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Depositional Patterns of the Campanian-Maastrichtian Sediments in the Anambra Basin

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Abstract This study reports environments of deposition and factors controlling their distribution in the Campano-Maastrichtian times in Anambra Basin, Nigeria, using standard palaeo-bathymetric scheme. The major objective was to provide better understanding of depositional patterns which relate to stratigraphy and formation of potential source and reservoir rocks in the basin. Results showed that during the Late-Maastrichtian time, sandstones /sands were the dominant facies which recorded an upward-thickening trend with corresponding thinning of the shale facies derived from distributary channels, tidal-flood-plain and shoreface deposits that make up the Ajali and Nsukka Formations. This was similar to the observed depositional pattern in the Early-Maastrichtian, but with shales being the dominant facies and represented as Mamu Formation. These suggest possible short episodes of marine influences in fluvial-dominated environments during Late-Maastrichtian, whereas the scenario was opposite during Early-Maastrichtian time, where shales facies dominated. During Late-Campanian time, multiple episodes of marine transgression with occasional fluvial incursions were inferred, marked by massive shale deposition with few sandstones facies within the thick shales facies, representing the Nkporo Shales. Episodes of crustal heating resulting from Late-Campanian tectonism were also encountered as intrusives, which may have severe implications when exploring for hydrocarbons in this area. The study further showed that the reservoirs are vertically and laterally extensive in most parts, but not generally continuous due to some syndepositional structural complexities, during Early - to Late-Maastrichtian times that may have resulted in truncations of the processes of sediments deposition. These deductions provide enhanced geologic information for development of new play concepts within the Anambra Basin in furtherance of new exploration campaigns in the frontier inland basins.

Keywords Palaeoclimate; palaeoecology; bioevents; fauna, flora

1. Introduction

The period of subsidence in Southern Benue Trough dating back to 84.0Ma was associated with intensive magmatism [1-7]. This corresponds to the time of the initiation of the Anambra Basin, which started during the Coniacian and reached its peak at the Santonian thermotectonic event [8]. Folding and faulting of the area became flexurally inverted to form the Abakaliki Anticlinorium. The Santonian tectonic pulses caused the displacement of the depocentres to the West and Southeastwards, thereby resulting in the formation of Anambra Basin and Afikpo Syncline [9-10].

The Formations under the Campanian Nkporo Group reflect a shallow marine shelf setting that graded into channelled low energy marshes. Extensive coastal swamps developed behind the poorly developed foreshores and shorefaces deposits now known as the Enugu shale. According to Reijers [11], the shallow open marine shelf sea was alternatively storm- and tide-dominated and in many respects comparable to that prevailing on the Nigeria's southwest coast. The Maastrichtian coal-bearing Mamu and the Ajali Formations formed during the overall regression of the Nkporo Group with associated progradation. The Nsukka Formation, which overlies the Ajali Sandstone, begins with coarse- to medium-grained sandstones and passes upward into well-bedded blue clays, fine-grained sandstones and carbonaceous shales with thin bands of limestone [5, 11].

Often times, the rocks bear evidence of their depositional environment, transporting medium and original mineralogical composition. Similarly, the presence of some faunal and floral species found in these sediments has been used to recognize palaeosalinity variations and proximity to shorelines [12]. These indicators serve as tools for reconstructing ancient ecology, environments of deposition and provenance of the rock forming sediments, as well as palaeogeographic histories of the study area.

Previous investigations revealed that environmental conditions play major roles in determining the distribution of fauna and flora in any depositional setting [13-15]. Benthic and Planktonic Foraminifers are widely used as tools to reconstruct palaeoenvironments and relative dating of sedimentary rocks. The calcareous or arenaceous tests of benthic foraminifers lend them good fossilization potential, which in combination with considerable abundances makes them useful tools in exploration. This is in contrast to planktonic foraminifers, which initially were mainly employed as biostratigraphical markers, and now as tools in palaeo-oceanographical studies. Foraminiferal assemblages have been used as proxies for palaeoenvironmental determination of the Maastrichtian sediments (Nkporo shale) of the Benin frank, south western Anambra basin [14].

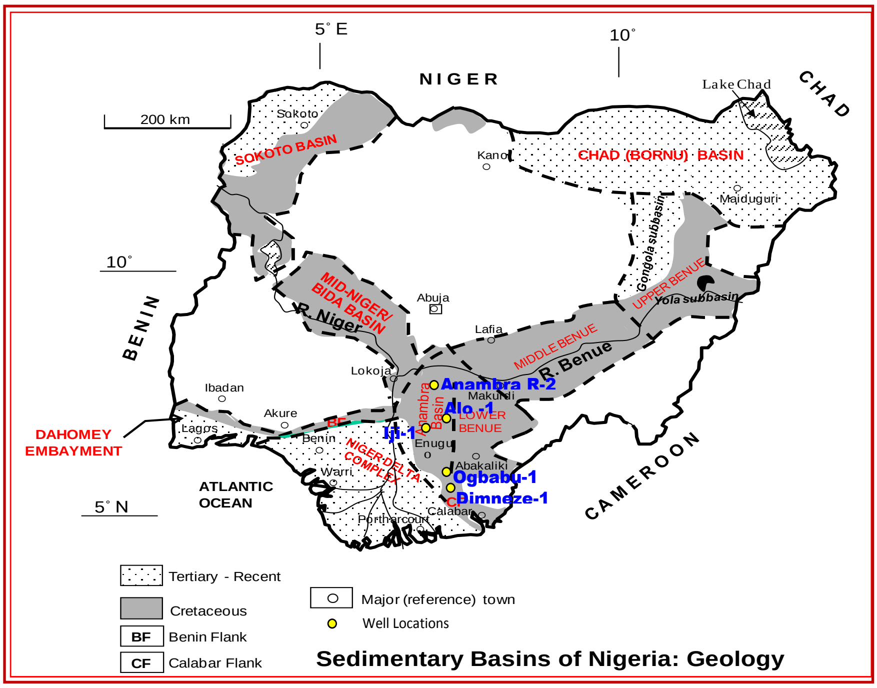

Figure 1: Map of the study area showing locations of the studied wells and the outcrop samples in Anambra Basin

Batten [13] reported a significant variation of palynofacies abundance in different depositional environment from barrier/beach and offshore sand to shoreface and over-bank deposits. In that report, opaque structureless organic matter is most abundant in barrier/beach and offshore sand, whereas cuticles, spores, and pollens are most common in shoreface and over-bank deposits. Umeji and Edet [16] established three biofacies zones in the Nkporo Shale and Mamu Formation on the bases of the recovered palynomorphs. They suggested that Nkporo Shale was deposited in an oscillating shoreline, in which the salinity fluctuated between marine at the base and brackish water at the top, giving way to the overlying Mamu Formation, which began with brackish water at the base and fresh water at its top. They concluded that the sedimentary environments ranged from lower upper shoreface to backshore swamp or lagoon for Nkporo Shale; while Mamu Formation ranged from lake or swamp to alluvial plain.

Palynological data was also used to reconstruct the palaeoclimatic and palaeoenvironment of deposition of the same area [14]. The high and low fossils abundance and diversity peaks are direct indicators of transgression and regression phases, respectively, are related to eustatic change in sea levels. Marine incursion resulted in Mid-Maastrichtian transgression, leading to the deposition of basal shale sequence of Mamu Formation, while the coal seams were deposited during the regressive phases in the Late Maastrichtian.

The four (4) wells used in this study are located in Anambra Basin within latitudes 5°30′ to 7°30′ and longitudes 6° 30′ to 8°00′ E. The wells include Well 'A' (Interval: 2000-5610ft), Well 'B' (Interval: 1000 - 8600ft), Well 'C' (Interval: 1000-7210ft) and Well 'D' (Interval: 3800 -10480ft) wells (Figure 1). In this study, both foraminiferal (faunal) and the terrestrial sporomorphs (pollen & spores) with few marine indicator palynomorph species recovered from these wells were used in assessing the various paleo-depositional environments of the formations.

1.1. Aim and Objectives

This study is aimed at providing better understanding of depositional patterns as they relate to stratigraphy and formation of potential source and reservoir rocks in the Anambra Basin, and to highlight genetically related stratal units and variations of sedimentary successions in terms of relative sea level fluctuations and basin tectonics. This involves interpreting the environments of deposition of the sediments, evaluating the factors controlling the distribution of Campano - Maastrichtian deposits based on the faunal (foraminifera) and floral (palynomorphs) distribution, biofacies and lithofacies distribution and defining their implications to further hydrocarbon exploration campaigns in the Anambra Basin, hence boosting the hydrocarbon reserves of the country.

Early studies indicated that the Anambra Basin is dominantly a gas-condensate basin. Evaluation of wells drilled in the past shows that the basin is most prospective where peripheral sandstones inter-finger with or are overlain by shale units [17]. Further exploration efforts on Turonian to Maastrichtian deposits which show good sand developments beneath the zone of fresh-water flushing, with good hydrocarbons potentials formed the major drive for this study. As Nigeria shifts its production emphasis from oil to gas, exploration in the gas-prone Anambra basin will probably surge and provide the ready source of revenue for the country.

2. Materials and Methods

The materials used in this study include ditch-cutting samples and wire line logs for four wells. Samples were analysed for foraminiferal micropaleontology/lithologic descriptions and palynological analyses. For Well 'A' Interval: 2000-5610ft (110 and 77 respectively), Well 'B' Interval: 1000 - 8600ft (105 and 62 samples respectively), Well 'C' Interval: 1000-7210ft (98 and 55 samples respectively) and Well 'D' Interval: 3800 - 10480ft (47 and 22 samples respectively). The samples were processed using standard processing procedures for both foraminiferal and Palynological analyses. The processed samples were analysed using high resolution digital microscopes. Fossils distribution charts were generated using Stratabugs software platform. The method adopted for this study involved literature review, generation and interpretation of data from the wells, definition of key stratigraphic and ecological fossil markers, identification of trends of fossil markers distribution and the biomarkers, reconstruction of palaeo-depositional setting using standard palaeo-bathymetric scheme, identification of lithofacies units and trends with regards to sediments deposition.

3. Results

The results obtained from faunal and floral analyses showed that Well 'B', Well 'C' and Well 'D' penetrated Late Maastrichtian deposits (Ajali/Nsukka Formations), and consist of intercalations of shale and sandstone with shale predominant towards the base of Ajali Formation, indicating transition into the Mamu Formation (Early Maastrichtian). The Mamu Formation (Early Maastrichtian) and Nkporo Shale (Late Campanian) were penetrated by three of the study wells (Wells A, B and C). See Figure 2 below.

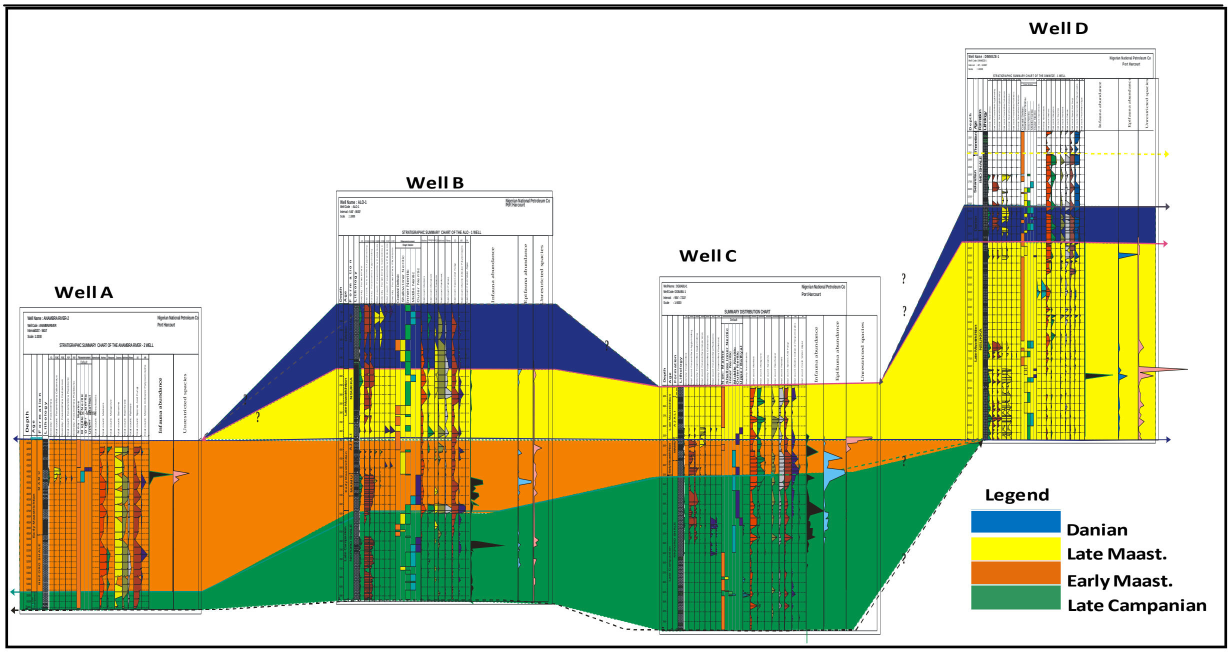

Figure 2: Age correlation across the studied wells in Anambra Basin

The Early/Late Maastrichtian boundary is marked by depressed tops and abundant co-occurrences of *Bolivina afra* and *B. explicata*; and stratigraphic extinction (LDOs) of *Bolivina afra* and *Bolivina explicata*, top occurrence of *Retidiporites miniporatus* and also the co-occurrences of *Orthokarstenia clavata* and *Globotruncanella havanensis* within the lower intervals and dated 69.42Ma. The Maastrichtian/Campanian boundary was delineated by the LDOs of benthic foraminifera *Textularia hockleyensis* and *Miliammina telemaquensis*, the base occurrence of *Ctenolophonidites costatus* and *Verrucatosporites alienus* and was dated 72.1Ma. These zones are further characterised by assemblages of age diagnostic benthic foraminiferal and microforal assemblages, with several other recoveries of both the faunal and floral fossil species.

The results showed co-occurrences of arenaceous and calcareous foraminiferal as well as the occurrence of pteridophyte and fungal spores, mangrove species and marine indicators within the Maastrichtian time slices in Well 'A', Well 'B', Well 'C' and Well 'D'. The sediments could be said to have been deposited in shallow to deep marine settings. The occurrences of restricted marine species such as *Bolivina spp, Nonionella spp, Valvulineria spp.* and the unrestricted species of Haplophragmoides, Ammobaculites, Miliammina, etc., indicate occasional marine incursion within their depths of occurrence.

Lithofacies Interpretations

The lithofacies units in this study were identified based on description of sediments in terms of colour, bedding, lithologic composition, texture and their fossils assemblages/associations, which ultimately give different environmental interpretations. Well 'A' recognized two lithofacies units in the study interval, namely, Shale/Sandstone Unit 1 and Shale Sandstone Unit 2. Lithofacies Unit 1 consists of mainly intercalations of shale and bands of sandstone (Table 4). The shale is dark grey, moderately hard and blocky. The sandstone is light grey, predominantly fine-grained, sub rounded to rounded and well sorted. The sediments represent the Nkporo Shale deposited in a paleobathymetric regime that fluctuated between Non-marine and Outer Neritic during the Early Maastrichtian times. The lithofacies unit 2 (Nkporo Shale) with thickness of 650ft thick, is predominantly homogenous shale with thin beds of sandstone. The shale is dark grey, moderately hard and blocky. The sandstone is light grey, predominantly fine-grained, consolidated, subrounded to rounded and well sorted. These sediments are associated with ferrugenised materials and were deposited in a predominantly Non-marine (to probably shallow marine) paleobathymetric regime during the Late Campanian - Early Maastrichtian times.

In Well 'B' interval studied, a total of four (4) lithofacies units were identified. These are Shale Unit 1 (Nkporo Shale), Shale/Sandstone Unit 2 (Mamu Formation), Sandstone/Shale Unit 3 (Ajali Sandstones) and Shale/Sandstone/Siltstone Unit 4 (Nsukka Formation). The basal unit (Nkporo Shale) is about 2840ft thick in this well (Table 1). It is predominantly shale lithofacies. The shale is grey to dark grey, blocky, occasionally sandy and ferrugenised. The lithofacies was deposited in paleobathymetric settings that fluctuated between the Non-marine and Outer Neritic during the Late Campanian to Early Maastrichtian times. The second unit (Mamu Formation) overlying the Shale lithofacies Unit, has a thickness of about 1,580ft and consists of shales with subordinate sandstone lithofacies. The shale is grey to dark grey, blocky, sometimes sandy and ferrugenised. The sandstone is light grey, coarse to medium-grained; occasionally fine-grained, subangular to angular and moderately sorted. These lithofacies are associated with ferrugenised materials and were deposited in the Middle to Outer Neritic paleo-water depths during the Early Maastrichtian times in this well.

Table 1: Lithofacies Summary of all the studied wells (Wells A, B, C & D).

Well (Age penet.)	Formations	Lithofacies Units	Facies	Description
A (E.M/L.C)	Nkporo Shale	I	Shale/Sandstone	Predominantly homogenous shale with thin beds of sandstone with ferrugenised materials
		II	Shale/Sandstone	Intercalations of shale and bands of sandstone
B (L.M/ E.M/ L.C}	Nsukka Formation	I	Shale/Sandstone / Siltstone	Predominantly shales with thin beds of sandstone and siltstones intercalations
	Ajali Sandstone	II	Sandstone/Shale	Intercalations of shale and bands of sandstone, occasionally gypsiferous and ferrugenised.
	Mamu Formation	III	Shale/Sandstone	Shales with subordinate sandstones and associated with ferrugenised materials
	Nkporo Shale	IV	Shales	Predominantly shales, occasionally sandy and ferrugenised
C (L.M/ E.M/ L.C)	Nsukka Formation	I	Shale/Sandstone	Intercalation of shales and sandstones on almost equal proportions
	Ajali Sandstone	II	Sandstone/Shale	Intercalation of shales and sandstones, with shales predominating
	Mamu Formation	III	Shale/Sandstone	Shales and sandstones intercalations, occasionally ferrugenised
	Nkporo Shale	IV	Shale/Intrusives	Predominantly shales, co-occurring with intrusives
D (L.M/ E.M/)	Nsukka Formation	I	Shale/Sandstone	Intercalation of shales and sandstones, with shales predominating

Note: L.M= Late Maastrichtian; E.M= Early Maastrichitian; L.C=Late Campanian

Lithofacies Unit 3 (Ajali Sandstone) with thickness of about 1,900ft is made up of alternating shale and sandstone lithofacies. The shale is grey to dark grey, blocky, occasionally sandy, gypsiferous and ferrugenised. The sandstone is grey, medium to fine-grained, sometimes coarse to medium-grained or fine-grained, sub-angular to angular, moderately sorted and sometimes moderately consolidated. These lithofacies unit was deposited in a predominantly Non-marine paleobathymetric setting; with periodic marine (shallow Inner/Inner Neritic) influence during the Early – Late Maastrichtian times in this well. Overlying this unit is Shale/Sandstone/Siltstone Lithofacies Unit, which is predominantly shale interval with sandstone and siltstone intercalations. The shale is dark grey, sub-fissile to fissile and moderate to hard. The sandstone is light grey to orange, coarse to medium-grained; sometimes medium to fine-grained, subangular to angular, moderately sorted and occasionally consolidated. These lithofacies were deposited in paleobathymetric settings that fluctuated between the Non-marine and Middle Neritic during the Late Maastrichtian to Danian times in this well.

Similarly, four lithofacies units were identified in Well C (Table 1). These were described as Shale/Intrusive rock Unit 1 (Nkporo Shale), Shale/Sandstone Unit 2 (Mamu Formation), Shale/Sandstone Unit 3 (Ajali Sandstone) and Heteroliths Unit 4 (Nsukka Formation). The basal Shale/Intrusive lithofacies unit represents the Nkporo Shale, with a thickness of about 4330ft and comprises of predominantly shale co-occurring with an intrusive rock. The shale is dark grey, moderately hard and blocky. The intrusive rock is dark grey, very hard and slightly calcareous. These lithofacies were deposited in paleobathymetric settings that fluctuated between the Non-marine and Inner Neritic during the Late Campanian – Early Maastrichtian times. The overlying lithofacies, Shale/Sandstone Unit represents Mamu Formation with thickness of about 580ft, and consists of shale and intercalations of sandstones. The shale is dark grey, moderately hard, blocky and occasionally ferruginised. The sandstones are light grey, predominantly medium to fine grained, subangular to rounded, poorly sorted and with moderate sphericity. The formation was deposited in a paleobathymetric regime that fluctuated between Inner to Outer Neritic during the Early Maastrichtian times.

Lithofacies Unit 3 consists of intercalations of shale and sandstone with shale unusually predominating, especially at the basal part; probably indicating the transition from the Mamu to Ajali Formation. The shale is dark grey, hard and blocky. The sandstone is light grey, fine grained, subrounded to rounded and well sorted. This lithofacies were deposited in a paleobathymetric regime that fluctuated between Inner and Middle Neritic during the Late Maastrichtian times. At the top of the analysed interval is the lithofacies unit 4, which represents the Nsukka Formation comprising of intercalations of shale and sandstone on almost an equal proportion. The shale is dark grey, moderately hard and blocky. The sandstone is light grey, medium to fine-grained, sub-rounded to rounded, moderately sorted with rare siltstone occurrences. This lithofacies is associated with pyrite and ferruginised materials and were deposited in paleowater depths that fluctuated between Non-marine and Outer Neritic settings during the Late Maastrichtian times.

In Well 'D' interval studied, only one lithofacies unit (Shale/Sandstone Unit), belonging to the Nsukka Formation was identified in the Late Maastrichtian - Danian (Early Palaeocene) ages (diachronous). The lithofacies unit has an approximate thickness of 7100ft in the well interval (Table 1). It comprises of intercalations of shale and sandstone with shale predominating. The shale is dark grey, moderately hard, blocky with rare siltstone and are occasionally ferruginised. The sandstone is light grey, fine grained, consolidated, subrounded to rounded, well sorted and occasionally ferruginised. These lithofacies were deposited in a paleobathymetric regime that fluctuated between Non-marine and Outer Neritic.

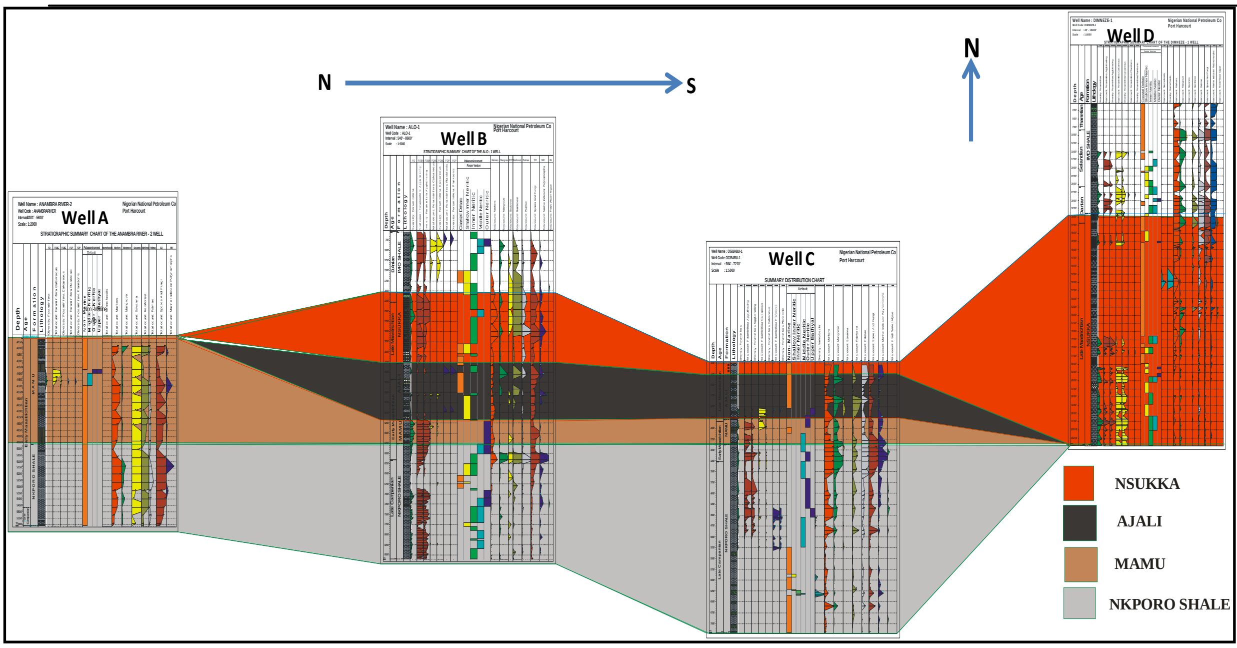

Figure 3: Correlation of the Stratigraphic Units across the studied wells in Anambra Basin

The Nkporo Shale, based on the three wells where it penetrated (Well A, Well B and Well C), increased in thickness in the N-S direction (Figure 3). This is succeeded in the stratigraphically younger direction by the Mamu Formation, commonly known as the Lower Coal Measure and was penetrated in the same three wells where the Nkporo Shale occurred. This lithostratigraphic unit decreases in thickness from the wells at the flank towards the Well 'C' area. The Ajali Sandstone, which overlies the Mamu Formation was penetrated in two wells (Well B and Well C) and indicated a slight decrease in thickness in the N-S direction. The Nsukka Formation sometimes referred to as the Upper Coal Measure, was deposited majorly during regressive phase of sediments deposition and overlies the Ajali Sandstone. This Formation was penetrated by three of the studied wells, Well 'B', Well C and Well D (Figure 2). It generally decreases in thickness in the N-S direction (Well C), but thickened towards the flank (Well D). The Nsukka Formation is overlain by the Imo Shale at places where they are observed.

Palaeoenvironmental Interpretations

Paleoenvironmental interpretation of the studied sections of the wells were based on foraminiferal (faunal), palynological (floral), lithological (facies) and wireline logs data. Palaeoenvironmental synthesis of the Well A indicates that the uppermost (4117- 4364ft) and lowermost sections (4495-5610ft) were completely barren of foraminifera, suggesting deposition of the sediments in a predominantly non-marine palaeobathymetric setting suggesting deposition within the distributary channels through fluvial flood plain/channel fill and river mouth bar/point bar environments of deposition (Table 1). Floral data indicates very rare to low occurrences of the mangrove, rainforest taxa and savanna taxa, co-occurring with rare to moderately high occurrences of pteridophyte spores, while the OWMs were absent in this section. The palynofacies suite also indicates the predominance of the humic components (vitrinite and inertinite) over the sapropelic (exinite) components. This palynofloral assemblage suggests sediments deposition in a predominantly non - marine paleoenvironmental setting.

However, the topmost section of this interval is characterized by rare to super-abundant occurrences of *Uvigerina havanensis*, *Bolivinaexplicata*, *B. africana*, *B. tenuicostata*, *B. denticulocamerata*, *Hopkinsina danvillensis* and *Orthokarstenia clavata*. The foraminiferal distribution suggests tidal point bar deposits in a predominantly middle to outer neritic paleobathymetric setting, with a slight deepening to upper bathyal realm. Palynofloral assemblages showed very rare to low occurrences of mangrove, savanna and rainforest species. Also rare to moderately high occurrences of pteridophyte spores were recorded, coexisting with low occurrences of marine-indicator palynomorphs (Figure 4A). Palynofacies data indicated high percentage of humic components and low percentage of sapropelic components, supporting a non-marine to shallow marine setting contrary to the deep marine setting interpreted from foraminiferal data.

In the Well 'B', sediments penetrated non-marine to shallow inner neritic palaeobathymetric setting in the upper part, indicated by distributary channel fills, fluvial point bar, fluvial flood plain, fluvial channel and river mouth bar deposits. The shallow inner/inner neritic in the middle and lowermost part of the interval was penetrated by shoreface and tidal mud flat deposits within the shallow marine palaeoenvironment (Table 1). The penetration of distributary channel fill and tidal mud flat deposits in the lower section suggested deposition within the middle/outer neritic palaeobathymetric settings in the open marine palaeoenvironment of deposition.

Palynofloral assemblage in this interval consists of the rare to super abundant occurrences of pteridophyte spores such as *Acrostichum spp., Laevigatosporites ovatus, Gleicheniidites senonicus, G. spp., Dictyophilidites harrisi, Martonisporites spp., Cicatosporites spp. and Granulatisporites spp.*, the rare to common occurrences of mangrove elements including *Psilatricolporites spp. and Echiperiporites spp.*, the absence of savanna elements; the scanty occurrence of freshwater algae in conjunction with rare to common occurrences of organic-walled microplanktons such as indeterminate dinocyst species and foraminiferal linings (Figure 4B). The palynofacies suite indicates predominance of humic elements (vitrinite and inertinite) over the sapropelic (exinites) counterpart in the upper section, which approximates a shallow to open/deep marine palaeoenvironment. However, relative percentage increase of the exinite elements in the lower sections was observed within the lower section, affirming the slight deepening as further confirmed from the foraminiferal data.

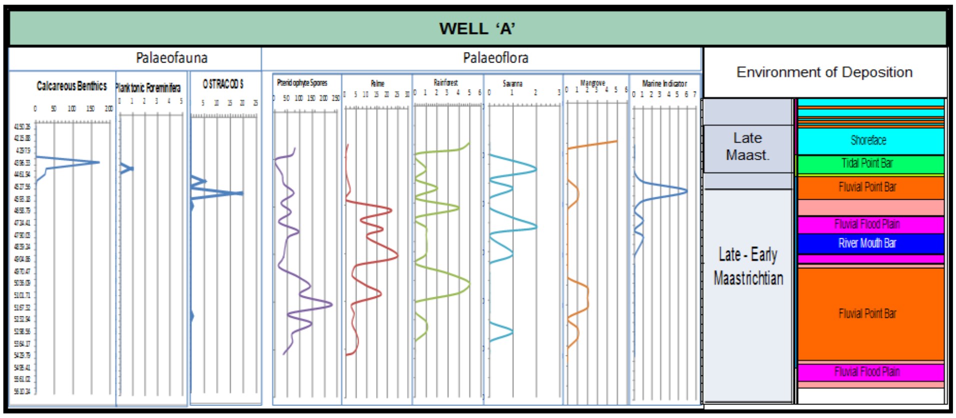

Figure 4A: Floral and Faunal distributions and Environment of Deposition from Well A in Anambra Basin

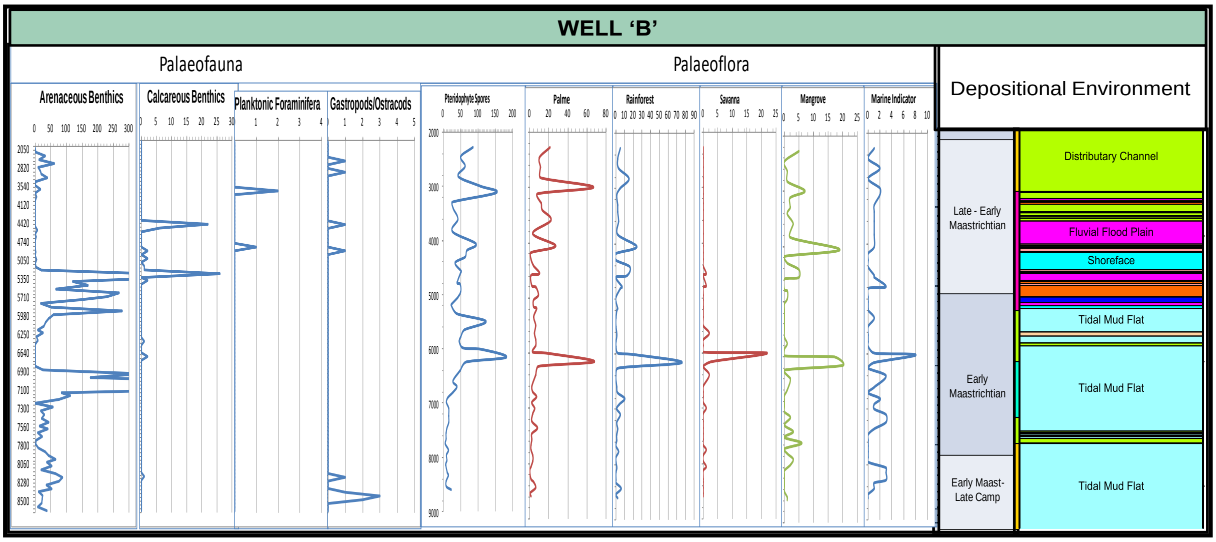

Figure 4B: Floral and Faunal distributions and Environment of Deposition from Well B in Anambra Basin

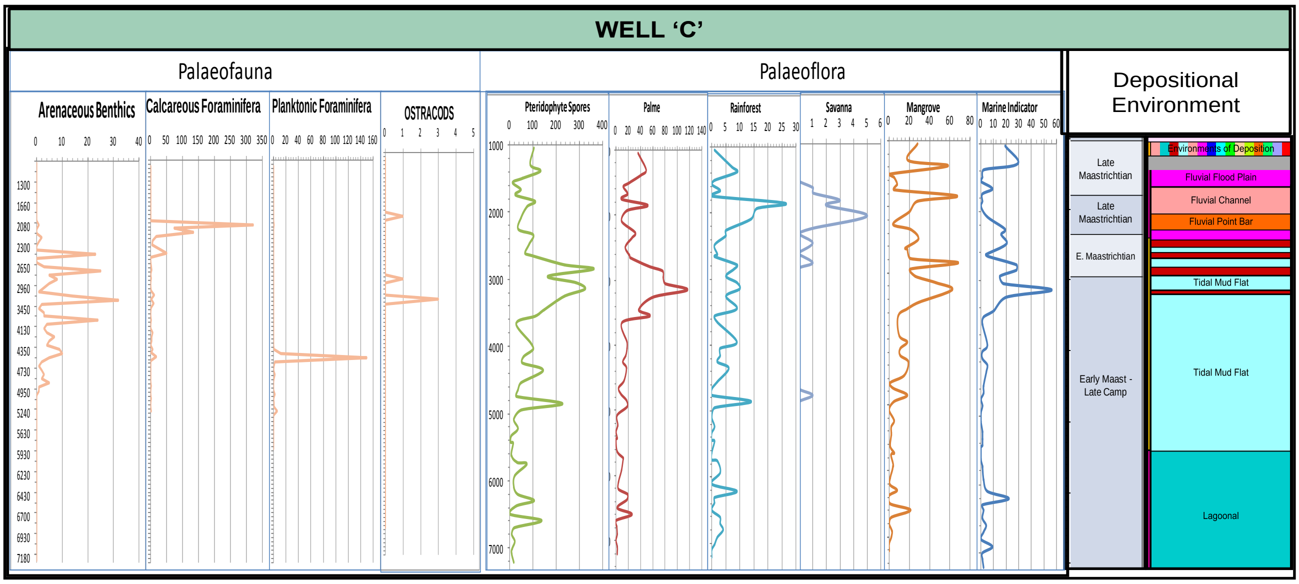

Figure 4C: Floral and Faunal distributions and Environment of Deposition from Well C in Anambra Basin

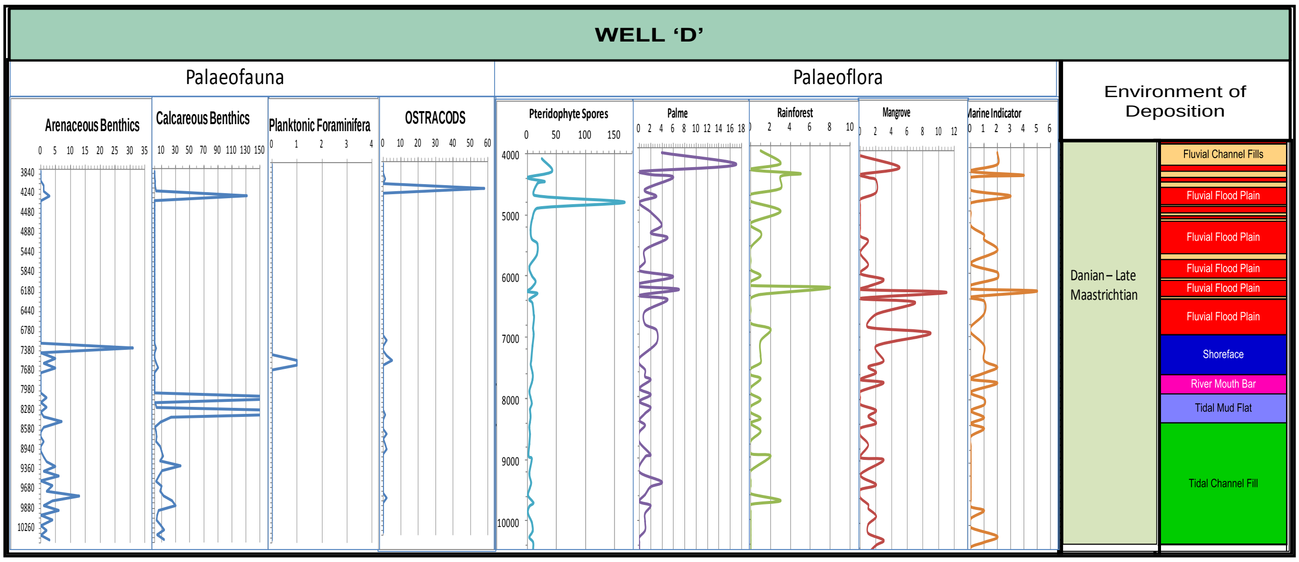

Figure 4D: Floral and Faunal distributions and Environment of Deposition from Well D in Anambra Basin

Faunal evidence indicated rare to abundant occurrences of *Anomalinoides midwayensis, A. umboniferus, Cibicides succedens, Elphidiella africana, Eponides elevatus, E. pseudoelevatus, Gavelinella danica, G. guineana, Lenticulina midwayensis* in association with *Ammobaculites spp, A. coprolithiformis, Haplophragmoides spp., H. excavata, H. sahariense, Miliammina spp, Trochammina spp., Textulariopsis gilbedina, Spiroplectammina hausorum,* amongst others, constitute the foraminiferal assemblage in this interval. The rare to common occurrences of *Haplophragmoides saheliense, H. sahariense, H. talokaense, Reophax spp. and Ammobaculites spp.,* defined this shallow inner to inner neritic paleobathymetric realm. The occurrences of these taxa are interlaced with intervals of non-recovery of foraminifera; indicative of the intermittent shoaling of palaeowater depth to non-marine palaeobathymetric regimes.

The interval studied in Well C showed that the uppermost and lowermost sections penetrated non marine sediments evidenced by fluvial channel fill, flood plain and point bar deposits in the upper section and lagoonal/estuarine deposits in the lowermost part, with no recovery of foraminifera. However, palynological suite in this section constitutes very rare to low occurrences of the savanna and mangrove taxa, but with the rare to moderately high occurrences of *pteridophyte* spores (Figure 4C). The palynofacies interpretation shows a predominance of vitrinite components over their exinite counterparts; with the inertinite components completely absent, pointing to a continental non-marine setting in the Late Maastrichtian age.

Nevertheless, the middle section of the interval (2040-5240ft), recorded some faunal and floral evidedences characterised by rare to abundant occurrences of *Bolivina explicata*, *Bolivina africana*, *Bolivina tenuicostata*, *Trochammina dutsuna*, *Haplophragmoides excavata*, *Haplophragmoides saheliense*, *Ammodiscus kiowensis*, *Textularia hockleyensis*, *Cibicides succedens*, *Planulina nacatochensis* and *Nonion* spp. These suggest sediments deposition in a predominantly inner to middle neritic palaeobathymetric with a slight deepening to outer neritic settings.

The palynofloral assemblages consists of very rare to moderately high occurrences of mangrove taxa, such as *Zonocostites spp* and *Psilatricolporites spp.*, rare to low occurrences of savanna elements such as, *Polyapollenites vacampoa* and *P. microreticulatus*, rainforest taxa, such as *Psilastephanocolporites spp.*, co-occurring with rare to high occurrences of pteridophyte spores, such as *Verrucatosporites alienus*, *Leiotriletes spp.* and *Laevigatosporites spp.* as well as low to moderately high occurrences of marine indicator palynomorphs (*Hystrichokolpoma spp.* and an indeterminate dinoflagellate cysts). The palynofacies suite indicates a higher percentage of vitrinite over the exinite; with the inertinite elements completely absent. This further suggests deposition of the sediments encountered in this interval in shallow to open marine palaeoenvironmental settings.

In Well D, sediments encountered were deposited in a non-marine (fluvial channel, river mouth bar and flood plain deposits) through shallow inner neritic (shoreface deposits) to inner/middle neritic (tidal sand bars/tidal mud flat deposits) paleobathymetric settings; in non-marine to open marine (transitional/shoreline) palaeoenvironments, as suggested by both faunal and floral distributions and assemblages. These include rare and sometimes common to abundant occurrences of *Ammobaculites spp.*, *Haplophragmoides spp.*, *Miliammina spp.*, *Nonion obducum*, *Hanzawaia concentrica*, *Anomalinoides abuillotensis*, *Valvulineria suturalis*, *V. midwayensis trochoidea* and *Nonion oyae* are associated with the rare occurrences of *Globigerina hagni*, *G. inaeqispira*, *Turborotalia cerroazulensis pomeroli*, *T. boweri*, *Globigerinatheca subconglobata micra* and *Acarinina pentacamerata* among others in the interval.

The floral assemblages in this interval consists of the very rare to low occurrences of mangrove, savanna and rainforest taxa; rare to very high occurrences of pteridophyte spores coupled with the rare to moderately high occurrences of marine-indicator taxa, suggesting a predominantly shallow marine paleoenvironmental setting; with occasional deepening, whereas in the lower part, very rare to low occurrences of pteridophyte spores, as well as the absence of savanna and freshwater algae (Figure 4D). This palyno-assemblage is suggestive of a continental/shallow marine deposit as indicated by overwhelmingly number of humic elements (inertinites predominate over the vitrinites) against their sapropelic (exinite) counterparts in the study interval.

Sequence Stratigraphic Interpretations

The sequence stratigraphic interpretation of sections in the study area was based on vertical relationships between lithofacies, palaeobathymetry, palynological and foraminiferal assemblages and on the existing stratigraphic framework of the Late Cretaceous-early Tertiary deposits in south- eastern Nigeria [18-19]. Recognition of parasequences sets and potential sequence boundaries and condensed sections, systems tracts and other stratal surfaces, including Maximum Flooding Surfaces (MFS) were recognized using published depositional models [17, 19]. Summary of the sequence stratigraphic interpretations for the studied wells are presented in the tables 2A-2D below.

Table 2A: Sequence Stratigraphic Summary of Well A

Depth Interval (ft)	Systems Tract / Key Surfaces
5610 - 5100	TST
5100 - 5100	MFS (72.0Ma)
5100 - 4820	HST
4820 - 4820	SB (71.0Ma)
4820 - 4660	LST
4660 - 4430	TST
4430 - 4430	MFS (69.5Ma)
4430 - 4117	HST

Table 2B: Sequence Stratigraphic Summary of Well B

Depth Interval (ft)	Systems Tract / Key Surfaces
8600 - 8075	TST
8075 - 8075	MFS (76.6Ma)
8075 - 7100	HST
7100 - 7100	SB (75.4Ma)
7100 - 5950	TST
5950 - 5950	MFS (72.0Ma)
5950 - 4260	HST
4260 - 4260	SB (71.0Ma)
4260 - 3780	TST
3780 - 3780	MFS (69.5Ma)
3780 - 3400	HST
3400 - 3400	SB (67.5Ma)
3400 - 2540	LST

Table 2C: Sequence Stratigraphic Summary of Well C

Depth Interval (ft)	Systems Tract / Key Surfaces
7210 - 6375	TST
6375 - 6375	MFS (76.6Ma)
6375 - 5400	HST
5400 - 5400	SB (75.4Ma)
5400 - 4550	TST
4550 - 4500	MFS (73.5Ma)
4500 - 3600	HST
3600 - 3600	SB (72.8Ma)
3600 - 3100	TST
3100 - 3100	MFS (72.0Ma)
3100 - 2500	HST
2500 - 2500	SB (71.0Ma)
2500 - 1000	LST

Table 2D: Sequence Stratigraphic Summary of Well D

Depth Interval (ft)	Systems Tract / Key Surfaces
10480 - 9750	TST
9750 - 9750	MFS (70.1Ma)
9750 - 8000	HST
8000 - 8000	SB (70.6Ma)
8000 - 7255	TST
7255 - 7255	MFS (69.5Ma)
7255 - 5260	HST
5260 - 5260	SB (67.5Ma)
5260 - 3380	LST

3380 - 1540	TST
1540 - 1540	MFS (60.0Ma)
1540 - 40	HST

The results show that Well A penetrated two candidate Maximum Flooding Surfaces (MFSs) and one Sequence Boundary (SB), dated as 72.0Ma, 69.5Ma; and 71.0Ma respectively. Well B penetrated three MFSs (76.6MA, 72.0Ma and 69.5Ma) and three SBs (75.4Ma, 71.0Ma and 67.5Ma). For Well C, three MFSs (76.6Ma, 73.5Ma and 72.0Ma) and three SBs (75.4Ma, 72.8Ma and 71.0Ma) were identified, while Well D identified three MFSs (70.1Ma, 69.5Ma and 60.0Ma) and two SBs dated 70.0Ma and 67.5Ma. A correlation of the four wells shows that Well 'B' and Well C penetrated the oldest sediments greater than 76.6Ma, while the youngest sediments, below 60.0Ma, were penetrated by Well D.

4. Discussions

The major depositional environments in the Anambra Basin include fluvial flood plain, fluvial channel, fluvial point bar, shoreface, distributary channel and tidal mud flat and lagoon. Sandstones deposition were more massive in the later part of Late Maastrichtian times, indicating prolonged period of marine regression and greater contributions in sediments deposition from the fluvial processes from distributary and tidal channels environments. Also, the Camapanian-Maastrichtian boundary indicated a termination of a prolonged period of marine transgression that brought about deposition of massive shale facies that dominated the Late Campanian time.

The depositional patterns within the Anambra Basin as observed from the studied wells show that during the Late Maastrichtian time, the sandstones facies recorded an upward thickening trend as the dominant facies, with corresponding thinning of the shale facies, derived from distributary channel deposits, tidal flood plain and shoreface deposits as observed in Wells B and C. The observed pattern was opposite in the Early Maastrichtian, with the shales being the dominant facies.

Sediments deposition during Late Maastrichtian time in the study area showed sandstones/shales facies intercalations with sandstones as dominance facies. The sandstones facies recorded an upward thickening trend, with corresponding thinning of the shale facies, as observed in Wells B and C. These were deposited as distributary channel deposits and the shales as tidal flood plain and shoreface deposits. However, the earliest Late Maastrichtian, dominant facies were shales that are thinner upward, whereas the sandstones facies thickened upwards and become blocky towards the topmost part, corresponding to Ajali Formation. These trends were observed in both Well B and Well C. The shales in these formations are generally grey to dark grey, moderately hard, blocky with rare siltstone and occasionally ferrugenised. The sandstone is light grey, fine to medium grained, occasionally coarse grained, consolidated, sub-rounded to rounded, well sorted and occasionally ferrugenised. These lithofacies are associated with ferrugenised materials and were deposited in a paleobathymetric regime that fluctuated from Non-marine through Inner and Middle to Outer Neritic during the Early-Late Maastrichtian and Late Campanian times.

These developments were also observed in the Early Maastrichtian age. Although the facies comprised of sandstones and shales, and were the dominant facies, which are interpreted as shoreface and tidal flat muds deposits in the earliest Early Maastrichtian time. The shales were thicker around the basal section and thinned upwards towards the Late Maastrichtian time in Wells B and C sections. In Well D section, the late Late Maastrichtian deposits were much younger, representing the Nsukka Formation. As observed in Well C, deposition trends in this unit were dominated by massive shales facies which continued, but thinning upward, whereas the sandstone facies, although thinning upward initially, gradually thickened from the midway and became thicker and blocky towards the end of Maastrichtian.

During Late Campanian time multiple episodes of marine transgression were observed marked by massive shales deposition episodes from combination of shoreface, tidal mud flats and flood plains, as observed in Wells A, B and C, which represent the Nkporo Shales. However, in Well B, some fluvial incursions that deposited few sandstones facies within the thick shale facies were inferred, whereas in Well C section studied, episodes of magmatic intrusions were encountered from the midway towards the basal part of the section. These were interpreted as episodes of crustal heating resulting from the Late Campanian tectonism. These may have severe implications when exploring for hydrocarbons in this area. However, it may offer the needed temperature regimes for hydrocarbons generation around the adjoining sections further away from the intrusive centers.

The observed missing sections between Well B and Well C, indicated by 72.0-75.4Ma section in Well B, and 72.0-72.8Ma, 72.0-73.5Ma, and 73.5-75.4Ma sections in Well C, are evidences of compressional or stratigraphic condensation episodes. These may correspond to periods of erosion, forced regression or unfilled incised valleys during or after sediments deposition.

The enumerated general trends are highly tentative considering that the available data covers a little portion of the entire Anambra Basin. Also, the non-availability of seismic data precluded the juxtaposition of these lithostratigraphic units with the defining structural elements as well as the lateral extent covered by the available data. Thus, the thickening/thinning trends are primarily attributed to the prevalent depositional/erosional processes at these times, coupled with the geomorphological setting of the Basin.

Generally, the sandstones deposition were more massive in the later part of Late Maastrichtian times, indicating prolonged period of marine regression and greater contributions in sediments deposition from the fluvial processes from distributary and tidal channels environments. Also, the Camapanian-Maastrichtian boundary indicated a termination of a prolonged period of marine transgression that brought about deposition of massive shale facies that dominated the Late Campanian time.

5. Conclusions

The observed depositional patterns in this study suggest that during deposition, there were possibly short episodes of marine influences in the fluvial dominated environments during the Late Maastrichtian, whereas the case was the opposite during the Early Maastrichtian time, where shales were the dominant facies. In terms of reservoir prospectivity, the study showed that the reservoirs are vertically and laterally extensive in most parts, but not generally continuous due to some syndepositional structural complexities, especially during the Early to Late Maastrichtian times that may have resulted in truncations of the processes of sediments deposition. Also, the magmatic intrusions encountered at some depths in the study area were interpreted as episodes of crustal heating resulting from the Late Campanian tectonism that may have severe implications when exploring for hydrocarbons in this area, although this may offer the needed temperature regimes for hydrocarbons generation around the adjoining sections further away from the intrusive centers.

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