**					1			**1**				5		1	2			**8**												
31	8300		1							4			1	**6**															4			1	1	2	**8**	10		**10**									
32	8375	1								4				**5**								1			**1**				6			3		2	**11**	13		**13**									
33	8450	2		3						3				**8**	1		**1**												12			6		2	**20**												
34	8525			7						8			1	**16**															4						**4**	6	1	**7**									
35	8600		2							1				**3**								1			**1**				4		2				**6**	13		**13**								1	**1**
36	8675									3				**3**															8		3	2		2	**15**	8		**8**									
37	8750									2				**2**				1				1			**2**				7						**7**	13	1	**14**		1		1					**2**
38	8825		1										1	**2**		1	**1**												4			1			**5**	1		**1**									
39	8900			7						1				**8**															3		2	1		1	**7**	3		**3**									
40	8975	1		4						3				**8**					1						**1**				2					6	**8**	4		**4**									
41	9050	1		3			1							**5**															4		13	2		2	**21**	12		**12**							1		**1**
42	9125			1						3				**4**		1	**1**												2		8				**10**	2		**2**		1							**1**
43	9200			6									2	**8**	1		**1**												11			3			**14**	23		**23**							2		**2**
44	9275	5		3						2			2	**12**		2	**2**		1						**1**				11		4	2			**17**	8		**8**									
45	9350									1			1	**2**						1					**1**				7			2	1		**10**	8		**8**									
46	9425			2						1				**3**															1		2	1		2	**6**	3		**3**									
47	9500			2						6			1	**9**													1		3		3	5		3	**15**	21		**21**		1							**1**
48	9575			2						2				**4**															2		2	1			**5**												

APPENDIX E

Palyno-ecological Groups of Palynomorphs from HB-001 Well continued

HB - 001 WELL

		SAVANNA TAXA													MONTANE TAXA			RAINFOREST SWAMP TAXA								FRESHWATER SWAMP TAXA										MANGROVE TAXA			OTHERS								
S/N	Sample depth (meter)/Taxa	*Polypodiaceoporites sp/Pteris sp*	*Cyperaceapolis sp*	*Coryius sp*	*Numulipollis neogenious*	*Podocarpus milanjianus*	*Fungal spore*	*Chenopodipollis sp*	*Canthiumidites sp*	*Monoporites annulatus*	*Echiperiporites estelae*	*Proteacidites sp*	*Steiresporites sp*	***Total Savanna taxa***	*Alnipollenites verus*	*Podocarpidites sp*	***Total Montane Taxa***	*Retibrevitricolporites protrudens*	*Pachydermites diederixi*	*Peregrinipollis nigericus*	*Sapotaceae*	*Retitricolporites irregularis*	*Elaeis guineensis*	*Praedapollis flexibilis*	***Total Rainforest taxa***	*Striatricolporites catatumbus*	*Gemmamonoporites hians*	*Crassoretitriletes venraadshooveni*	*Laevigatosporites sp*	*Pediastrum sp*	*Botyococcus braunii*	*Verrucatosporites sp*	*Magnastriatites howardi*	*Acrostichium aureum*	***Total freshwater swamp taxa***	*Zonocostites ramonae*	*Psilatricolporites crassus*	***Total Mangrove taxa***	*Concentricytes sp*	*Nympheaepollis clarus*	*Pollen in det.*	*Lycopodium sp*	*Charred graminae cuticle II*	*Echinate pliocenicus*	*Trilete spore*	*Echistephanoporite echinatus*	***Total***
49	9650			1						3				**4**															1			2			**3**	3		**3**									
50	9725	2		1						2				**5**															1			1			**2**	2		**2**									
51	9800									1				**1**															2		4	2		1	**9**	4	1	**5**									
52	9875									3	1		1	**5**		1	**1**														4	6	1	6	**17**												
53	9950	1	2							3			1	**7**															2		4	3			**9**	6		**6**									
54	10025									1				**1**					2						**2**				2		8	1			**11**		1	**1**									
55	10100									1			2	**3**					1						**1**				2		14	3			**19**												
56	10175						1			2			1	**4**															3		4				**7**	4		**4**									
57	10250									1				**1**															6		4	1		2	**13**	16		**16**									
58	10325									2			3	**5**					1						**1**				2		4		1		**7**	11		**11**									
59	10550									1			1	**2**									1		**1**						1	1		1	**3**	2		**2**									
60	10400									1				**1**							1				**1**				4		3	1			**8**	9		**9**									
61	10475						4			2				**6**		1	**1**												4			2			**6**	14		**14**									
62	10625									1			2	**3**		2	**2**												3		1	2			**6**												
63	10700									3				**3**					2	1		4			**7**						12				**12**	6		**6**									
64	10775	1		1						1				**3**		2	**2**		1						**1**				3		3				**6**	7		**7**									
65	10850					1			2	1				**4**															2		12	3		2	**19**												
66	10925									2				**2**				1					1		**2**				2		3				**5**	3		**3**									
67	11000	1	1							6			1	**9**															18		4	2		1	**25**	16		**16**									
68	11075									7			2	**9**															2		7				**9**	7		**7**									
69	11150									1				**1**					2						**2**				3		2	2			**7**	13	1	**14**									
70	11225									1				**1**		1	**1**												2		4				**6**												
71	11300						1		1					**2**					1						**1**				3		7	1			**11**	6	2	**8**									
72	11375	1												**1**															1		11	1		1	**14**	3		**3**									
73	11450																										1		6		11	3		2	**23**	5		**5**									
74	11525									3			2	**5**	1		**1**												1		8			6	**15**												
75	11600															1	**1**				3		1		**4**				3		8	1		1	**13**												
76	11675												1	**1**							2				**2**				3			2		4	**9**												
77	11750												3	**3**									1		**1**				3		8	1		2	**14**							1					**1**
78	11825	1												**1**	1	1	**2**												5		8	6			**19**	6		**6**									
79	11900	1							1	3				**5**															7		5	1			**13**	17	2	**19**									
80	11975	1								2				**3**															6		7	3		3	**19**	7	1	**8**									
81	12050	2								3				**5**					3			2			**5**				7			3		12	**22**	20		**20**									
82	12125									1				**1**									1		**1**				17		8	1		3	**29**	13		**13**									
83	12200									5				**5**		2	**2**												10	2	17	3			**32**	2		**2**									
84	12275	2												**2**							3		1		**4**				9		8	1		3	**21**												
85	12350	2												**2**							3				**3**				3		12	3		12	**30**	12		**12**									
86	12425							1						**1**								3			**3**				12			1			**13**	3		**3**									
87	12500			3										**3**								1			**1**						7			2	**9**	8		**8**									
88	12575		1							3			1	**5**		1	**1**												8		7	1		1	**17**												
89	12650									1			2	**3**							2				**2**						6	2			**8**	17		**17**									
90	12725									2				**2**					1						**1**				31		14	3			**48**	12	3	**15**	1	1							**2**
91	12800	1		4						2			5	**12**		2	**2**												4		17	1		3	**25**	8		**8**									
92	12875			4			1			1				**6**		1	**1**		1			1			**2**						11	2	1		**14**	8		**8**			1						**1**
93	12950			2						6			4	**12**	1		**1**					1			**1**				2		3	1			**6**	4		**4**									
94	13025			6						2				**8**															6		4	2			**12**	4		**4**									
95	13100									1			1	**2**					1			1			**2**				12		8	3			**23**	12		**12**									
96	13160			14						3				**17**															13		18	2			**33**	14	1	**15**									

APPENDIX F

Palyno-ecological Groups of Palynomorphs from HD-001 Well

HD - 001 WELL

SAVANNA TAXA

S/N	Sample depth (meter)/Taxa	Polypodiaceoporites sp/Pteris sp	Cyperaceapollis sp	Coryius sp	Numulipollis neogenious	Podocarpus milanjianus	Retistephanolpites gracilis	Fungal spore	Chenopodipollis sp	Echitricolporites spinosus	Tricolporopollenites microehinatus	Retitricolpites bendensis	Canthiumidites sp	Marginipollis concinnus	Ephedripites sp	Monoporites annulatus	Echiperiporites estelae	Proteacidites sp	Steiresporites sp	Polyadopollenites vancampoae	Total Savanna taxa
1	4875	2	6													10			5		23
2	5025	2	1										1			25			5		34
3	5190	5	2	2												25			2		36
4	5340		2	2												29			6		39
5	5490	3	2													12			2		19
6	5640	12	5													45			5		67
7	5790	12	1													39			1		53
8	5940	7	1																3		11
9	6090	6	7													9			2		24
10	6240	5	2													18			4		29
11	6390	1														7					8
12	6540	3						2								4					9
13	6690	1																	2		3
14	6840	2											1			4			3		10
15	6990	2														13		1			16
16	7140				1											18			4		23
17	7290	7		2	1																10
18	7440															22			2		24
19	7590			3												13			1		17
20	7740	2	1													19			1		23
21	7815	8	2													23			3		36
22	7890		1			1										23					25
23	7965												2			43		1	1		47
24	8040	3											1			21					25
25	8115															11					11
26	8190	3															1				4
27	8265	2	1	1												19					23
28	8340	1	2	2												12			1		18
29	8415	2														7			4		13
30	8490	2														17		1	2		22
31	8565	2	3													14					19
32	8640															8			1		9
33	8715		1	2												12			2		17
34	8865	3		1												16					20
35	8940	2		1												12			2		17
36	9015	1											2			14			1		18
37	9090	1		2												4			1		8
38	9165	5	1	1															1		8
39	9240	3		7												2					12
40	9315	1	2	1												7					11

MONTANE TAXA / RAINFOREST SWAMP TAXA

S/N	Sample depth (meter)/Taxa	Alnipollenites verus	Podocarpidites sp	Ericipidites sp	Psilastephanocolporites sp	Total Montane Taxa	Retibrevitricolporites protrudens	Pachydermites diederixi	Peregrinipollis nigericus	Bombacacidities sp	Sapotaceae	Retitricolporites irregularis	Adenantherites simplex	Ctenolophonidites costalus	Elaeis guineensis	Racemonocolpites sp	Cleistopholis patterns	Sapotaccoidaepollenties spp	Psilatriporites sp	Spirosyncolpites bruni	Praedapollis flexibilis	Total Rainforest taxa
1	4875							3				4			2							9
2	5025						2					3										5
3	5190						3	3			1	1										8
4	5340	4				4	2	4				3			2							11
5	5490						2	4														6
6	5640						1	10													2	13
7	5790						3				6	6										15
8	5940						2	2				2			1							7
9	6090						1	2														3
10	6240							7														7
11	6390							3			1											4
12	6540						2	4			3											9
13	6690	9				9						1										1
14	6840							2			3				1							6
15	6990						1	3							1							5
16	7140						2				3											5
17	7290						6	3				3										12
18	7440							1				1										2
19	7590						1	2				1			1							5
20	7740	1				1		2			6											8
21	7815						1				14											15
22	7890						2	3			7											12
23	7965							3			7	3										13
24	8040						1	2			5											8
25	8115						1	2			3											6
26	8190						1				2	2										5
27	8265							1														1
28	8340	1				1					2											2
29	8415						1	3														4
30	8490							1			1	1										3
31	8565						1				1											2
32	8640						2	1														3
33	8715										1											1
34	8865	1				1		3			2											5
35	8940	1				1					1											1
36	9015						1	1			3								1			6
37	9090																					
38	9165	2				2	2	2				1										5
39	9240																					
40	9315	1				1		3														3

FRESHWATER SWAMP TAXA / MANGROVE TAXA

S/N	Sample depth (meter)/Taxa	Striatricolporites catatumbus	Verrutricolporites rotundiporus	Gemmamonoporites hians	Retitricolporites sp	Multiareolites formurua	Crassoretitriletes venraadshooveni	Laevigatosporites sp	Padeistrum sp	Botyococcus Braunii	Verrucatosporites sp	Marginipollis concinnus	Magnastriatites howardi	Multiareolites formosus	Acrostichium aureum	Total freshwater swamp taxa	Zonocostites ramonae	Psilatricolporites crassus	Psilatricolporites sp	Total Mangrove taxa
1	4875					1		27		14	28				13	83	37	3		40
2	5025	2	1			2		60		4	14	1			7	91	75	3		78
3	5190							65		12	33					110	50			50
4	5340							60	1	17	22					100	45			45
5	5490		1					28		20	30					79	28	5		33
6	5640							85		31	37		1			154	63	12		75
7	5790							38		25	15		1		8	87	50	4		54
8	5940		1					28		31	18			1	8	87	34			34
9	6090			1				7		7	15				12	42	30	1		31
10	6240		1					25		7	13			1		47	26			26
11	6390	2						6			13			1	3	25	16	4		20
12	6540							13		3	8				7	31	27	2		29
13	6690							7		10	8					25	14	2		16
14	6840							10		6	12				4	32	25	1		26
15	6990			1				22		32	3				8	66	25			25
16	7140						1			20	21	1			13	56	11	2		13
17	7290		1	1				37		78	1				8	126	26	1		27
18	7440							30		36	7	1			17	91	13			13
19	7590							14		57	8				6	85	27	2		29
20	7740							25		56	16				14	111	28			28
21	7815			3				32		80					21	136	42	4		46
22	7890							42		59	16				20	137	10	3		13
23	7965			3				41		105	21				19	189	46	2		48
24	8040			2				29	1	60	5				12	109	21	1		22
25	8115			1				21	2	47	7				3	81	22	2		24
26	8190						1		2	65					13	81	23	2		25
27	8265			1				25		59	8				13	106	27			27
28	8340							13	1	45	8		1		6	74	16			16
29	8415							13		57	1		1		6	78	16			16
30	8490							34		62	7		1		13	117	14	3		17
31	8565			1				29		105	10				12	157	13			13
32	8640							15		40	12				1	68		2		2
33	8715	1						32		53	14				8	108	9			9
34	8865			1	1			30		46	13				8	99	18			18
35	8940							22		33					8	63	9			9
36	9015									43	16				7	66	11			11
37	9090			1				3		24	12					40	7			7
38	9165							22		17	8				6	53	19	1		20
39	9240							1		3	3				3	10	2			2
40	9315							16		2	3					21	7			7

OTHERS / DINOCYST

S/N	Sample depth (meter)/Taxa	Concentricytes sp	Spore In det.	Aletisporites sp	Nympheaepollis clarus	Pollen in det.	P. cursus	Spiniferites sp	Lycopodium sp	Verrutricolporites sp	Echinate pollen	Echitriletes sp	Psilamonocolpites sp	Gemmate pollen	Podocarpite sp	Leiorphaeridia sp	Retistephanocolpites williamsi	Retimonocolpite sp	Total	Dinocyst in determinate
1	4875																			
2	5025	1	3																4	
3	5190			1															1	
4	5340				1		2												3	
5	5490					3													3	
6	5640	1			3		1												5	
7	5790							1											1	1
8	5940																			
9	6090				2														2	
10	6240				3														3	
11	6390								1										1	
12	6540				1					1									2	
13	6690				1				1										2	
14	6840																			
15	6990								1										1	
16	7140				3				3		1								7	
17	7290								1										1	
18	7440								2										2	
19	7590			1	1														2	
20	7740	1							2	1									4	
21	7815				1				2										3	
22	7890		3		2						1								6	
23	7965				2				1										3	
24	8040									1									1	
25	8115						1		1										2	
26	8190								2										2	
27	8265	1							2			1							4	
28	8340			1					1										2	
29	8415								1										1	
30	8490												1						1	
31	8565								2				1						3	
32	8640			1										1					2	
33	8715																			2
34	8865			1					2										3	
35	8940																			
36	9015					1			1				1						3	1
37	9090													1					1	
38	9165										1			1					2	
39	9240														1				1	
40	9315	1								1									2	

APPENDIX F

.0 Palyno-ecological Groups of Palynomorphs from HD-001 Well continued

HD - 001 WELL

SAVANNA TAXA

S/N	Sample depth (meter)/Taxa	Polypodiaceoporites sp/Pteris sp	Cyperaceapolis sp	Coryius sp	Numulipollis neogenious	Podocarpus milanjianus	Retistephanolpites gracilis	Fungal spore	Chenopodipollis sp	Echitricolporites spinosus	Tricolporopollenites microehinatus	Retitricolpites bendensis	Canthiumidites sp	Marginipollis concinnus	Ephedripites sp	Monoporites annulatus	Echiperiporites estelae	Proteacidites sp	Steiresporites sp	Polyadopollenites vancampoae	**Total Savanna taxa**
41	9390					1							2				1				**4**
42	9465	3					1									7	1				**12**
43	9540	1	1	3												7			1		**13**
44	9615	2											1			6					**9**
45	9690			1													1		2		**4**
46	9765	4		4									1			3			1		**13**
47	9840			15															1		**16**
48	9915	5	2	3												4			4		**18**
49	9990	2		6												5			2		**15**
50	10065	5		1															2		**8**
51	10140			3												12					**15**
52	10215	2											1			4		1			**8**
53	10290	1		3												3					**7**
54	10365	2		5												1					**8**
55	10440	1		1				1								2					**5**
56	10515	2		9				1								2	1				**15**
57	10590	3		5												4					**12**
58	10665	5		3												3					**11**
59	10740	1		3												1					**5**
60	10815	2		3														1			**6**
61	10890	1	1	4																	**6**
62	10965	3		7									1			2					**13**
63	11040			27												4		1			**32**
64	11115	1		3				1					1			2					**8**
65	11190			6																	**6**
66	11265	2		4																	**6**
67	11340	1		1												1					**3**
68	11415	1														2			1		**4**
69	11490			9																	**9**
70	11565			3																	**3**
71	11640			7										1			1				**9**
72	11715	2		4												6			1		**13**
73	11790	1		2												2					**5**
74	11865	3		6															1		**10**
75	11940	1		6				1								2					**10**
76	12015	2		7												1					**10**
77	12090	1		8															1		**10**

MONTANE TAXA / RAINFOREST SWAMP TAXA

S/N	Sample depth (meter)/Taxa	Alnipollenites verus	Podocarpidites sp	Ericipidites sp	Psilastephanocolporites sp	**Total Montane Taxa**	Retibrevitricolporites protrudens	Pachydermites diederixi	Peregrinipollis nigericus	Bombacacidities sp	Sapotaceae	Retitricolporites irregularis	Adenantherites simplex	Ctenolophonidites costalus	Elaeis guineensis	Racemonocolpites sp	Cleistopholis patterns	Sapotaccoidaepollenties sp	Psilatriporites sp	Spirosyncolpites bruni	Praedapollis flexibilis	**Total Rainforest taxa**
41	9390							2														**2**
42	9465						1	2														**3**
43	9540	2				**2**	1															**1**
44	9615						1															**1**
45	9690							2			1											**3**
46	9765										2											**2**
47	9840							5														**5**
48	9915																					
49	9990						4	4				1										**9**
50	10065						2								1							**3**
51	10140							1				1										**2**
52	10215						1					1										**2**
53	10290							1			1											**2**
54	10365							1														**1**
55	10440							1														**1**
56	10515							3			1	1										**5**
57	10590						1	3	1		2	1										**8**
58	10665		1			**1**		3														**3**
59	10740							1				1										**2**
60	10815						4	2			2											**8**
61	10890						1	1				1										**3**
62	10965											2										**2**
63	11040							1			3	3										**7**
64	11115	1				**1**		1			2	1										**4**
65	11190		1			**1**	1	1				1										**3**
66	11265		3			**3**						1										**1**
67	11340	1	2			**3**		1														**1**
68	11415										2	1										**3**
69	11490		1			**1**					2	1										**3**
70	11565		1			**1**																
71	11640										1											**1**
72	11715		2			**2**	1	1			2	1										**5**
73	11790																					
74	11865		2			**2**	3															**3**
75	11940																		1			**1**
76	12015		1			**1**						1										**1**
77	12090		2			**2**		2			2	1										**5**

FRESHWATER SWAMP TAXA / MANGROVE TAXA

S/N	Sample depth (meter)/Taxa	Striatricolporites catatumbus	Verrutricolporites rotundiporus	Gemmamonoporites hians	Retitricolporites sp	Multiareolites formurua	Crassoretitriletes venraadshooveni	Laevigatosporites sp	Padeistrum sp	Botyococcus Braunii	Verrucatosporites sp	Marginipollis concinnus	Magnastriatites howardi	Multiareolites formosus	Acrostichium aureum	**Total freshwater swamp taxa**	Zonocostites ramonae	Psilatricolporites crassus	Psilatricolporites sp	**Total Mangrove taxa**
41	9390							20		1	17					**38**	9	4		13
42	9465							23		3	11				6	**43**	2	2		4
43	9540							7		2	2				3	**14**	7	3		10
44	9615							18		9	17					**44**	12	1		13
45	9690							12		7	20				12	**51**				0
46	9765							17			7				7	**31**	3	3		6
47	9840							16		7	6		1			**30**				
48	9915							5		3	9				8	**25**	7			7
49	9990									4	10					**14**	17	1		18
50	10065							17		2	8		1		4	**32**	3	3		6
51	10140							19		2	4				4	**29**	8			8
52	10215							6		3	2				1	**12**	3			3
53	10290							17							1	**18**	7	1		8
54	10365							9		1					2	**12**	3			3
55	10440							10								**10**	3			3
56	10515						1	25			13				4	**43**	1			1
57	10590							12							3	**15**	5			5
58	10665							22		2	3				3	**30**	5			5
59	10740			1				8		2	1				2	**14**	3			3
60	10815							7		2	5					**14**	3	2		5
61	10890							6		1	1				2	**10**	1			1
62	10965		1	1				32		2	3				6	**45**	12	1		13
63	11040							25			7			1	11	**44**	13			13
64	11115			1				10		2	3					**16**	7	1		8
65	11190							3		1					1	**5**	1			1
66	11265							12			2				5	**19**	3			3
67	11340							4		1	1				3	**9**	3	1		4
68	11415			1				17		1	3					**22**	3			3
69	11490							7			1				3	**11**	2			2
70	11565			1				11			3				3	**18**	2		1	3
71	11640							18		1						**19**		1		1
72	11715							25			6				7	**38**	3	1		4
73	11790			1				12		1	2				1	**17**	3			3
74	11865			2				25			7				3	**37**	3			3
75	11940							13		1	8					**22**	6			6
76	12015			1				5			8					**14**	1			1
77	12090			1				19		3	6					**29**	17			17

OTHERS / DINOCYST

S/N	Sample depth (meter)/Taxa	Concentricytes sp	Spore In det.	Aletisporites sp	Nympheaepollis clarus	Pollen in det.	P. cursus	Spiniferites sp	Lycopodium sp	Verrutricolporites sp	Echinate pollen	Echitriletes sp	Psilamonocolpites sp	Gemmate pollen	Podocarpite sp	Leiorphaeridia sp	Retistephanocolpites williamsi	Retimonocolpite sp	**Total**	Dinocyst in determinate
41	9390					2			1										**3**	
42	9465								2										**2**	
43	9540																			
44	9615										1								**1**	
45	9690																			
46	9765																			
47	9840													1					**1**	
48	9915														1				**1**	
49	9990																			
50	10065																1		**1**	
51	10140																1	1	**2**	
52	10215												1						**1**	
53	10290											1							**1**	
54	10365																			
55	10440								1										**1**	
56	10515								2										**2**	
57	10590																			
58	10665	2																	**2**	
59	10740												1					1	**2**	
60	10815																			
61	10890																			
62	10965								1										**1**	
63	11040																			
64	11115								1										**1**	
65	11190																	1	**1**	
66	11265								1										**1**	
67	11340																			
68	11415																			
69	11490																			
70	11565																	1	**1**	
71	11640																			
72	11715																			
73	11790								1										**1**	
74	11865								2										**2**	
75	11940										2								**2**	
76	12015																			
77	12090								2										**2**	