# Paleodepositional Environment and Reservoir Biosequence Stratigraphy of Late Paleogene-Neogene Sediments from the KB-1 well, Coastal Swamp Depobelt, Niger Delta Basin, Nigeria

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## Abstract

Lithofacies and palynological analyses of well cutting samples retrieved from KB-1 well located in the Coastal Swamp depositional belt of the Niger Delta Basin have been carried out in order to define paleodepositional environment and erect a biosequence stratigraphic frame so as to type and characterize different sand reservoirs formed within the sedimentary pile. Lithofacies analysis revealed sand, clay shale and coal as the lithotypes and twelve facies types ranging from silty shale to pebbly sands. Palynological analyses of selected samples through conventional acid treatment, sieving, density separation of selected samples to obtain preserved palynomorphs, yielded 75 pollen, 28 spore and 8 dinocysts form species. A synthesis of lithofacies data sets and environmentally sensitive and age-significant palynotaxa enabled the identification of eighteen paleodepositional cycles ranging from coastal deltaic to deep marine of Oligo-Miocene age. Eighteen systems tracts distributed within six sequences hosting six candidate maximum flooding surfaces (MFSs) and five sequence boundaries (SBs) were identified. An evaluation of the petroleum play in the well area revealed four transgressive (TRS), six highstand (HSR) and five lowstand (LSR) reservoir sand bodies formed in different bathymetric domains with varying sedimentologic and inferred static petrophysical reservoir properties.

**Keywords:** Paleodepositional environment, reservoir sequence Stratigraphy, biosignals, systems tracts, petroleum play.

## Introduction

The definition of lithofacies for understanding reservoir properties and to glean insight into the depositional settings of clastic sediments is a veritable tool in sequence stratigraphic interpretations of sedimentary sequences. Although not without inherent limitations in its application to fingerprinting reservoir paleodepositional environments (Selley, 2000), lithofacies signatures provides a fundamental basis for inferring, understanding, unravelling and defining depositional processes operative within specific depositional space and or depositional complexes. A major consideration in erecting sequence stratigraphic framework for a sedimentary profile is the sound definition of paleodepositional environment(s) based on sedimentary characteristics and a variety of depositional environmental proxies including paleontologic materials. The combination of lithofacies data sets (bearing in mind the mode of transport and deposition of different size calibre) and biosignals provides substantial grounds for defining and erecting paleodepositional models. This is so, as biosignals are process-controlled, responding to and correspondingly recording environment-driven Earth processes.

The trends presented by recovered palynomorphs from sediments have been carefully correlated with climate-driven vegetation development and eustatic sea-level changes through geologic time (Poumot, 1989; Armentrout and Clement, 1991; Oyede, 1992; Rull, 1997a and b; 2000a and b; Oboh-Ikuenobe et al. 2005; Olajide et al. 2012; Osokpor and Ogbe, 2017). Adequate understanding and speciation of palyno-taxa based on vegetation domain (e.g. mangrove swamp forest, freshwater swamp, rainforest, grass land species, etc.) and bathymetric consideration for marine species, enables a maximization of their unique potential in paleoenvironmental interpretations required for defining sequence stratigraphic elements in ancient sedimentary piles.

The inherent limitation posed by sole reliance on lithofacies in paleoenvironmental interpretation as highlighted above, informs the integration of biofacies data in defining paleodepositional environment in order to erect a sequence stratigraphic frame for the studied well section in this article. Sequence delineation of sedimentary piles into systems tracts affords a recognition petroleum plays by characterization of various reservoir types with distinct petrophysical properties (Catuneanu, 2006); hence this article is of practical importance and not mere academic exercise.

## Geologic Setting

The Niger Delta Basin (Fig. 1) which stands as a significant oil province in the world, is located on the Atlantic coast of West Africa, where it has built out over the trailing edge of the African continental margin and adjacent oceanic crust since the Eocene (Evamy et al. 1978) and totalling about 75,000Km$^2$. Stratigraphically, the Niger Delta Basin consists of three diachronous formations which makes a maximum clastic fill of about 12,000 m (Short and Stauble, 1967; Evamy et al. 1978; Lambert-Aikhionbare and Ibe, 1984).

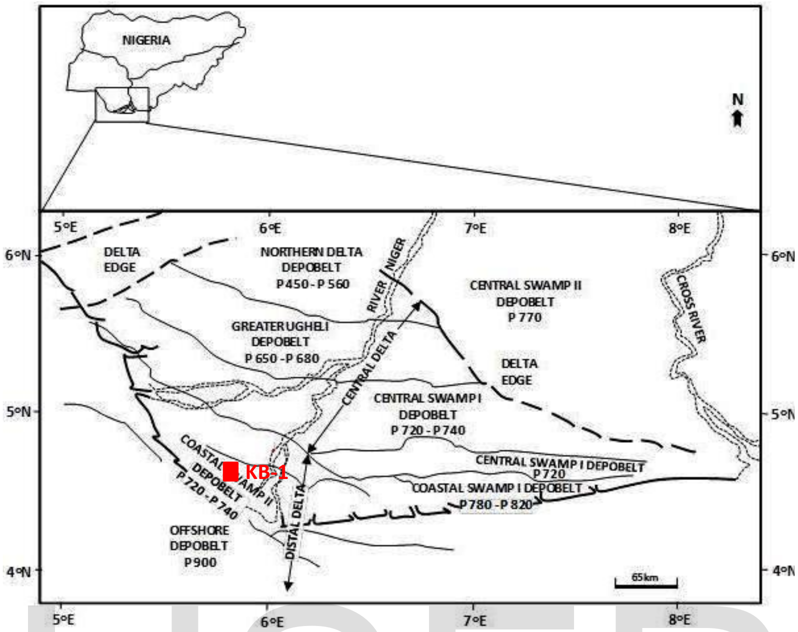


Figure 1: Niger Delta Basin geologic map showing location of study well in the Coastal Swamp depobelt (Modified after Doust and Omatsola 1990).



The clastic fill of the Niger Delta Basin displays a three-fold stratigraphic subdivision, the Akata, Agbada and Benin Formations (Fig. 2), which reflects the main sedimentary environments of a regressive megasequence (Ekweozor and Okoye, 1980; Doust and Omatsola 1989; Morgan 2003, Reijers, 2011). The Akata Formation is of deep marine origin and consists of organic-rich, parallel-laminated, slope and basin-floor, pro-delta, marine muds. The Akata Formation with a thickness of 3 – 4 km is generally viewed as the main source sediments in the Niger Delta Basin (Osokpor and Osokpor, 2017; Osokpor and Overare, 2019). The Akata Formation is typically overpressured due to the rapid sedimentation of sands on the shale of the formation (Doust and Omatsola 1989; Haack et al. 2000). Unconformably overlying the Akata Shale Formation is the 3 km thick Agbada Formation which consists of mixed clastics (sand and shale). The sediments of the Agbada Formation formed in a paralic environment. Sand intervals in the Agbada Formation acts as the main hydrocarbons reservoirs in the Niger Delta Basin. The Benin Formation characterized by various sand facies and which rest on the top of the delta is mainly of continental fluvial origin.

## Study Area

The study area is located within the Coastal Swamp Depositional belt (Fig. 1), a megastructural unit of the Niger Delta Basin. The well from which samples were retrieved for this study belongs to Shell Petroleum and Development Company, but coded KB (Fig. 1) in this article for confidentiality purposes.

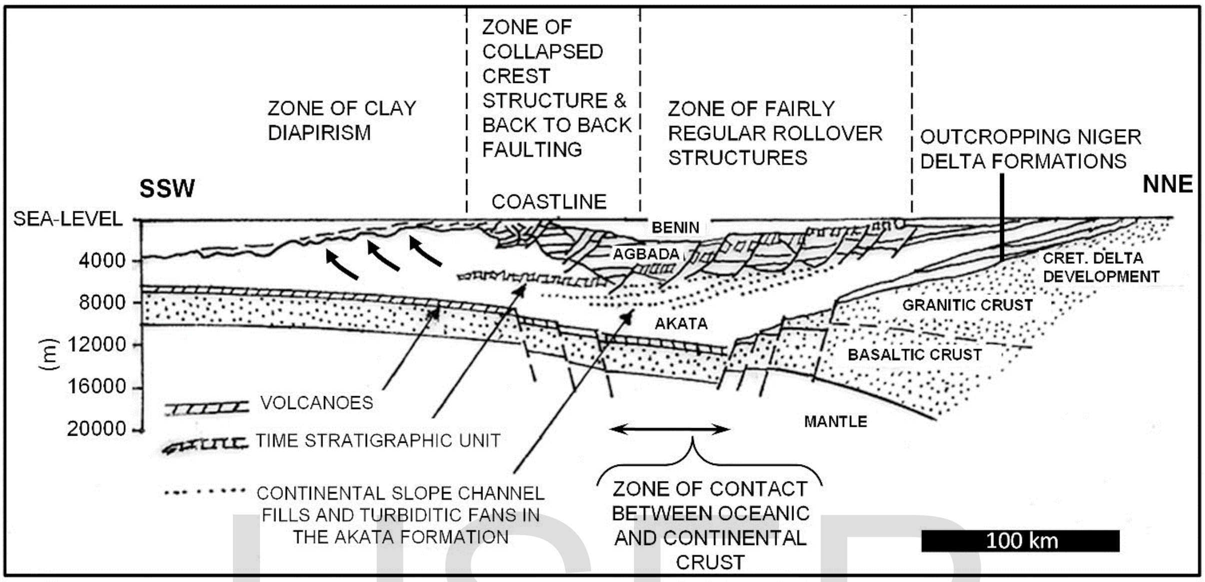


Fig. 2: Schematic stratigraphic cross section of the subsurface Cenozoic Niger Delta Basin showing the principal stratigraphic units along the depositional dip of the basin and outcropping formations in the northern aspects overlying Cretaceous sediments of the Anambra Basin (Evamy et al. 1978).

## Research Material and Methods

### *Textural and Palynological Analysis*

This phase of the work involved an initial quality control which entailed sample layout to depth match with well log, following which, microscopic grain description which involved the use of stereo microscope and comparative grain size chart for analysis of grain attributes such as, roundness and sphericity, sorting, dominant and secondary lithotype, accessory minerals, fossil content, colour, diagenetic state was performed on one hundred and fifty nine ditch cutting samples.

Following the above procedure, thirty three (33) non-composited shale samples were selected for palynological sample processing and analysis based on facies, interval of interest, and confirmation of sedimentological inferences. Depth occurrence of suitable lithologies determined sampling intervals for different sections of the well. For the lower section of the well which occupies a depth range of 3082 – 3589m, sampling range from 50 - 128m (av. = 88m). The mid-section which ranged from 1469 – 1945m, sampling ranged from 18 – 73 m, (av. = 39.7m), while the top section of the well with a depth range of 318 – 699m, sampling ranged from 19 – 165 m, with a mean sampling interval value of 90.7m. Standard method described by Traverse (1988) was adopted in sample processing, during which shale samples were subjected to different stages of acid treatment, sieving, density separation and concentration of organic matter through centrifuging, staining with safranin O, mounting on slides and covering with cover slips. Slides were viewed under x40 and x100 objectives using an Olympus CH30 camera-attached microscope. Identification of species was based on reference to published literatures, following which photomicrographs of index taxa were taken.

***Biozonation***

Age-dating the sediments of the well section involved zonal divisions based solely on the distribution of pollen form species due to the paucity of age-significant dinocyst and spore species in the well. The zones were delineated by the first and last occurrences, and presence and/or abundance of two or more species. The ages of the delineated zones were determined by comparison with zones established, used and correlated with the Geological Time Scale (e.g. Germeraad et al. 1968; Legoux, 1978; Evamy et al. 1978; Frederiksen, 1980a; Salard-Cheboldaeff, 1990; Salami, 1990; Shaw, 1998, 1999; Guerstein et al. 2004; Oloto, 2009; Brown and Loucks, 2009; Lucas and Ishiekwene, 2010; Dickey and Yancey, 2010; van Geel et al. 2011, Osokpor et al. 2015, e.t.c). The determined ages were then used in conjunction with results derived from lithofacies analyses to established and draw up the lithostratigraphy for the well.

## Results and Discussion

***Lithofacies***

Results from whole grain microscopic analysis of sediment samples, revealed four lithotypes and twelve facies types within the well section as detailed in (Fig. 3) and shown in the lithologic section of the well (Fig. 4).

***Palynological Results***

Sediments from the KB-1 well yielded seventy five (75) pollen, twenty eight (28) spore and eight (08) dinocyst form species. Palynomorph species recovered from the well were speciated as form species into miospores (Fig. 5 and 6) and dinocysts species (Fig. 6). This enabled identification and quantification of species. Speciation of age significant forms also enabled age dating of the sediments. Depth distribution and age ranges of these form species are shown in figure 5 and 7, while representative forms of some identified species are shown in figure 6.

| F A C I E S | | | |
|---|---|---|---|
| **LITHOTYPES** | **FT** | **Lithofacies Name** | **Short description** |
| **Sand** | 1 | Very fine-grained sand | Very fine – medium-grained sand, sub< – subr, contain shinny coaly materials, shaly, dark grey |
| | 2 | Medium-grained sand | Very fine – granular, subr – r, black shale component |
| | 3 | Shaly very coarse sand | Very fine – granular, sub< – subr, black shale component poor – v.poorly sorted |
| | 4 | Very coarse sand | Very fine – pebbly, subr – wr, very fine and pebbly grains occur as subordinate population, poor – well sorted |
| | 5 | Granules | Medium – granular, subr – r, poorly sorted |
| | 6 | Pebbly sand | Very fine – pebbly, subr – wr, moderate - poorly sorted. |
| **Clay** | 7 | Sandy Clay | Very fine subr – vw rounded sand grains, |
| **Shale** | 8 | Sandy Shale | Very fine – pebbly subr – wr sand grains, contain $CaCO_3$ in some sections, light to dark grey, carbonaceous material. |
| | 9 | Silty Shale | Silty, woody carbonaceous materials, medium - dark grey. |
| | 10 | Coaly Shale | Coaly with subordinate very fine sand, dark grey |
| | 11 | Shale | Fine shale with subordinate silt component, woody and carbonaceous material, medium – dark grey |
| **Coal** | 12 | Coal | Black coal with black wood and carbonaceous materials. |



Fig. 3. Lithotypes, facies types and short description of well cutting samples.

***Biozonation***

Sediments from the KB-1 well range in age from Late Oligocene – Recent (Fig. 7). These ages were ascertained by the erection of a biozonation scheme taking cognizance of the first and last occurrences, presence and/co-occurrence of age-diagnostic dinocyst and miospore species as detailed below.

One (1) biozone is established for the Late Oligocene while three (3) biozones are established for the Neogene section (Fig. 7), as detailed below.

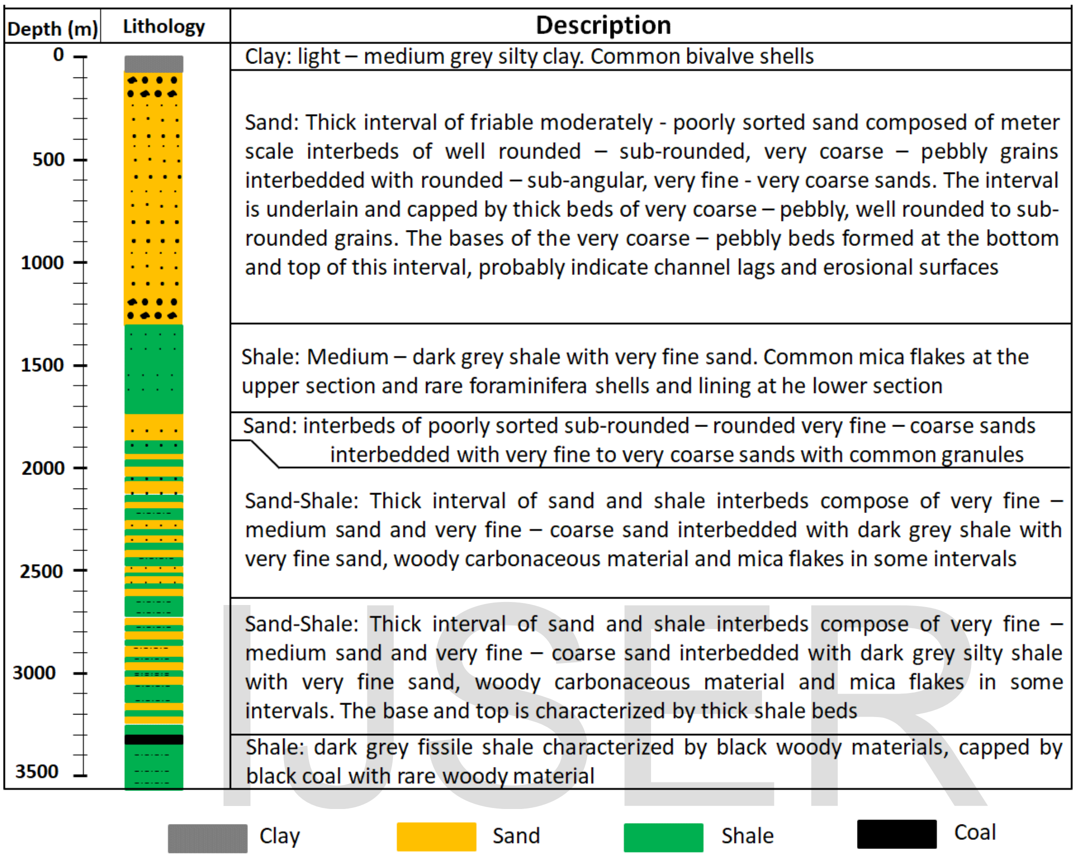


Fig. 4: Lithologic log of KB-1 well showing the different lithotypes (lithofacies) described in the well.

### *Gemmatriporites sp.* zone – A: Oligocene (Chattian)

**Reference section:** 3589 – 3082 m. (Fig. 7)

**Definition:** The base of the zone could not be defined as species having their first appearance are difficult to differentiate because this zone represents the base of the well, although two palynoforms, *Stephanocolpites sp. and Platycaryapollenites swasticoides* have their last appearance at this interval. The top of this zone is marked by the last appearance of *Gemmatriporites sp.*, *Retidiporites magdalenensis*, *Ephedra sp. II* and III, and *Longapatites sp.* The last occurrences of *Momipites wyomingensis*, *M. ventifluminis*, *Casuarinidites convexsus*, *Pinus alata*, *Intraporopollenites sp.*, *Pinus strobipites*, *Plicatopollis sp.*, *Caryapollenites imparalis, and Ephedra sp. I,* also occur within this zone.

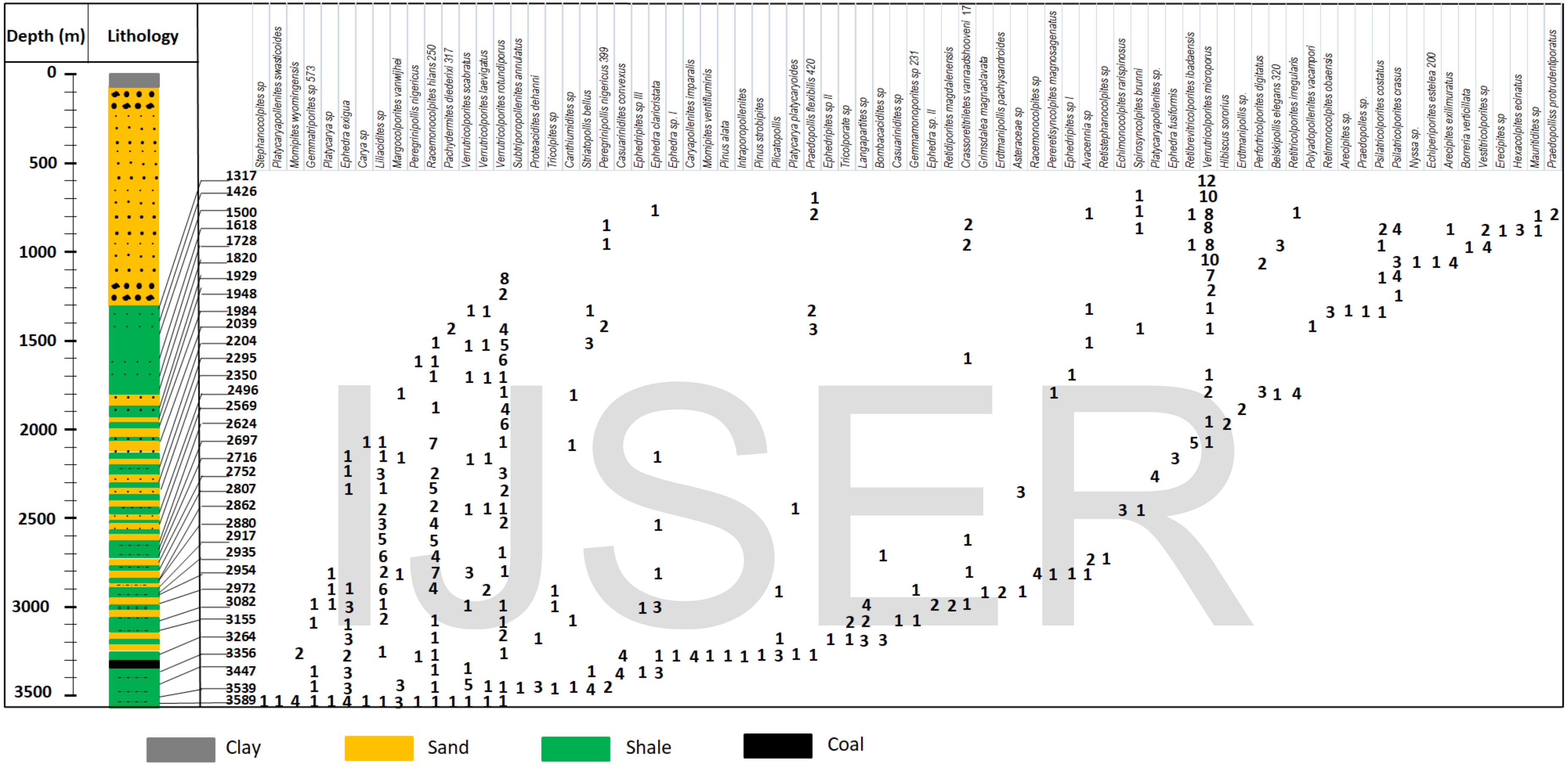

Fig. 5. Palynomorph species count with depth recovered from the well section.

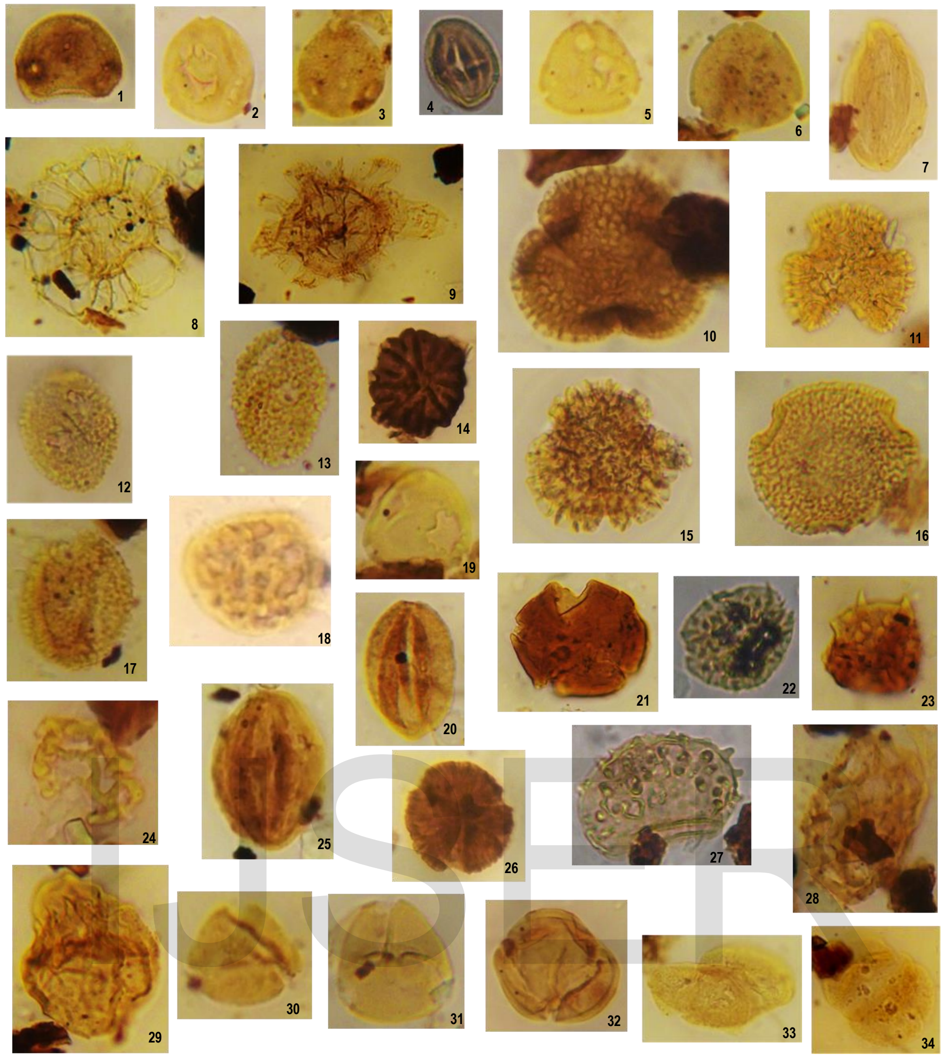

Fig. 6: Photomicrographs of some age-significant and Paleoenvironmental diagnostic palynomorphs recovered from the well. 1. *Subtriporopollenites annulatus* (KB-3539), 2. *Casuarinidites convexus* (KB-3356), 3. *Retibrevitricolporites protrudens* (KB-3155), 4. *Sapotaceae pollenites* 303, 5. *Momipites wyomingensis* (KB-3356), 6. *Momipites wyomingensis* (KB-3356), 7. *Striatopollis bellus* (KB-1984), 8. *Nematosphaeropsis labyrinthea* (KB-3264), 9. *Cordosphaeridium sp.* (KB-3539), 10. *Bombacacidites sp.* (KB-2935), 11. *Retitricolporites irregularis* 510 (KB-1500), 12. *Arecipites exilimuratus* (KB-2697), 13. *Liliacidites sp.* (KB-3539), 14. *Ctenolophonidites sp.* (KB-2880), 15. *Retitricolporites irregularis* 511 (KB-2496), 16. *Canthiumidites sp.* (KB-2697), 17. *Racemonocolpites hians* (KB-2954), 18. *Erdmanipollis pachysandroides* (KB-2972), 19. *Caryapollenites imparalis* (KB-3356), 20. *Ephedra exigua* (KB-3539), 21. *Pachydermites diederixi* (KB-3539), 22. *Mauritidites sp.* (KB-1999), 23. *Mauritidites sp.* (KB-1618), 24. *Spirosyncolpites brunni* (KB-1426), 25. *Ephedra claricristata* (KB-3447), 26. *Margocolporites vanweijhei* (KB-3356), 27. *Verrucatosporites usmensis*, 28. *Peregrinipollis nigericus* (KB-2039), 29. *Praedopollis protrudentiporatus* (KB-2039), 30. *Platycarya sp.* (KB-3080), 31. *Platycarya swasticoides* (KB-2752), 32. *Platycarya platycaryoides* (KB-2862), 33. *Pinus strobipites* (KB-3356), 34. *Pinus alata* (KB-3356)

These forms are known to be Paleogene marker species in many basins worldwide (Leffingwell, 1971; Anderson, 1960; Doyle, 1969; Elsik, 1968a and b, 1974; Federiksen, 1980, 1983; Srivastava, 1972; Pocknall, 1987).

Other species appearing within the zone include *Platycarya sp., Carya sp., Liliacidites sp, Margocolporites vanwijhei, Stephanocolpites sp., Ephedia exigua, Subtriporopollenites annulatus, Canthiumidites sp. Tricolpites sp., Liliacidites sp., E. claricristata, Striatopollis bellus, Bombacacidites sp., Retibrevitricolporites protrudens, Pachydermites diederixi, Longapertites sp., Verrutricolporites laevigatus, V. scabratus,* and *V. rotundiporus.*

**Discussion:** This zone is equivalent to the mid-section of the *Verrucatosporites usmensis* zone of Germeraad *et al*. (1968) and the P620 zone of Evamy *et al*. (1978), the upper section of the *Grimsdalea polygonalis* Zone of Oloto (1994 and 2009) and the lower section of Zone I of Olajide *et al.* (2012). The zone falls within the upper part of the Akata Formation in this well location.

***Verrutricolporites laevigatus/Verrutricolporites scabratus* zone – B: Early Miocene.**

**Reference section:** 2972 – 2697 m. (Fig. 7).

**Definition:** The base of this zone is at the top of zone A and is defined by a marked abundance of *Verrutricolporites laevigatus* and *V. scabratus,* the first occurrence of *Edtmanipollis pachysandroides*, *Grimdalea magnaclavata*, and the last occurrence of *Plicatopollis sp.* The top of the zone is marked by the last occurrence of *Verrutricolporites laevigatus* and *Carya sp*, an abundance of *V. scabratus* and the first occurrence of *Verrutricolporites microporus*. Other notable species within this zone include *Ephedra exigua*, *Carya sp., Platycarya sp., which* also have their last occurrence within this zone, and *Liliacidites sp., Canthiumidites sp., Bombacacidites sp.,* and *Platycarya Platycaryoides*.

**Discussion:** This zone is equivalent to the upper section of the *Verrucatosporites usmensis* zone of Germeraad *et al.* (1968), the P630 – P680 zones of Evamy *et al.* (1978) and the *Lygodiumsporites adriennis* (L-1), the B3 – E 2-1 zones of Legoux (1978), the *Pachydermites diederixi* zone of Oloto (1994, 2009), the *Retitricolporites irregularis* (K) *and Pachydermites diederixi* (L) zones of Lucas and Ishiekwene (2010) and the upper section of Zone I of Olajide *et al.* (2012), equivalent to the Early Miocene.

***Verrutricolporites rotundiporus* zone – C: Middle Miocene.**

**Reference section:** 2972 – 2964m ah.

**Definition:** The base of the zone is at the top of zone B and is marked by a conspicuous abundance of *Verrutricolpories rotundiporus*, absence of *V. laevigatus* and the appearance of *Hibiscus soriorus*. The top of this zone is indicated by a marked increase in *V. rotundiporus* beyond which a paucity of the population of this species is observed, and a bloom in *V. microporus*. The zone is also marked by the first occurrence of *perfotricolporites digitatus* and last occurrence of *Canthiumidites sp.*, *Striatopolis bellus*, *Peregrinipollis nigericus* and *Margocolporites vanwijhei*. Other species present within the zone include, *Praedopollis flexibilis 420*, *Crassoretitriletes vanraadshooveni 17*, *Spirosyncolpites brunni*, *Retitricolporites irregularis*, and *V. microporus*.

**Discussion:** This zone is equivalent to the *Magnastriatites howardi* zone of Germeraad *et al.* (1968), the P700 (P720 – P780) zones of Evamy *et al.* (1978), the E3 – G zones of Legoux, (1978), the *Polypodiaceisporites gracillimus* (N - 1) zone of Oloto (1994, 2009), and the lower section of Zone II of Olajide *et al.* (2012), all corresponding to the Middle Miocene.

***Belskipolis elegans*/*Verrutricolporites microporus* zone – D** and **E: Late Miocene.**

**Reference Section:** 1820 -1317m. (Fig. 7).

**Definition:** The base of this zone is at the top of zone C and is demarcated by a marked increase in *Verrutricolporites microporus*, disappearance of *V. rotundiporus*, last occurrence of *Perfortricolporites digitatus*, and first occurrence of *Echiperiporites estelea 200*. The top of this zone is placed at 1317m ah the uppermost horizon in this well from which shale could be obtained for biostratigraphic purposes and based on the range of *V. microporus* which extends to this horizon. Other species of interest present within this zone include *Belskipolis elegans*, *Retitricolporites irregularis*, *Spirosyncolpites brunni*, *Crassoretitriletes vanraadshooveni 17*, *Praedopollis flexibilis 420*, *P. protrudentiporatus*, *Mauritidites sp. and Peregrinipollis nigericus 399*

**Discussion:** This zone correlates with the *Magnastriates howardi* zone of Gemeraad *et al.* (1968), the H and J1 zones of Legoux (1978), the P800 (P820 – P870) zone of Evamy *et al.* (1978), the *Ctenolophonidites lisame* (O - 1) and *Striatricolporites catatumbus* (P - 1) zones of Oloto (1994, 2009), corresponding to the Late Miocene.

**Reference Section:** 1280 – 37ah

**Pliocene – Recent:** The Pliocene – Recent sediment of the KB-1 well is here interpreted to be of the Benin Formation. This interpretation (depth range of 1280 – 37 m), is based largely on the lithofacies characteristics (Fig. 4). The lithofacies characteristics correlates with those described for the formation (Reyment, 1965; Short and Stauble, 1967; Whiteman, 1982, Nwajide, 2013; Osokpor and Ogbe, 2017, Osokpor and Emudianughe, 2019). Based on lithofacies framework and biozonation scheme generated and drawn from this study for the KB-1 well section, (Figs. 4 and 7), the sediments from the bottom of the well (3589 m) to 2716 m, are correlated with the Akata Formation; sediments from a depth range of 2716 – 1317 m, is correlated with the paralic Agbada Formation, while 1317 – 37m, is correlated with the Benin Formation of the Niger Delta Basin (Figs. 4 and 7).

## Paleodepositional Environment and Sequence Stratigraphy

### *Paleodepositional Environment*

Results and interpretation based on paleodepositional environment proxies obtained from litho- and biofacies characteristics point to deposition in changing paleodepositional settings. These enabled the definition of eighteen paleodepositional cycles (**A** – **R**), which ranged from continental (delta plain) to deep marine (bathyal) paleodepositional settings (Fig. 8).

**Cycle A** (3589 – 3072m) is characterized by coaly shale lithofacies at the lower section and an alternating sequence of silty shale, shale, coal and sandy shale lithofacies in a cyclic pattern at the upper section (Fig. 3). *Cordosphaeridium sp*. and diverse species of *Spinifirites*, both middle – outer neritic dinocyst species at the lower section and *Nematosphaeropsis labyrinthea* a deep marine gonyaulacacean taxa at the upper section of the interval, indicate a deepening paleobathymetric condition through time from distal delta plain to neritic (Figs. 4 and 5). A synthesis of the gross lithofacies characteristics and the biosignal elements present in this interval indicates deposition in distal delta plain to middle neritic paleodepositional environment (Fig. 5) probably caused by an attendant rise in relative sea level.

**Cycles B**, **C**, **D**, **E**, **F**, and **G** (3072 – 3027 m, 3008 – 2964 m, 2954 – 2880 m, 2862 – 2850 m, 2844 – 2807 m and 2797 – 2652 m), is grossly characterized by silty shale overlain by sandy shale at the lower section, an alternating sequence of medium – very coarse grained sand, sandy shale, pebbly granular sand and silty shale at the mid-section, and inter-bedded shale, shaly sand and very coarse sand lithofacies at the upper section (Fig. 4), depicting a form of rhythmic sedimentation. The occurrence of shallow marine dinocysts marker species such as *Lingolodinium sp.* in cycle C and *Nematosphaeropsis labyrinthea* (Fig. 6), a deep marine species, in cycle D, fluctuating pollen abundance in which mangrove assemblage show a general increase and abundance in cycle D (2954 – 2880 m), reduction in cycle E, very low population in Cycle F and an increase in cycle G, coupled with the variation in lithofacies characteristics in the different cycles, all point to cyclical change in paleobathymetric conditions which probably orchestrated the establishment of paleodepositional settings ranging from inner neritic to bathyal (Fig. 8) for this section of the well. Based on the evidences above, cycles B and D, are interpreted to have been formed in a middle neritic paleodepositional environment; cycles C and F, inner – middle neritic; cycle E, outer neritic, while cycle G which caps the section was deposited in a bathyal paleoenvironment (Fig. 8).

**Cycle H** overlies cycle G, and spans a depth range of 2624 – 2522m. This interval records the presence of *Impagidinium sp.* an outer neritic dinocyst species, a marked increase in mangrove spectra pointing to flooding of coastal vegetation which can be achieved during well-established marine conditions and an alternating sequence of sandy shale, very coarse sand and shale (Fig. 4). The integration of the above characteristics defines a mid – outer neritic paleodepositional environment for this section (Fig. 8).

**Cycle I** (2518 - 2460m), is characterized by poorly sorted granule-sized sand at the base, overlain by shale with black carbonaceous materials and capped by very coarse sand lithofacies (Fig. 4). This interval records a complete absence of marine palynomorphs and mangrove element, but a dominance of freshwater swamp and rainforest pollen species (Fig. 9), indicating a reduction (Rull, 2000) and probably a dying out of mangrove vegetation and its replacement by back-mangrove forest vegetation that could have been the result of subsidence-induced fall in sea level and thus a return of shallower water conditions of probably inner – middle neritic paleodepositional environment compared to the preceding section (cycle H) (Fig. 8).

**Cycle**s **J**, **K**, **L**, **M** and **N** (2441- 1875 m), is characterized by alternating sequences of sandy shale, shale, very coarse sand, medium grained sand, coarse grained sand and silty shale lithofacies (Fig. 4).

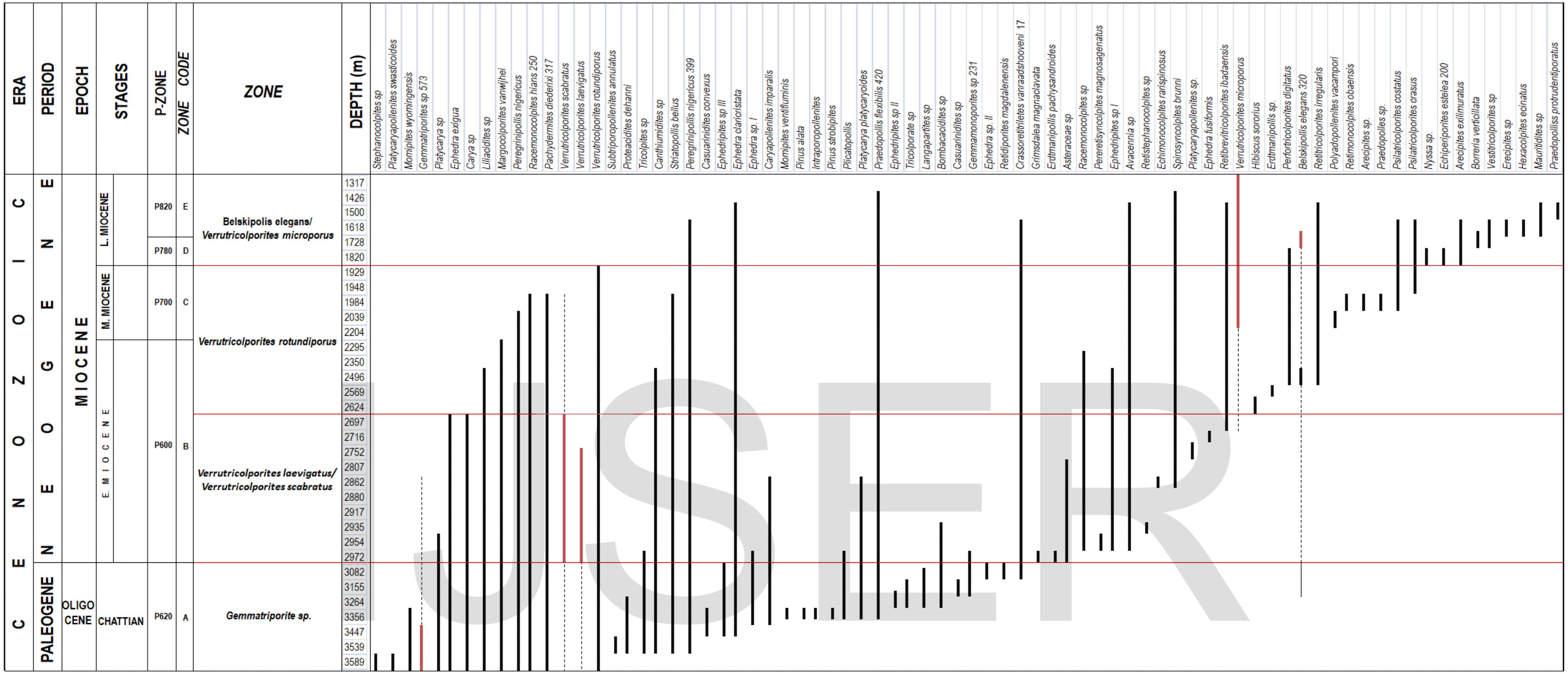


Fig. 7. Stratigraphic range chart of some miospore species recovered from the well section and used to define biozones for the well location.

This interval is marked by abundant mangrove pollen, freshwater swamp forest pollen species such as *Striatopollis bellus*, *Peregrinipollis nigericus*, *Racemonocolpites hians* and the rainforest pollen species *Praedopollis flexibilis* (Fig. 7). These characteristics indicate sedimentation in paleodepositional environments ranging from mid – outer neritic at the base (cycle J), outer neritic – bathyal (cycle K), mid – outer neritic (cycle L), bathyal (cycle M) to outer neritic – bathyal (cycle N) (Fig. 8), indicating oscillatory sea level conditions generated by variations in the incoming solar radiation (Poumot, 1989; Rull, 1997a).

**Cycle O** (1856 – 1747 m) is marked by a thick sequence of sub-angular – sub-rounded, poorly sorted medium – coarse-grained sand with sharp base and yielded abundant mangrove species, *Arecipites exilimuratus* (Figs. 6 and 7) and *Perfotricolporites digitatus* (Figs. 7) both of which are freshwater swamp forest species from interbedded shale at 1820 m. This interval is interpreted as a distal delta plain paleodepositional setting in which channels and back swamps existed based mainly on the lithologic characteristics which indicate a continental condition and a complete absence of marine palynomorphs species. Also in relation to the preceding cycle, N, this interval is evidently shallower than the preceding cycle N below.

**Cycle P** (1731 – 1636 m), is characterized by an abrupt change in lithofacies from sand dominated to dark grey shale lithofacies with very subordinate very fine – very coarse angular – well rounded sand grains, indicative of a shift in depositional environment from shallow to deeper bathymetric conditions. The presence of *Heterosphaeridium sp.* and the quantitative abundance of rainforest and freshwater swamp forest species such as *Arecipites exilimuratus*, and *Racemonocolpites hians* (Figs. 6 and 7), points to a warm and wet climate regime which may have caused an increase in sea level, and thus a deeper paleowater condition ranging from outer neritic to probably bathyal paleodepositional environment (Fig. 8).

**Cycle Q** (1636 – 1317 m), is characterized dominantly by sandy shale and coarse – pebbly, sub-angular – rounded poorly sorted very coarse sand lithofacies (Fig. 4). The biosignal (total palynomorph count) show a complete absence of marine palynomorphs indicative of probably turbid water condition and a dominance of pollen over spore with mangrove species constituting over 40% of the total palynomorphs count. *Spirosyncolpites brunni*, *Praedopollis sp.*, *Retitricolporites irregularis*, *Bombacacidites sp.*, *Retibrevitricolporites obodoensis*, *R. ibadaensis* and *Mauritidites sp.* (Figs. 6 and 7), are some of the identified rainforest and freshwater swamp forest species recovered from this interval. The lithofacies characteristics points to deposition in shallow water setting, in which there seem to have existed a balance between marine and fluvial processes. This view is buttressed by the high mangrove species percentage in conjunction with the lithofacies characteristics which points to a sea level still stand regime in a paralic paleoenvironment, as different from the preceding cycle.

**Cycle R** (1280 – 37 m), occur as the uppermost section in the well and is composed dominantly of alternating sequences of medium, coarse, very coarse, granule-size and pebbly sand lithofacies, characterized by medium – pebbly, rounded – sub-rounded, moderately – poorly sorted sands (Fig. 4), characteristic of fluvial generated lithofacies. The topmost part of this cycle is composed of dark grey clay sequence characterized by very fine – medium, sub-rounded – very well rounded sand grains (Fig. 4) and indeterminate freshwater swamp pelecypods species indicative of deposition in channel overbank areas. The gross characteristics presented by this cycle is indicative of deposition in a delta plain paleodepositional environment (Fig. 8) ranging from mid-channel to overbank settings.

## Sequence Stratigraphy

### Systems Tracts

The well sections studied penetrated stratigraphic sequences ranging in age from Late Oligocene to Late Miocene (Figs. 7 and 9). Eighteen Systems tracts distributed within six second-order sequences, have been established for the well. These sequences host six candidate maximum flooding surfaces (MFS) and five sequence boundaries (SB), (Fig. 9). The sequences range from 3589 – 2850 m (sequence 1), 2840 – 2522 (sequence 2), 2518 – 2350 m (sequence 3), 2350 – 1875 m (sequence 4), 1856 – 1317 m (sequence 5) and 1280 – 37 m (sequence 6).

**Lowstand Systems Tracts (LST):** Five LSTs were identified in the section. The first LST commenced at the 21.8 Ma sequence boundary (SB) which marks the Late Aquitanian stage within the Evamy et al. (1978) P630 zone at a depth range of 2840 – 2807 m (LST-1) (Fig. 10). LST-2, starts from the 20.4 Ma SB and occupies 2518 – 2460 m depth range (Fig. 10). It falls with the Early Burdigalian stage and coeval with the Evamy et al. (1978) P650 zone. The 17.7 Ma SB marks the base of LST-3 at a depth of 2350 m and range up to 2259 m and it is of Late Burdigalian age (Bur 4). LST-4 commences at the 16.7 Ma SB within the P680 zone (Evamy et al. 1978), at 1856 m and range up to 1747 m. LST-5, which is of Early Seravillian (Ser 1) (SCiN Chronochart, 2010), commences at the 15.0 Ma SB at 1280 m and range up to 37 m (Fig. 10). Paleodepositional consideration based on lithofacies, biosignals and stacking patterns for the LSTs indicates deposition in near-shore to shallow marine shelfal paleodepositional settings. These intervals generally records a very low occurrence or complete absence of mangrove pollen, a corresponding abundance of sporomorphs and occurrence of the shallow marine dinocyst species, *Multispinula quanta (Selenopemphix sp.)* and complete absence of other dinocysts species, indicative of shallow water event. The intervals also display thick coarsening-up sand interbeds reflective of progradation.

***Biosignals from Lowstand Systems Tracts***:

**LST-1 -** This interval records a very low mangrove pollen occurrence, and a complete absence of dinocysts, both indicative of shallowing water event. The probable erosion of the intervening highstand systems tract (HST) points to a relative sea level fall below the paleo shelf edge which may have resulted in sediment bypass in the paleo shelf during which time the initial HST sediments were eroded, hence the sequence boundary (SB) at the base rest directly on the maximum flooding surface, and thus is inferred to be a type-1 sequence boundary.

**LST-2 –** This interval is characterized by abundant rainforest and freshwater swamp forest species such as *Retitricolporites irregularis*, *P. diederixi*, *Praedopollis flexibilis* and *Perfortricolporites digitatus* (Fig. 4), and also a complete absence of mangrove pollen element. These biosignals is normally the product of high rainfall that is generated by warm climate condition which also drives a relative sea level rise. The dominant presence of rainforest vegetation pollens and the absence of mangrove swamp pollen species indicate a dying out of mangrove forest due to a fall in sea level which left the mangrove forest swamp land stranded at higher elevation and a subsequent succession by rainforest vegetation. Also recovered is the shallow marine dinocyst species, *Multispinula quanta (Selenopemphix sp.),* that further strengthened shallowing sea level condition. These biosignals thus reveal a subsidence-driven fall in relative sea level for the interval during the Late Burdigalian, contrary to climate-driven event.

| DEPTH RANGE (m) | AGE | DEPOSITIONAL ENVIRONMENT | DEPOSITIONAL CYCLE | Paleobathymetric Zones DP | IN | MN | ON | Ba |
|---|---|---|---|---|---|---|---|---|
| 37 - 1280 | Pliocene-Recent | Delta plain | R | ■ | | | | |
| 1317 - 1636 | Late Miocene | Marginal – Mid Neritic | Q | | ■ | ■ | | |
| 1636 - 1731 | | Outer Neritic - Bathyal | P | | | | ■ | ■ |
| 1731 - 1856 | | Inner - Middle Neritic | O | | ■ | ■ | | |
| 1875 - 2167 | | Outer Neritic - Bathyal | N | | | | ■ | ■ |
| 2167 - 2204 | Middle Miocene | Bathyal | M | | | | | ■ |
| 2295 - 2350 | | Mid - Outer Neritic | L | | | ■ | ■ | |
| 2368 - 2387 | | Outer Neritic - Bathyal | K | | | | ■ | ■ |
| 2387 - 2441 | | Bathyal | J | | ■ | ■ | ■ | |
| 2460 - 2518 | | Inner - Mid Neritic | I | | ■ | ■ | | |
| 2522 - 2624 | | Mid - Outer Neritic | H | | | ■ | ■ | |
| 2652 - 2797 | | Bathyal | G | | | | | ■ |
| 2807 - 2844 | Early Miocene | Inner - Mid Neritic | F | | ■ | ■ | | |
| 2850 - 2862 | | Outer Neritic | E | | | | ■ | |
| 2880 - 2954 | | Middle Neritic | D | | | ■ | | |
| 2964 - 3008 | | Outer Neritic | C | | ■ | ■ | | |
| 3027 - 3072 | | Middle Neritic | B | | | ■ | | |
| 3072 - 3589 | Oligocene | Deltaic Plain – Outer Neritic | A | ■ | ■ | ■ | | |

DP: Delta Plain, IN: Inner Neritic, MN: Middle Neritic, ON: Outer Neritic, Ba: Bathyal



Fig. 8: Summary paleodepositional environment delineation with depth in the KB-1 well

**LST-3 -** Biosignal from this interval show a moderate abundance of mangrove pollen and high sporomorph count. These signals points to a minor fall in relative sea level which favoured the incomplete disappearance of the mangrove vegetation, thus suggestive of a Shelf Margin Systems Tract (SMST) and a probable Type-2 sequence boundary at the base of this interval, formed during the Late Early Miocene in this well area.

**LST-4 –** This interval contains moderate mangrove pollen percentage, *A. exilimuratus* and *Perfortricolporites digitatus* both freshwater swamp forest species, thus indicating a subsidence-driven relative fall in sea level in the Lower Late Miocene (Tortonian) as noticed in LST-2.

**Transgressive Systems Tracts (TST)**: The well host seven TSTs which ranged from 3589 – 3072 m (TST-1), 3008 – 2964 m (TST-2), 2862 – 2850 m (TST-3), 2797 – 2652 m (TST-4), 2441 – 2387 m (TST-5), 2204 – 2167 m (TST-6) and 1731 – 1636 m (TST-7). The seven TSTs identified are capped by seven maximum flooding surfaces (MFSs).

The definition of these tracts are based on the gross lithofacies characteristics which exhibits retrogradational parasequence stacking patterns, reduced spore and corresponding high pollen percentages, with a dominance of freshwater swamp forest such as *R. hians* , *Peregrinipollis sp., Striatopollis bellus,* marine planktics such as *Nematosphaeropsis labyrinthea*, *Cordosphaeridium sp.*, and diverse species of *Spiniferites sp.*, and rainforest pollen species such as *Pachydermites diederixi*, *Sapotacea sp.*, *Bombacacidites sp.*, *Ctonolophonidites sp.*, *Spirosyncolpites brunni*. The abundance of freshwater swamp and rainforest pollen species indicates dense tropical vegetation type formed by wet and warm climatic conditions. These signals thus infer warm global climate that may have resulted in the melt and release of water from polar ice caps into the global ancient oceans which probably caused a eustatic rise in sea level and consequent transgression that affected this well area. Evidence of this is the Early Miocene epoch transgression that flooded and drowned coastal coal swamps in this well area, that generated the coaly shale and coal lithofacies present in the lower section of the well (Fig. 4).

**Maximum Flooding Surfaces:** The 24.3 Ma maximum flooding surface is the first MFS that starts at 3072 m, coinciding with the P628 zone of Evamy et al. (1978) within the *Bolivina 26* Marker Shale. The second MFS, the 23.2 Ma MFS of Early Aquitanian age is established at 2964 m (Fig. 10). It correlates with the P628 zone of Evamy et al. (1978). The third MFS is established at the 22.0 Ma MFS at 2850 m and is of a Late Aquitanian age (Aq 2) within the

P630 zone of Evamy et al. (1978) below the Alabamina 2 Marker Shale (Reijers, 2011). The 20.7 Ma MFS at 2652 m is he fourth MFS and it coincides with P650 of Evamy et al. (1978) (Fig. 10) and formed within the *Alabamina 2* Marker Shale (Reijers, 2011; SCiN Chronochart, 2010). The Late Burdigalian (Bur 3) 19.4 Ma MFS formed within the *Oghara* Marker Shale (Reijers, 2011, SCiN Chronochart, 2010) is the fifth MFS in the well and it correlates with the P670 zone of Evamy et al. (1978). The 17.4 Ma MFS marks the sixth MFS formed at a depth of 2167 m, located within the P680 zone (Evamy et al. 1978), and of a Late Burdigalian (Bur 4) stage (Figs.10). The 15.9 Ma maximum flooding surface is formed at 1636 m which marks the Burdigalian-Langhian transition within the P680 zone boundary of Evamy et al. (1978) (Figs. 10). Abrupt facies change which depicts deepening and corresponding palynomorph abundance/reduction have been considered to reflect flooding sea level trends for the various TSTs.

**Highstand Systems Tracts:** Six highstand systems tracts (Fig. 9 and 10) were defined in the well section. These systems tracts exhibit progradational and aggradational stacking patterns based on litho- and biofacies signatures.



A general trend of higher pollen abundance over sporomorphs is displayed by all the HSTs. These intervals show an abundance of the mangrove forest species *Zonocostites ramonae* and *Spinizonocolpites echinatus*. Mangrove pollen species make up over 40% of the total pollen population in these intervals. Beside the mangrove species, the pollen population is dominated by *Racemonocolpites hians*, *Bombacacidites sp.*, *Striatopollis bellus*, *P. flexibilis*, *Peregrinipollis nigericus*, *Spirosyncolpites brunni*, *Retibrevitricolporites obodoensis*, *R. ibadaensis* and *Ctenolophonidites sp.*, as freshwater swamp forest and rainforest species vegetative elements. Common occurrence of the freshwater algae *Pediatrum* is also noticed. Also recorded is the common occurrence and abundance of spores produced by numerous families of ferns (*Sporites verrucatus* and *Verrucatosporites usmensis*), while *Psilatricolporites sp.*, *Laevigatosporites sp.*, and *Arecipites exilimuratus*, produced by rainforest and mangrove vegetation, indicate a warm and wet tropical climate conditions. These signatures are known to indicate sea-level highstand (Poumot, 1989). The recovery of the freshwater algae *Cymatosphaera sp.*, and shallow marine palyno-taxa such as *Impagidinium sp.*, *Homotriblium sp.*, and *Spiniferites ramosus*, indicate the formation of HST in shallow marine paleo milieu.

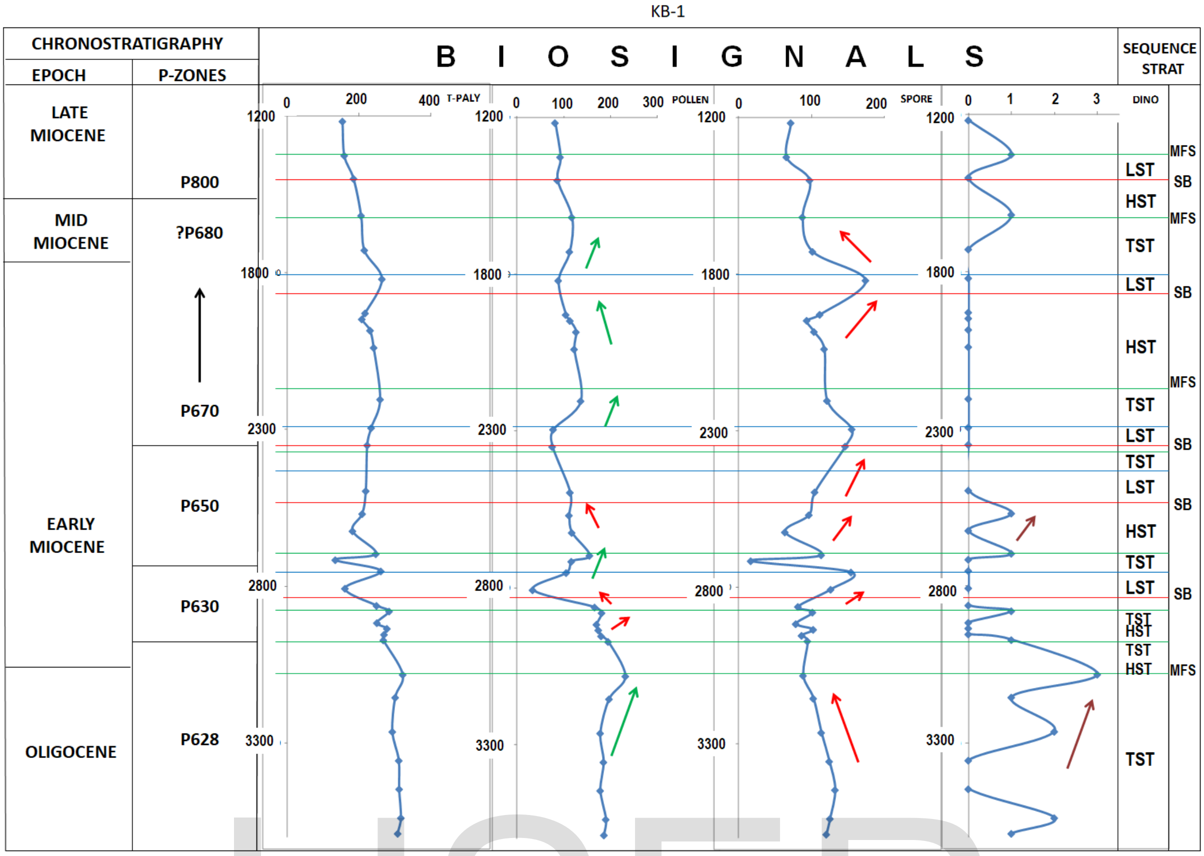


Fig. 9: Quantitative depth plot of palynomorphs counts showing various biosignals, chronostratigraphic subdivision (epochs and P-zones) and associated sequence stratigraphic elements correlated with age in the well.



## Petroleum Play

The understanding of the depositional environment and the systems tract in which each sand body in the sedimentary pile in the well area is formed gives insight on the reservoir potential of the various sand bodies described in this well. The sand in the well, formed in both transgressive, highstand and lowstand systems tracts (Fig. 11). Different depositional environments are known to be characterized by different environmental factors that in turn impart characteristic sand/mud ratio of clastic sediments formed. Important amongst these is the energy regime that varies with bathymetric conditions. Sediments deposited along shorelines are characteristically more agitated and winnowed; hence imparted static reservoir properties are improved upon compared to sands formed far offshore in low energy condition. A range of depositional environments and their petroleum plays have been identified and interpreted within defined systems tracts for the well sections.

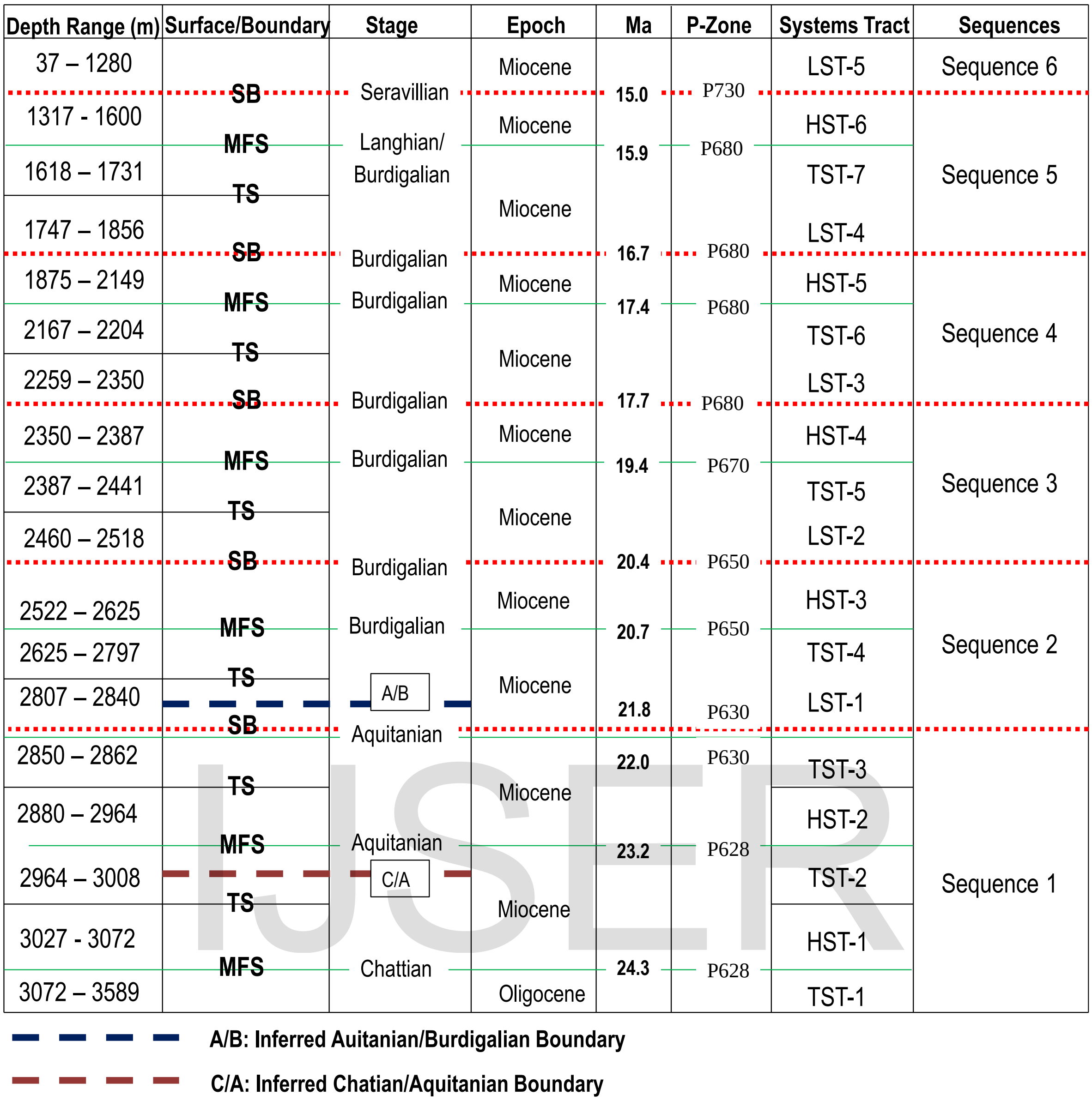


Fig. 10: A Summary of Sequence Stratigraphic Elements recognized at various depths in the well (P-Zones, Stage range and Boundaries adopted from SCiN Chronochart, 2010)

***Transgressive systems tract reservoirs:*** The transgressive reservoirs occur at four intervals in the well section (Fig. 11). Transgressive reservoir-1 (TSR-1) occurs at a depth range of 3246 – 3155 m and formed on the continental shelf (middle neritic bathymetric zone), TRS-2 occurs at 2954 m, as a thin sand body also formed in the continental shelf, TSR-3 and TSR-4 occurs at 2734 and 2185 m, formed in deep marine (bathyal) (Figs. 8 and 11). The petroleum play of the transgressive systems is bimodally distributed, some being related to the continental shelf-based transgressive wedge, and others being part of the deep-water wedge (Catuneanu, 2006). The best reservoirs on the continental shelf, likely close to the shelf edge, are concentrated along the coastline, being represented by backstepping beaches (open shoreline settings), estuary-mouth complexes, retrograding bay head deltas or even prograding deltas (Catuneanu, 2006). The thickness and lithofacies type (very coarse sand) of TSR-1 in contrast to TSR-2, 3 and 4 suggests a retrograding continental shelf-wedge (see defined depositional environment above) and thus forms the best of the four transgressive sands in the well. TSR-2, 3 and 4 occur as relatively thin sands formed in deeper bathymetric zones compared to TSR-1 described above. They occur as deep-water wedge (Fig. 8) characterized by low sand/mud ratios and a consequent poorer static reservoir qualities.

***Highstand systems tract reservoirs:*** Six highstand systems tract reservoirs (HSRs) have been identified in the well section. HSR-1 occurs as a thin sand interval composed of medium grained clastics at 3027 m and formed in a middle neritic setting (Fig. 8). The thin nature and finer grained composition of this reservoir sand characterizes late stage highstand deltas recognized to have wide distribution (Catuneanu, 2006). The predictive potential of sequence stratigraphy is appreciated in this vain, that although this sand body is assessed through one well, its lateral extent can be inferred/predicted. HSR-2 occurs at 2917 – 2880m as an approximately 37m thick continental shelf wedge characterized by coarse grained sands (Fig. 8). The grain size and thickness trends of this interval points to a localized delta that progrades a shelf-type setting (Catuneanu, 2006). Based on lithofacies, it possesses a high sand/mud ratio which imparts good reservoir qualities.



HSR-3 is made up of two sand bodies, a lower thin unit at 2606m and an upper thick unit at 2583 – 2527m, composed of very coarse grained sands formed middle-outer neritic settings (Figs. 4, 8 and 11). The thickness and lithofacies characteristics betray a strand plain for the lower sand body and a river delta for the upper unit. These two sand bodies represent early HST, while the fine grained (shale) interval formed on top of the interval at 2522m represents late HST (Catuneanu, 2006) and acts as seal to the underlying early stage reservoir sands. HSR-4 is a thin sand unit at 2350m, composed of coarse – very coarse sands formed in an outer neritic depositional environment of a late stage highstand systems tract (Figs. 4, 8 and 11).

The lithofacies signature and the thin nature of the sand body infer fluvial systems sediment bypass during the preceding lowstand systems onto shelf edge-slope transitional setting. HSR-5 reservoirs consists of three sand bodies, a thick lower 58 m which occur at 2115 – 2057m made up of very coarse grained sand formed as thick sand wedge formed in an outer neritic environment probably as shelf edge delta wedge with high sand/mud ratio, a middle thin sand body at 1966m, also composed of very coarse sand of probably incised valley fill. The third sand body which occurs at 1911m, as the upper sand unit within the HSR-5 reservoirs is composed of medium-coarse grained sand and formed in deep-water (Fig. 11).

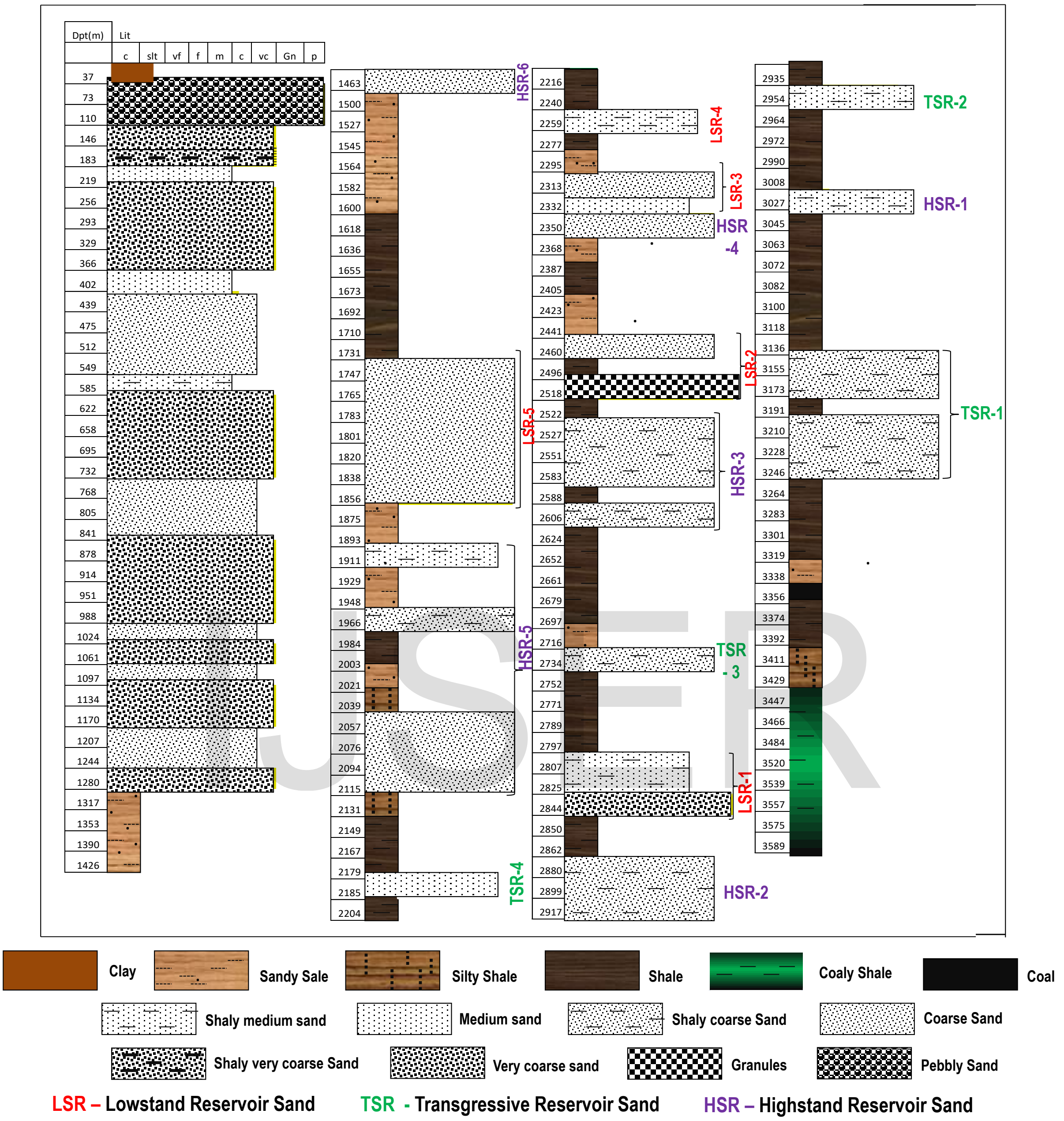


Fig. 11: Vertical lithofacies section of the well showing transgressive reservoir (TRS), highstand (HSR) and lowstand (LSR) reservoir sands at different depths in the well.

It is inferred to be slope aprons formed in the upper bathyal zone. The HSR-6 reservoir at 1463m is thin sand body composed of very coarse grained clastic components with high sand/mud ratio deposited in an inner neritic bathymetric zone (Figs. 4, 8 and 11). The characteristic lithofacies and the sand thickness points to fluvial sands debouched on ancient shorelines strand plains in this well location.

***Lowstand systems tract reservoirs:*** Five sand bodies in the well have been designated lowstand reservoirs (LSR) (Figs. 10 and 11). These occur at 2518 m, LSR-1, 2460 m, LSR-2, 2332 – 2313 m, LSR-3, 2259 m, LSR-4 and 1856 – 1747 m, LSR-5. LSR-1is a thin sand body composed of pebbly clastic grains deposited in an inner neritic depositional setting (Figs. 4, 8 and 11). The lithofacies and the nearness to coastal margin suggests fluvial channel emptying into near-shore environment where wave activities may have winnowed the fines thereby imparting a high sand/mud ratio that may have distributed the coarse fraction along strike, thus created a laterally extensive sand reservoir. LSR-2 is thin and characterized by high sand/mud ration composed of coarse grain sand deposited in a middle neritic setting (Fig. 8). LSR-3 is a 19 m thick coarsening-up sand body composed of medium-very coarse sand with high sand/mud ratio formed in a middle to outer neritic environment (Fig. 8) and was probably built as a prograding wedge during early base level rise. LSR-4 is a thin medium to coarse grain low sand/mud ratio sand body formed in bathyal zone (Figs. 8 and 11) probably as slope apron. The lowering of the net sand/mud ratio of this reservoir can be explained to be related to the trapping of sand within aggrading fluvial to shallow-marine systems following the onset of base-level rise which resulted in a net decrease in the volume of sediment available for deep-water gravity flows, that resulted in the observed sand/mud ratio (Catuneanu, 2006). LSR-5 is a thick 109 m coarse grain sand body formed as distal delta plain-shore face sand with high sand/mud ratio, capped by a 95 m thick deep marine shale (Figs. 8 and 11).



## Conclusion

The description of lithofacies and its integration with biosignals in defining possible ranges of paleoenvironmental conditions under which various lithofacies were formed and preserved within the KB-1 well has served as a basis for the delineation of systems tracts that in turn enabled the sequence stratigraphic characterization of various reservoirs types. The different depositional environment defined in the sedimentary succession provided insight on the different energy regime operative within geologic domains that ultimately determined the sedimentologic and corresponding petrophysical properties of reservoir sand bodies. The sequence and systems tract approach to reservoir typing of the sand bodies have shed light on an aspect of the petroleum play within the succession, which can be usefully extrapolated to and/or correlated with adjoining well areas or prospects.

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