BIO-ELECTROSEQUENCE INTERPRETATION OF LATE CRETACEOUS SEDIMENTS OF THE SOUTHERN BORNU BASIN, NIGERIA

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ABSTRACT

Integrated analysis that involves physical sedimentological, standard palynological and electrofacies analyses on ditch cuttings and suite of wireline logs from Gaibu–1 Well, southern Bornu were examined to identify critical sequence elements and construct a bio-sequence stratigraphical framework. Four (4) palynozones consisting of *Triorites africaensis, Cretacaeiporites scabratus - Odontochitina costata, Droseridites senonicus* and *Syncolporites/Milfordia* spp Assemblage Zones construed to be Late Cretaceous – younger successions. Nine (9) depositional sequences each with candidate maximum flooding surfaces (375, 900, 1875, 2250, 2600, 3050, 3400, 3800, 4300 m) marked by marker shales with high abundance and diversity of palynomorphs. Thus, equate with the local lithostratigraphy and global large-scale depositional cycles with candidate sequence boundaries (50, 725, 1625, 2175, 2490, 2850, 3300, 3610, 3960, 4470 m) ranging about 96.28 to 70.07 Ma. The delineated transgressive surfaces along the built sequences mark the subjected onset of marine flooding characterised with interchange of progradational to retrogradational facies. Delineated sequence elements generally show up-hole from progradational to retrogradational and aggradational that represents Lowstand Systems Tracts (LSTs), Transgressive Systems Tracts (TSTs) and Highstand Systems Tracts (HSTs) respectively. The LSTs are seen in form of prograding complex and slope fans, suggestive of good reservoirs. The TSTs consist of channel sand units and shales that depict retrogradational marine units, which could serve as both seals and source rocks for the sand units. The HSTs are made up of interplay of aggradational to progradational sediment packages that could serve as a potential source rock. The palaeoenvironmental indices depict the successions are deposited within continental to open marine settings.

KEYWORDS: Aggradational, Progradational, Retrogradational, Sequence Stratigraphic, Paleoenvironment, Palynomorph.

1.0   INTRODUCTION

The Gaibu-1 Well was drilled in the southern segment of the Bornu Sub-basin (Nigeria's portion of the mega Chad Basin), northeastern Nigeria (Figure 1). The last two to three decades have witnessed intense research and exploration efforts on the basin (Olugbemiro 1997; Adekoya *et al*. 2014), owing to the discovery of commercial quantity of hydrocarbons in the upper portion of the mega Chad Basin (Termit Basin – Harouna and Philip, 2012). While, these researches covered the basin's geo–history (Genik,1993; Hartley and Allen, 1994; Obaje *et al*. 2004), stratigraphic palynology (Ola-Buraimo 2009; Ola–Buraimo and Boboye 2011; Ola-Buraimo 2012; Ola-Buraimo and Oluwajana 2012), foraminifera biostratigraphy (Adegoke 2012; Boboye 2012) and hydrocarbon potentials (Okosun 1995; Olugbemiro *et al.* 1997; Zaborski *et al*. 1998; Obaje *et al*. 2006; Hamza *et al*. 2011; Mohammed and Tela 2012; Adegoke *et al*. 2015). Conversely, they concentrated mostly on the northern segment of the basin. This left much information gap about the sequence architecture of the subsurface successions in the southern portion of the basin in contrast to the northern region. However, the biomarker characteristics of organic matter from two wells by Moumouni *et al*. (2007), and biostratigraphic studies of Campanian – Turonian sediments by Morohunkola *et al*. (2010) remain notable researches published on the southern portion of the basin.

Van Wangoner *et al*. (1990) and Nwajide and Reijers (1996) opined that sequence stratigraphy offers a fundamental method for investigating time-rock interactions in sedimentary strata. Examination of subsurface palynoflora and sedimentological composition is a veritable means to establish sequence stratigraphic architecture and palaeo-depositional environment models from a well-control point (Giwa *et al*. 2006). Additionally, identification and visualization of stratigraphic surfaces, reservoir facies associations, strata architecture, and structural features within system tracts are easily achieved when the sequence stratigraphic approach is adopted in subsurface studies (Nwajide and Reijers 1996). This manuscript attempt integration of the recouped lithic characteristics, palynological data and wireline log dataset to construe

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facies distribution, palaeo-depositional model and bio-sequence stratigraphic framework of the late Cretaceous sedimentary strata penetrated by the Gaibu-1 Well in the southern Bornu Sub-basin, Nigeria. In addition, this research will enhance a better understanding on the lithic and biofacies compositions in support of interpretative sequence stratigraphic architecture of the southern Bornu Basin.

2.0 ORIGIN AND GEOLOGIC SETTING OF THE BORNU SUB-BASIN

The Bornu Basin forms part of the subgroup basins that make up the "West and Central African Rift Systems" (WCARS) (Fairhead 1986). The WCARS were segmented by Fairhead (1986) into two coeval and genetically related systems- the West African Rift Subsystem (WARS) and Central African Rift Subsystem (CARS). The evolution of the Bornu Sub-basin is linked with the third and failed arm of the triple junction initiated in the Albian owing to the breakup of Gondwana and the subsequent opening of the South Atlantic and the Indian Oceans (Burke et al. 1972; Burke 1976; Fairhead 1986; Fairhead and Green 1989; Fairhead and Binks 1991). Conducted geophysical investigation by early workers affirmed that the rifting was continuous and connected with the Benue rift system through the Gongola rift to the Lake Chad region (Louis 1970; Cratchley et al. 1984; Avbovbo et al. 1986; Grove 1986; Fairhead and Okereke 1987; Fairhead and Green 1989).

As postulated by Avbovbo et al. (1986), the basin's geologic setting was evolutionally enhanced by the pre–Albian, the Albian – Maastrichtian, and the Maastrichtian – Danian geological events. These threesomes led to termination and collapse of the basement as subcrustal swells, connected with sedimentation, erosion, folding, faulting and volcanism processes; cessation of the last trios in the fore-listed processes took place beneath the K-T boundary unconformity (Obaje 2009). The stratigraphy of Bornu Sub-basin has been widely studied, though with accompanied and unresolved controversies till date, especially on the lithological composition (Hamza et al. 2011; Adekoya et al. 2014). In comparison to the contiguous Benue Trough, the southern Bornu Sub-basin remains under-investigated, due to less exploratory wells and exposed outcrops. The proximity of the northern Benue Trough (see Figure 1) to the present study area where some research works have been conducted enabled some geological observations extrapolated from the previous into the southern Bornu Basin. Although other workers have shown that such inference leads to oversimplifications of geological fact and thus grossly misleading (Nwajide 2013).
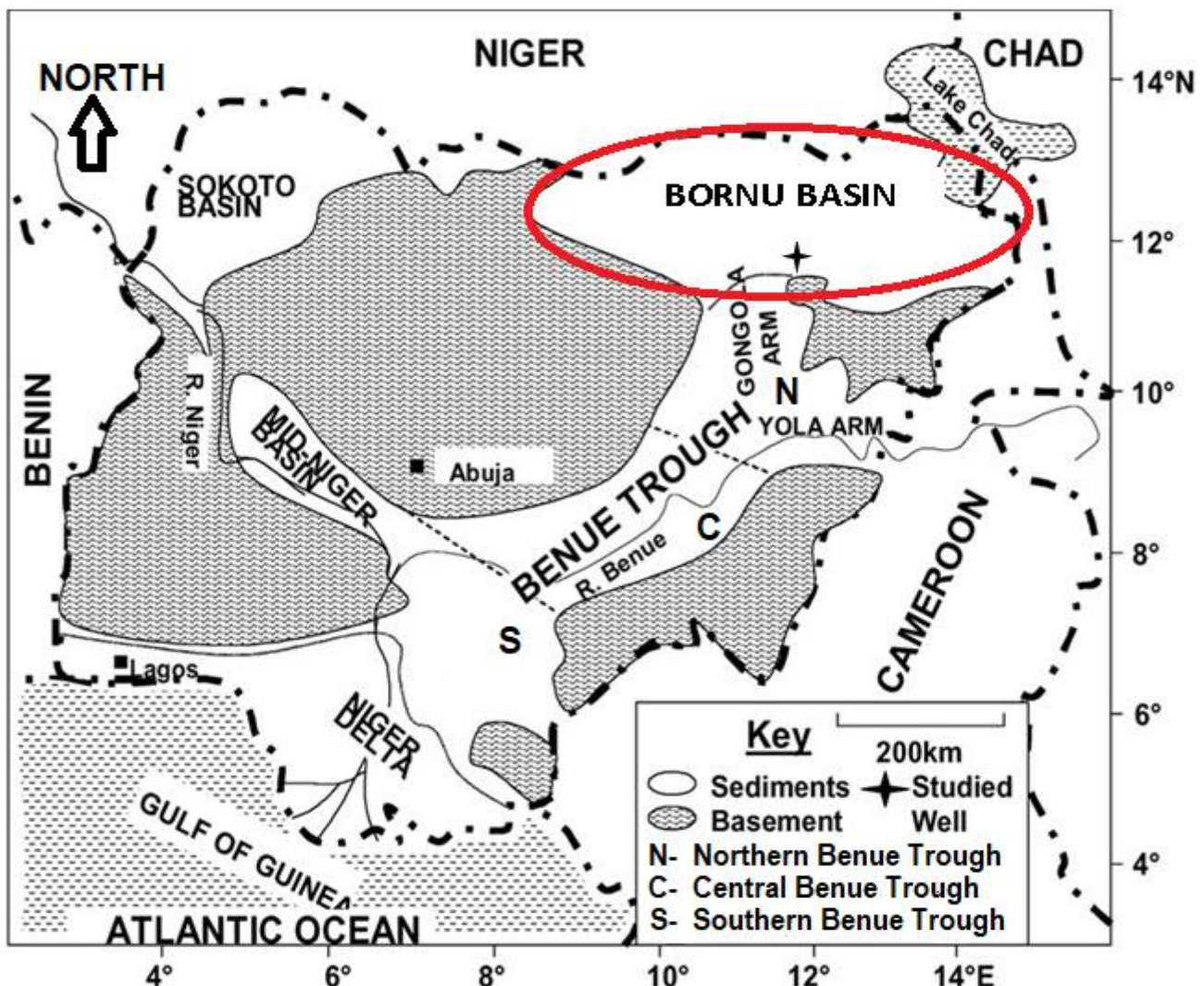

Figure. 1: Generalized geological map of Nigeria showing Bornu Basin and the location of Gaibu–1 Well (Modified after Abubakar et al. 2006).

3. MATERIALS AND METHODS

Two hundred and ten (210) ditch cuttings and a suite of wireline logs containing the spontaneous potential (SP), resistivity and gamma ray (GR) logs from the Gaibu-1 Well were used for this study. The samples (1500 to 4600 m) were composited at 200 m into sixty-four (64) samples for qualitative studies to understand downhole lithological variation and palynological events in the succession.

Sedimentological description was carried out on well-mixed samples of the stacked sediments under a binocular microscope. The textural parameters, such as grain size, shape, sorting, colour, lithology, and post depositional imprints such as ferruginised materials, fossil contents, presence of accessory minerals, carbonaceous materials were documented. The standard monograph plate of Western Atlas was used as a guide in describing textural parameters.

The International Standard for Palynological Analysis procedures for modern studies was used for recouping the palynomorphs (Moore *et al.* 1991). Exactly 15 grams of each selected samples were broken with mortar and pestle, and conveyed into respective plastic beaker. The samples were soaked and treated with 32 % of Hydrochloric acid (HCl) to eliminate possible carbonate materials and further neutralized with the addition of distilled water and decanted. This was followed by the addition of Hydrofluoric acid (40 %) to the samples to allow total digestion of silicate minerals present when left for 24 hours before decanting. The samples were further retreated with 10 % HCl to remove the Fluro-silicate compounds that might be present from earlier treatment, while completely neutralized with distilled water. The decanted samples were filtered using 125 μm mesh, while the filtrates were washed with distilled water using 10μm mesh sieve for retrieving the residues. The residues were treated with Zinc Bromide gel ($ZnBr_2$) to aid the separation of organics from inorganic materials within the residues, thereafter distilled water was added to wash off the $ZnBr_2$ and later apply centrifugation. Two drops of the residues were pipette at the centre of each labeled glass slides and allowed to dry under ultraviolet light. Petropoxy resin was used as a mounting medium before placing the glass cover slips to allow drying. The prepared palynological slides were scanned and analysed under Leitz Diaplan Microscope (Lietz Wetzlar Type).

Identified fossil flora/palynomorphs and diagnostic markers during microscopy were aided by comparing and referencing illustrations from published literatures (Jan du Chêne *et al.* 1978; Lawal and Moullade 1986; Salard-Cheboldaeff 1990) for defining the associated assemblages and zonation. Careful palynozones were established with the aid of local calibrated (interval) bioevents of First Downhole Occurrence (FDO) or Last Appearance datum (LAD) of diagnostic markers ascribed from each defined interval to prevent the caving / admixture of microfossils associated with ditch cuttings, while the ages derived were relative to the published literatures. Recouped slides, sieved and un-sieved residue were stored at Department of Applied Geology, Federal University of Technology, Akure, Nigeria.

Electrofacies analysis and determination of system tract was done on PETREL[TM] -processed wireline log data of the Gaibu-1 Well. Subsurface lithologies were mapped using lithologic logs (GR and SP logs) in conjunction with resistivity log. A number of distinctive trends representing accumulation of sediments were recognised on the GR and resistivity logs that enabled the determination of the various depositional settings and respective facies succession (Asquith and Krygowski 2004). Key stratigraphic surfaces including parasequences and parasequence stacking patterns, interpretation of sequence and system tracts were recognised from the log characters and bio-data to make-up the depositional sequences using Vail and Wornadt (1991) methods. Delineation of candidate maximum flooding surfaces (MFSs) by microfaunal horizon with the highest diversity and abundance of palynomorphs (dominant of dinoflagellates cysts) were used to constrain the gamma ray log characterised with high gamma ray, low SP, low resistivity values – this typically characterised the shaliest part of the section (Vail and Wornadt 1991). The candidate sequence boundaries (SBs) were identified at horizons of paucity to no palynomorph count relative to lowest gamma ray, corresponding high resistivity and SP signatures/values. Furthermore, Embry and Johannessen (1992) method of Transgressive – Regressive (T – R) Sequences was integrated to expatiate on the sediment supply/deposited within the systems tract delineated from Gaibu–1 Well succession.

Two methods were incorporated to determine the sandstone percentage. First, the sandstone readings were derived from the gamma-ray log motifs by mathematically subtracting from the volume of shale, given as $V_{sh} = GR_{log} – GR_{min} / GR_{max} – GR_{min}$ (Clavier *et al.* 1971). Note that V_{sh} is the volume of shale, GR_{log} is the gamma-ray log, GR_{min} is the sandstone baseline (i.e minimum gamma-ray reading) and GR_{max} is the shale baseline (i.e maximum gamma-ray reading). Further deduction was carried out on a 200 m calibrated interval of the well section to estimate the quantity and relative percentages of sandstone distribution within the depth interval following Olabode (2000) and Aziz (2013) method. The summation of sandstone percentage (Olabode 2000) was given as SdPt = (SdTh / ThIn) * 100. Sandstone percentage is (SdPt), total sandstone thickness is (SdTh) and Thickness Interval is (ThIn).

4. RESULTS AND DISCUSSION

4.1   Lithic Characteristics of Gaibu-1 Well

The samples consist predominantly of siliciclastic sediments (sand and shale) with minor marl, clays and subordinate carbonaceous materials, displaying varied textures and a wide range of colour (Table 1). An illustration of sandstone distribution based on the conducted sandstone analysis in the well is presented in Table 2, while Figure 2 shows the sandstone distribution as derived from wireline log and ditch cutting description. Statistical calculation yielded 31.96 % for the total sandstone thickness percentage in Gaibu-1 Well, thus signifying the well penetrated more shaly lithologies than sandstones (Table 2). The histogram chart (Figure 2), shows a progressive and erratic fluctuation in sandstone thickness relative to associated non-sandstone downhole. The thickest sandstone interval occurs at the depth of 2000 – 2200 m, whereas

the thinnest sandstone interval lies between 1000 – 1200 m.

4.2   Palynology

The well yielded moderately rich and fairly - preserved pollen, spores, dinoflagellate cysts and freshwater algae assemblages. A total of 89 palynomorphs species were recovered. The microfloral assemblages are preponderated by essentially land-derived forms, such as *Podocarpidities* spp*, Classopollis* spp*., Monocolpites* spp*., Tricolporopollenites* spp*., Milfordia* spp and *Cyathidites minor*. Palynozonation interpretation is generally base on the evolutionary lineage, extinction and quantitative occurrence of the palynomorphs. Four distinct palynozones- A (1) to A (4) earlier defined by previous workers were established for the investigated interval in the Gaibu-1Well (Figures 3 and 4), southern Bornu Sub-basin based on the first and last appearances of diagnostic markers (Jardiné and Magloire 1965; Willians 1975; 1977; Jan du Chêne *et al.* 1978; Lawal and Moullade 1986; Salard-Cheboldaeff 1990; Jan du Chêne 2000). The palynozones identified in the studied succession are; A (1) – *Triorites africaensis* Assemblage Zone*,* A (2) - *Cretacaeiporites scabratus / Odontochitina costata* Assemblage Zone, A (3) - *Droseridites senonicus* Assemblage Zone, A (4) - *Syncolporites/Milfordia* spp Assemblage Zone.

The A (1) and A (2) correlate with the *Bacchidium polypes* and *Triorites africaensis* Assemblage Zones of Williams (1975, 1977) and Lawal and Moullade (1986) respectively, whereas A (3) and A (4) correlate with *Surculosphaeridium lonifucatum – Cordospaeridium truncigerum* and *Cretacaeiporites scabratus – Droseridites senonicus* Assemblage Zones of Williams (1975, 1977) and Lawal and Moullade (1986) respectively (Figure 3). These palynozones are highlighted below.

Table 1: Summarized lithic characteristic, formation and respective age within the studied interval of the sequences penetrated by Gaibu–1 Well, Bornu Basin, Nigeria.

| Units	Depth(m)	Unit Description	Formation	Age
1	1500 – 1620	Light brown silty sandstone of medium to coarse grain, angular in shape, poorly sorted, intercalation of shale	Gombe	Maastrichtian
	1620 – 2660	Thickly bedded black shale that is fissile in texture, with minute portion of siltstone,	Upper Fika	Campanian - Maastrichtian
3	2660 – 2760	Brownish sandy shale, the sand are of medium to coarse grain, poorly sorted	Middle Fika	Campanian
4	2760 – 2900	Blackish grey sandy shale, the sand are of medium to coarse grain, poorly sorted & angular in shape, alternation with black shale	Lower Fika	Turonian - Santonian
5	2900 – 3450	Greyish sandy shale with reddish brown sand of fine to medium grain and poorly sorted. Its angular to subangular in shape	Gongila	Cenomanian – Turonian
6	3450 – 4600	Brownish sandy shale, the sand that is fine to very coarse grain, poorly sorted as matrix-supported with shale.	Bima	Cenomanian
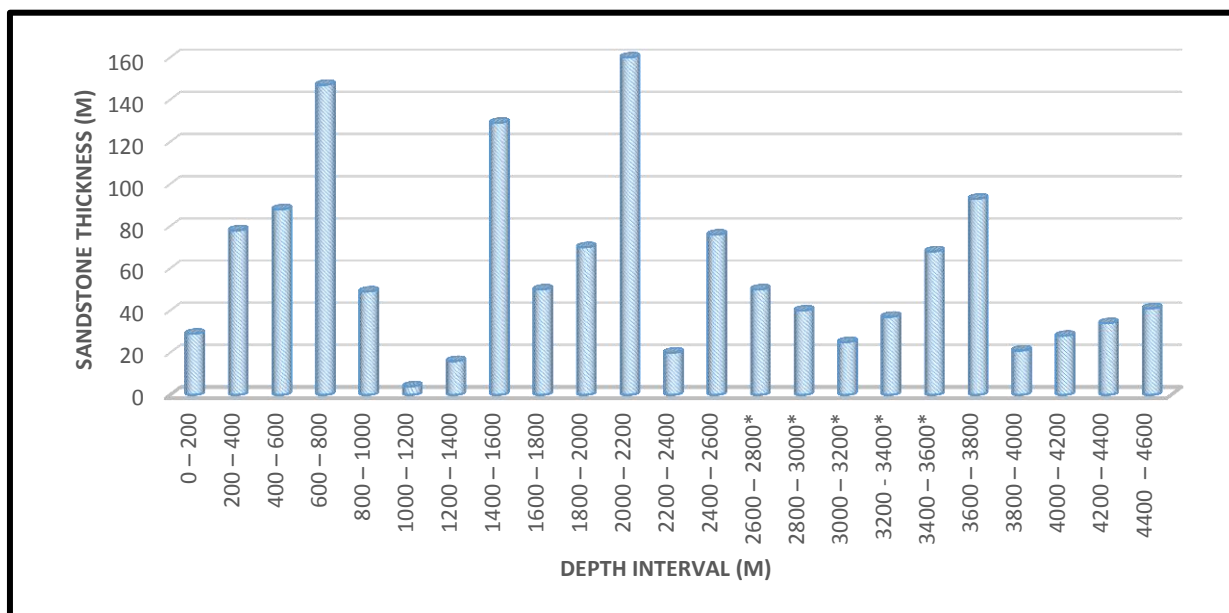
Figure 2: Sandstone thickness distribution across the Gaibu-1 Well section. Starred interval connotes sandstone thickness deduced from ditch cuttings.

Table 2: Sandstone analysis for Gaibu–1 Well, showing regular interval thickness with sandstone constituted thickness and percentage. Complement with ditch cutting data for well log section missing.

S/N	Depth interval (m)	Sandstone thickness (m)	Interval thickness (m)	Log Sandstone %	Ditch cuttings Sandstone %
1	0 – 200	29	200	14.5	No data
2	200 – 400	78	200	39	No data
3	400 – 600	83	200	41.5	No data
4	600 – 800	147	200	73.5	No data
5	800 – 1000	49	200	24.5	No data
6	1000 – 1200	4	200	2	No data
7	1200 – 1400	11	200	5.5	No data
8	1400 – 1600	129	200	64.5	70
9	1600 – 1800	50	200	25	12
10	1800 – 2000	65	200	32.5	10
11	2000 – 2200	160	200	80	85
12	2200 – 2400	15	200	7.5	9
13	2400 – 2600	76	200	38	15
14	2600 – 2800	No data	200	No data	50
15	2800 – 3000	No data	200	No data	40
16	3000 – 3200	No data	200	No data	25
17	3200 – 3400	No data	200	No data	37
18	3400 – 3600	No data	200	No data	68
19	3600 – 3800	93	200	46.5	58
20	3800 – 4000	21	200	10.5	17
21	4000 – 4200	28	200	14	13
22	4200 – 4400	34	200	17	15
23	4400 – 4600	41	200	20.5	27
Total	-	1333	4600	-	-

Total Sandstone Thickness = 1333; Total Thickness= 4600
Total Sandstone % = ((1333/4600) x 100) = **31.96%**

4.2.1   Palynological Zonation

Zone A (1): *Triorites africaensis* Assemblage Zone
Interval: 3420 – 4600 m (Figures 3 and 4)
Age: late Cenomanian

Characteristics
This is the oldest and deepest zone penetrated in Gaibu-1 well (Figure 3 and 4). The lowest limit of this zone may not be present in the interval studied, but

tentatively placed at the base of the well. The top of the zone is placed at 3420 m based on the Last Down hole Occurrence (LDO) of *Triorites africaensis* (Abubakar *et al.* 2006) and *Cicatricosporites* spp. (Jan du Chene *et al.* 1978), in the absence of *Afropolis jardinus* and *Proteacidites* cf. *africaensis*. Further associated bioevents comprise of the appearance of *Classopolis* spp, and *Cingulatisporites ornatus* with the highest abundance of *Alnus vera* (Williams 1977), thus suggest the assigned late Cenomanian age. However, this aligned with Jardine and Malgloire (1965) and Deaf *et al.* (2014) assemblage definition. Other associated taxa include *Cyathidites* spp*., Verrucatosporites* spp*., Polypodiaceoisporities* spp*., Retimonocolpites* spp., *Triporate* spp*., Retitricolpites* spp., *Cyathidites minor,* and *Retitricolporities* spp*.* In term of palynomorphs' population and diversity, the microflora recovered is quite low in gymnosperm and angiosperm pollen grains count with few counts of dinoflagellate cysts.

Zone A (2): *Cretacaeiporites scabratus - Odontochitina costata* Assemblage Zone
Interval: 2940 – 3420 m (Figures 3 and 4)
Age: Turonian

Characteristics
The top of the interval is marked by the FDO of *Odontochitina costata,* and *Cupanieidites reticularis* with relative peak abundance of *Tricolporopollenites* spp at depth interval 2940 m. The base is marked with the LDO of *Triorites africaensis* at depth interval 3420 m, further characterise by some bioevents such as abrupt

disappearance of *Proxapertites* spp, as earlier noted by Lawal and Moullade (1986) that corresponds with FDO of *Gnetaceaepollenites* spp. used as a late Cenomanian index species. This zone is similar to an acme zone of Lawal and Moullade (1986), typified by the predominance of *Cretacaeiporites scabratus* and *Cretacaeiporites mulleri*. The interval is further defined by the associated assemblages of taxa such as *Cicatricosisporites* spp*., Inaperturopollenites* spp*., Cyathidites* spp*., Psilatricolporites triangulates, Psilatricolpites* spp*., Psilatricolporities* spp*., Monosulcites* spp*., Verrucatosporites* spp*.* and *Retimonocolpites* spp*.* The characteristics of this palynozone as defined by distinctive marker taxa help to propose Turonian age to this sequence (Figures 3 and 4).

Zone A (3): *Droseridites senonicus* Assemblage Zone
Interval: 2500 – 2940 m (Figures 3 and 4)
Age: Santonian – Campanian

Characteristics
The top of this zone is marked by FDO of *Buttinia andreevii* with *Canningia capillata.* Other microspores present are *Polypodiaceoisporites retitrugatus*, *Cyathidites infectus, Monocolpites* spp., *Verrucatosporites* spp., *Tricolporopollenites* spp. and *Spiniferites ramosus.* The base of this zone is marked by the FDO of *Odontochitina costata,* and *Cupanieidites reticularis.* The presence of *Canningia capillata* shows that this section of the well is of Santonian age as proposed by Lawal (1982).
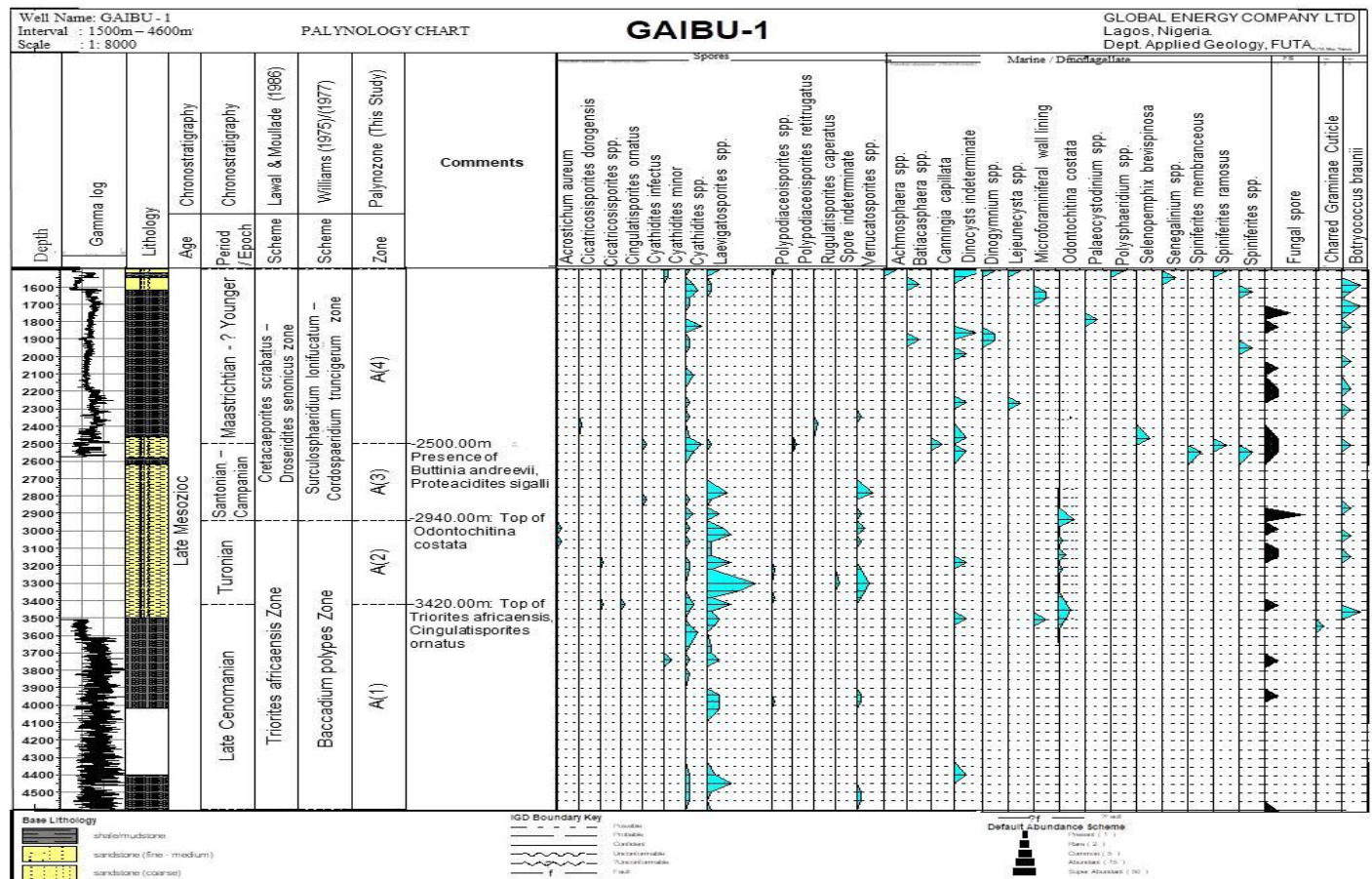

Figure 3: Spores and dinoflagellate distribution and bioevents chart for Gaibu–1 Well, incorporating the gamma ray log and interpreted lithologic log Bornu Basin, Nigeria.

Figure 4: Palynomorphs distribution and bioevents chart for Gaibu–1 Well, incorporating the gamma ray log and interpreted lithologic log Bornu Basin, Nigeria.

Owing to the paucity of palynomorphs, especially the marker species and presence of Campano-Maastrichtian species within this section could not enable enlisting the Santonian – Campanian boundary. This zone is assigned a Santonian to Campanian (Figures 3 and 4).

Zone A (4): *Syncolporites/Milfordia* spp. Assemblage Zone
Interval: 1500 – 2500 m (Figures 3 and 4)
Age: Maastrichtian - ? Younger

Characteristics
The upper limit of the study well is provisionally taken as the upper boundary/limit to this palynozone. The FDO of *Buttinia andreevii* with *Canningia capillata* were taken as the base of the interval. The interval is composed of assemblage of palynomorphs that depict Maastrichtian and younger ages. The spot occurrence of *Rugulatisporites caperatus* (a strictly Maastrichtian marker) at the base of the interval endorses this interpretation. The interval consists of *Milfordia* spp*., Monosulcites* spp*., Oligosphaeridium* spp., *Longapertities marginatus, Periretisyncolpites* spp*., Monoporites annulatus, Spiniferites* spp*., Lejeunecysta* spp*., Batiacasphaera* spp*.* and *Cyathidites* spp*.* and microplanktons such as *Senegalinium* spp*., Polysphaeridium* spp*.* and *Dinogymnium* spp*.* and microforaminiferal test lining. The composited assemblages of recouped taxa are indicative of Maastrichtian to ? Younger age (Figures 3 and 4).

4.3   Electro-Sequence Elements Interpretation
The sequence stratigraphic elements were determined with the use of deduced systems tracts and key surfaces such as transgressive surfaces, candidate maximum flooding surfaces and candidate sequence boundaries (Figures 5a and b; Table 3). Nine depositional sequences with their associated systems tracts were identified (Figures 5a and b). Observed variation in the thickness of the systems tracts suggests fluctuations in sediment accumulation rate due to erratic conditions such as availability of accommodation space, effects of gravity tectonics as well as regional and eustatic changes (Nwajide and Reijers 1996).

4.3.1   Candidate Sequence Boundary (SB)
The unconformity and the correlative submarine erosional surfaces between the sequences displayed major uppermost sequence boundaries in consonance with the assertions of Allix (1983) and Lawal and Moullade (1986), although these could not be dated due to paucity of marker taxa in this study. The base of the Gaibu–1 Well was taken to be the total depth drilled. This base consists of developing progradational parasequence set closing on the sequence boundary I (Figure 5a). The sequence boundaries (I, II, VI and IX) are major subaerial – erosional surfaces, they probably coincide with the transgressive surfaces normally connected with siliciclastic sediments (Holland 2008). They are often overlain by retrogradational to aggradational parasequences set (Figure 5a and b). Moreover, sequence boundaries (III and VIII) are the base of a probable incised valley, marked by a truncation and a basinward shift in facies. While the overlain lowstand systems tracts are of aggradational and progradational parasequence sets.

4.3.2   Lowstand Systems Tract (LST)
In this study, the lowstand systems tract are dominantly fine to medium grained sands, bounded beneath and above by sequence boundary and transgressive surface

respectively. Little imprints of ferruginisation were observed within the deposit. Two types of sediments are diagnostic of this systems tract within the studied interval – slope fans and low prograding complex (Figures 5a and b) that were relatively observed in two vertical sequences (sequence VIII and III) respectively.

The evolution of the lowstand systems tract Slope Fan (LST-SF) is interpreted to have resulted when the decrease in the rate of eustatic sea level < the rate of its associated subsidence. It is characterised by crescent shapes in distinct leveed channel unit, thickening sands and finning upwards of each channel sands from a sharp base (multistorey upward finning) in this study. This was identified within the depth interval of 1350 – 1625 m in sequence VIII (Figure 5b). The Lowstand systems tract Prograding Complex (LST-PC) develops by progradation of the slope as the relative sea level advances towards the previous shelf edge. LST-PC was identified at 3500 – 3600 m depth interval in sequence III (Figure 5a). It is typified with a shallowing upward delta or terrace, with common patterns of one or more parasequences with thick intervals of blocky sand bodies in an overall coarsening upward pattern.

4.3.3   Transgressive Systems Tract (TST)
The transgressive systems tracts composed mainly of massive transgressive (retrogradational) marine shales with retrogradational sandstone units. Thus, a finning upward sequence is connected with the transgressive systems tract (Hunt and Tucker, 1992). The transgressive episode that marks the maximum flooding surface (MFS) is the upper boundary of the TST. Condensed sections typified by high fossil abundance and diversity are developed on these surfaces. The transgressive systems tract could be taking as good source rock while sequence IX shows sandstones of good reservoir quality within the well section (Figure 5b).

4.3.4   Highstand Systems Tract (HST)
The development of highstand systems tract in this study is characterised by intervals of coarsening and shallowing upwards, it is predominant of heterolithic sediments with depositional environment ranging from transitional setting to near-shore / marginal environment. They are mostly capped by a progradational parasequence set. These strata are fairly long in extent to that of the transgressive systems tract with increase in shales and are interpreted to reflect accommodation during periods of base sea level rise. This scenario is often regarded as probable indicator of a deepening depositional facies and an organic activity-friendly environment (Embry and Johann Essen, 1992).
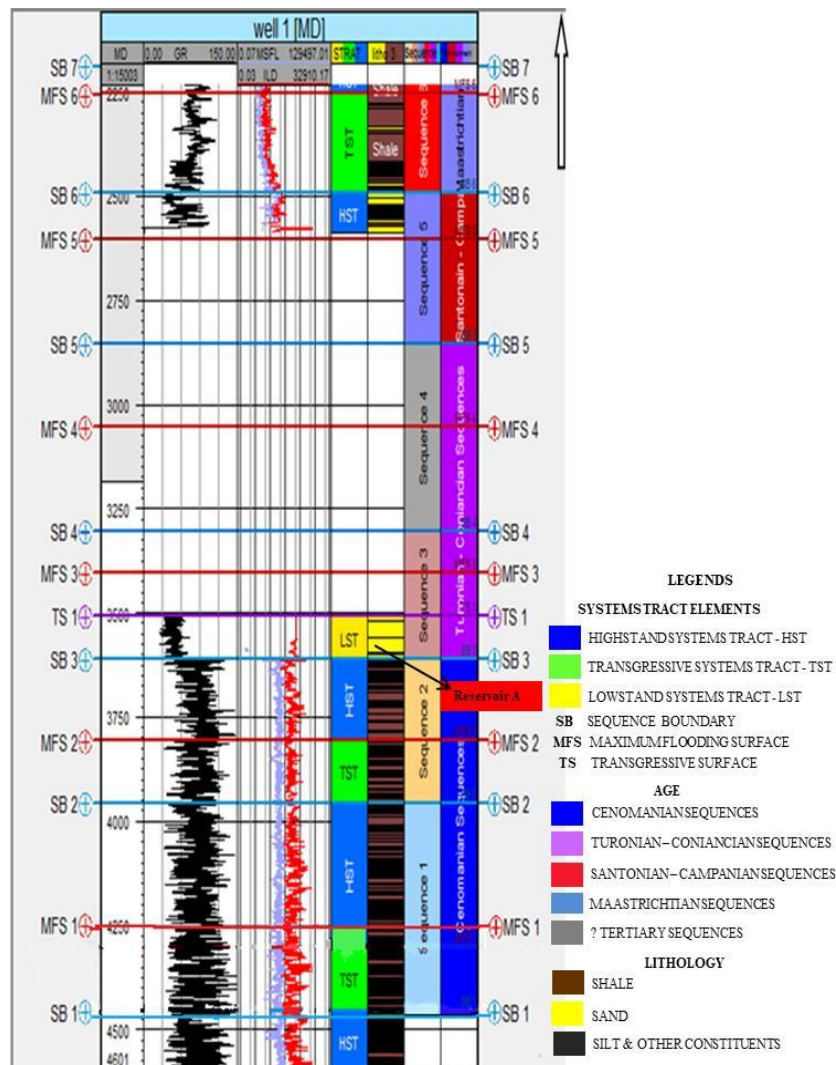

Figure 5a: Electrosequence chart for Gaibu–1 Well (2250 m – 4600 m), consisting of sequence I to sequence VII with its descriptive legend.
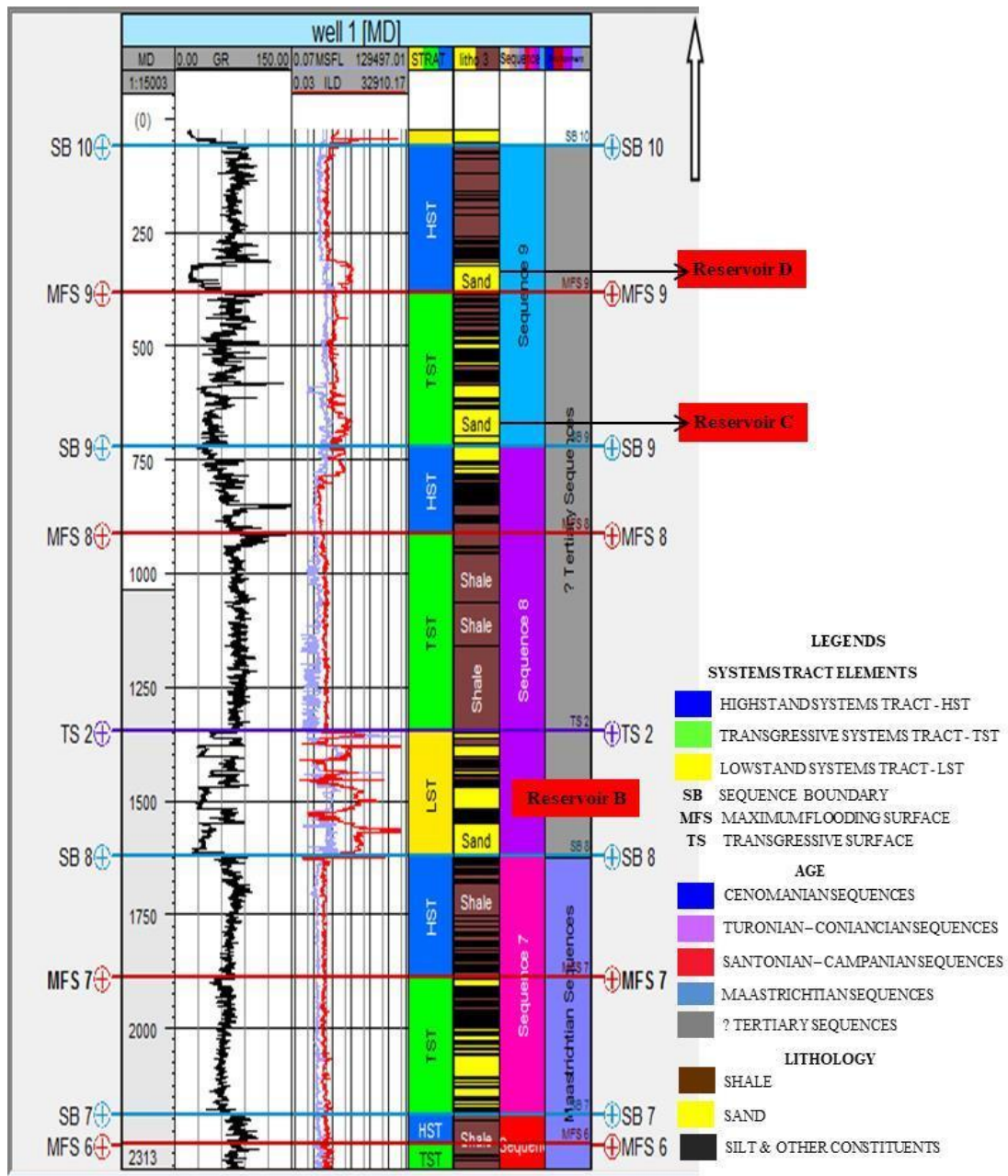
Figure 5b: Electrosequence chart for Gaibu–1 Well (0 m – 2313 m), consisting of sequence VI to sequence IX with its descriptive legend.

Table 3: Sequence stratigraphic elements mapped datum in Gaibu–1 Well.

Sequence Boundary	Bottom (m)	Transgressive Surface (m)	MFS (m)	Top (m)
9	725	-	375	50
8	1625	1350	900	725
7	2175	-	1875	1625
6	2490	-	2250	2175
5	2850	-	2600	2490
4	3300	-	3050	2850
3	3610	3500	3400	3300
2	3960	-	3800	3610
1	4470	-	4250	3960

A similar HST in the Mesozoic strata of Argentina Basin, with alternating shale and sandstone (fine to medium grained) characterising its parasequence was described by Legarreta and Uliana (1991). Minor coarsening upward and fining upward parasequences arranged in a generally aggradational to retrogradational stacking pattern are common in this current study and it suggests a highstand systems tracts deposits (Figure 5a and b).

4.4. Depositional Sequences

Nine (9) depositional sequences were recognized in the studied section of the Gaibu–1 Well (Figures 5a and b; Table 3). However, due to unrecorded log suit data between depth interval 2575 – 3500 m, depositional sequences (III, IV and V) were determined wholly from the biostratigraphic data (Figure 3; Table 4). The depositional sequences vary with their respective systems tract, sequence III and VIII show a complete

depositional sequence amidst other sequences. Each depositional sequence is distinct with their depositional packages as inferred from the log motifs, coupled with the analysed lithic characteristics of the well (Figure 6). The net sand and shale proportion in each of the sequences (Figure 6) explicitly display the major lithic / sediments constituents with their corresponding depositional sequence percentages (Figure 7). Thus, literally show respective thickness of each sequences penetrated by Gaibu-1 Well. The depositional sequence thicknesses are moderate and evenly distributed, with depositional sequence VIII is having the highest, while depositional sequences III and VI are having the lowest thickness.

Table 4: Integrated sequence stratigraphic surfaces and palynomorphs for delineation of maximum flooding surfaces and environment of deposition.

| Sequence	Interval (m)	MFS (m)	Constituent Taxa	Environment of Deposition
9	50 – 725	375	Based on the log motif (highest gamma ray value) on the Wireline log	Marginal marine
8	725 – 1625	900	Based on the log motif (highest gamma ray value) on the Wireline log	Marginal marine
7	1625 – 2175	1875	Based on the occurrence of *Dinogynmium* spp.	Open marine
6	2175 – 2490	2250	Based on the occurrence of *Dinogynmium spp, Spinizonocolpites baculatus*	Marginal marine
5	2490 – 2850	2600	Based on the occurrence of *Cyclagelospheara rotaclypeata, Cylindratlithus seratus, Spiniferities ramosus*	Marginal marine
4	2850 – 3300	3050	Based on the occurrence of palynomorphs	Marginal marine
3	3300 – 3610	3400	Based on the occurrence of *Dinigynmium* spp.	Coastal deltaic
2	3610 – 3960	3800	Based on the occurrence of palynomorphs and highest gamma ray log motif	Marginal marine
1	3960 – 4470	4250	Based on the occurrence of palynomorphs and highest gamma ray log motif	Coastal deltaic
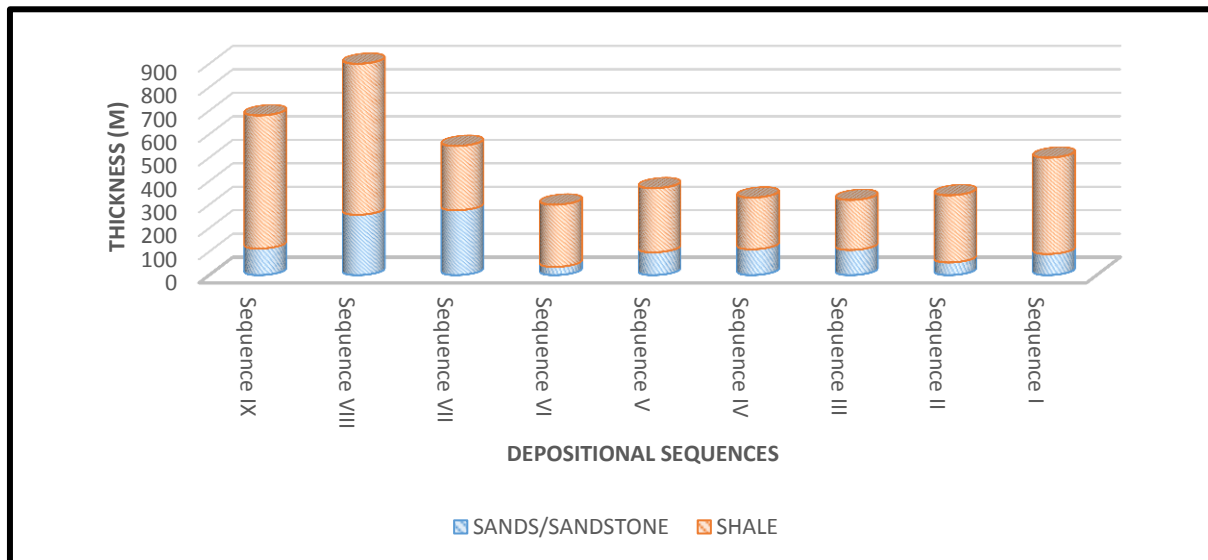
Figure 6: Net sandstone/sands and shale proportion in Gaibu–1 Well for each depositional sequences, Sequence VIII has highest sand/shale ratio thickness with highest shale proportion, sequence VII has the highest sand ratio and sequence VI has lowest sand/shale ratio and thickness.
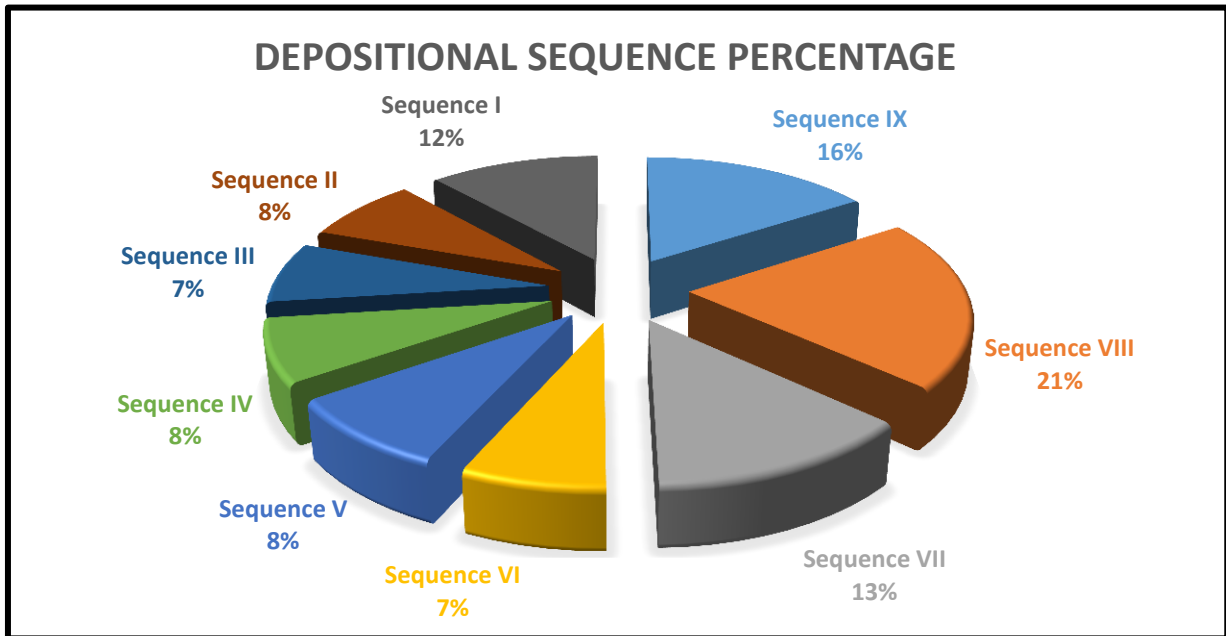
Figure 7: Depositional sequence percentage of Gaibu–1 Well, Sequence VIII has highest thickness percentage, sequence III and VI has lowest percentage thickness within the well section studied.
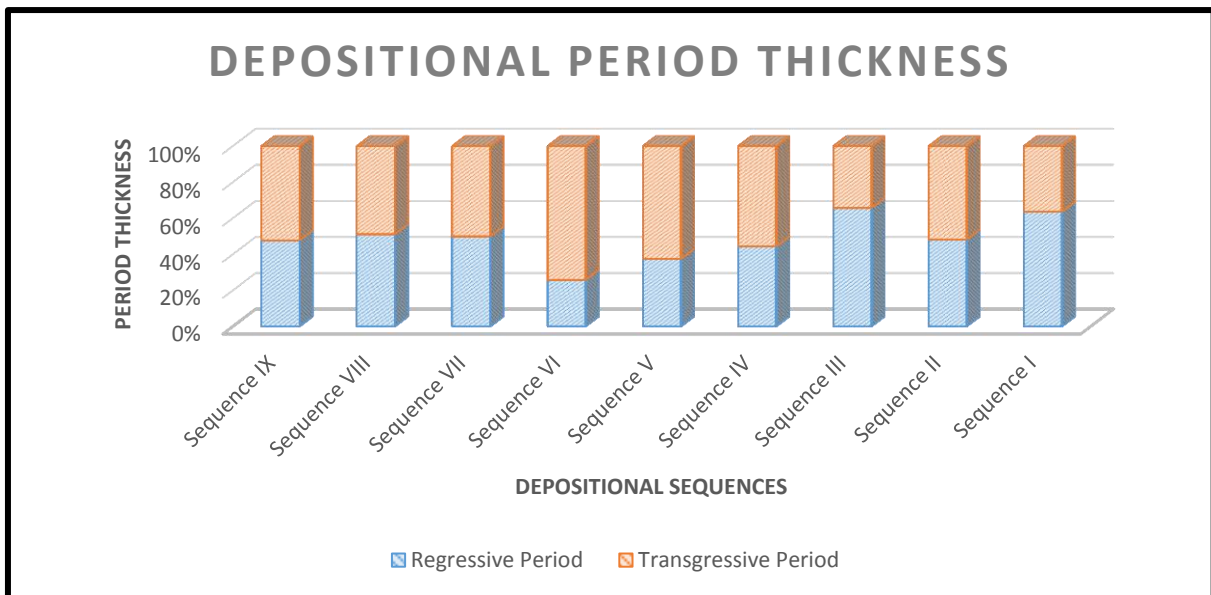

Figure 8: Depositional cycle using T – R sequences elements to highlight each period thickness up dip within the studied well section. The cycle shows even distribution pattern, while sequence III shows more dominant of normal regression event. Sequence VI has highest thickness percentage for transgressive period relative to sediment supply (Catuneanu *et al.* 2011).

The use of Transgressive – Regressive (T – R) Sequence method adequately highlighted accommodation / sediment supply events quite prominent in the transgressive period to regressive period in this study (Figures 8 and 9). Their relationship prompted a look into their sand ratio, with sequence III and VIII dominant of forestepping parasequences sands relative to sequence VI and VII dominant of backstepping parasequences sands (Figure 5a and b). However, the overall depositional sequences show how successions are typical of sediments deposited during a period of positive accommodation relative to rates space creation and sediment supply (Catuneanu *et al.* 2011).

4.5 Sequence Architecture
The LST - SF identified in sequence VIII, it consists of thick sandstone bodies characterised by multistory retrogradational parasequences of fining upward intervals, and the sands are capped by transgressive marine shales. However, the LST – PC in sequence III characterised by parasequences composing of aggrading stacking pattern of sand units, though the data was incomplete at that section. Moreover, most transgressive systems tract in this study suggest allochthonous type driving mechanism in the deposition of sediments within the sequences, possibly eustatic
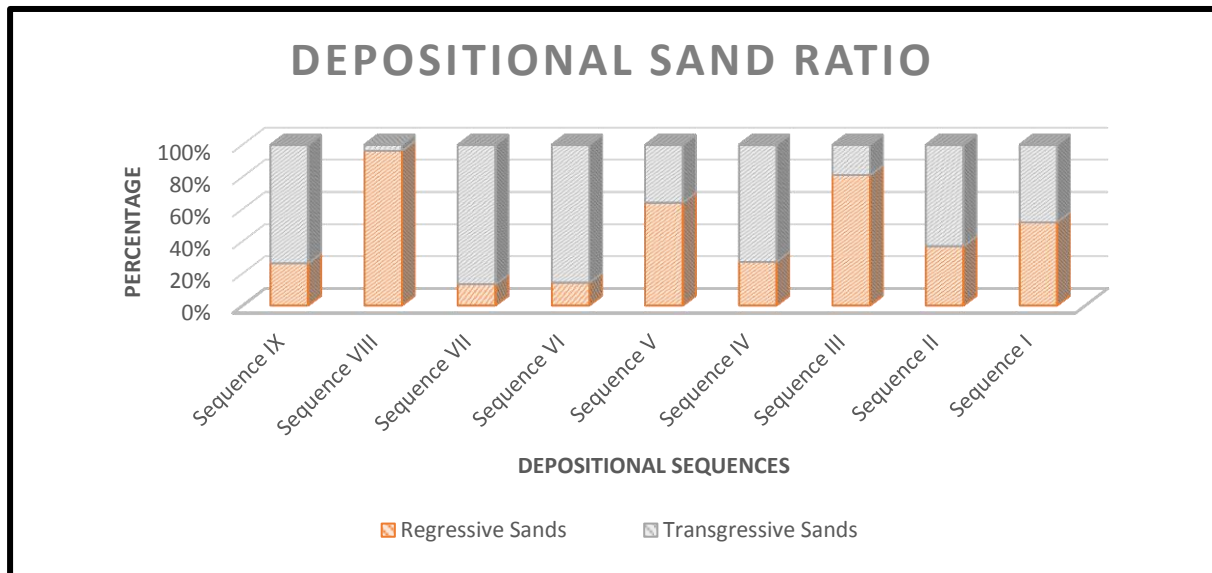
Figure 9: Depositional sand ratio percentage of both regressive and transgressive systems in Gaibu–1 Well.

change in sea level is responsible for the building of the sequence succession. However, the flooding events are buttressed by the repetitive flooding evidences reported globally (Haq *et al.*, 1988; Snedden and Liu, 2010) and thus observed in this study.

With reference to the total depth of the well, the lower section before the sequence I shows stacking patterns exhibiting upward – coarsening but predominantly interdigitated with progradational parasequence set until it closes on the candidate sequence boundary (SB). The sequence I contains only candidate MFS, and it is placed at the top of the retrograding strata based on the abundance of palynomorphs, the TST consist of heterolithic sediments (alternation of sands and shales), making the parasequences difficult to identify. The sands are relatively thin when compared with the shales. The HST consists of non - monotonous shale with good occurrence of palynomorps, exhibits a progradational parasequence set. The stacking patterns of the HST with the bio-lithic characteristics suggest a continental to marginal marine deposits during the Cenomanian period.

The sequence II is an incomplete interdigitated sequence very similar to the sequence I in its characteristics, portraying retrogradational parasequence set as it reaches the marine peak and developed a progradational parasequence set as it trends landward. The sequence III is a complete sequence bounded below by LST-PC and capped by HST though some of the well log data were not available for this study, which has hampered the best interpretation of the section. The LST is appreciably thick, indicating presence of sands that interrupted the continuity of the marginal – marine shale bodies. During this period, majorly aggrading and slight prograding sediments were common. In sequence VI, intercalation of retrograding sands and marine shales mark the beginning of transgression period in the sequence, while the HST is capped by the stacking pattern exhibiting upward shallowing lithofacies (Van Wagoner *et al.* 1990), which is indicative of regression exhibited by the landward trending of the sequence.

Sequence VII is an incomplete sequence, largely containing retrograding sands and shales which could largely associate with autochthonous sediments and capped by a prograding non-monotonous shale, truncated by an erosion to create another deposition. In complete sequence VIII, the sequence began with lowstand slope fan (LST-SF) with retrogradational patterns, characterised by thick intervals of blocky sand bodies, this occur when the rate of eustatic sea level fall becomes less than the rate of rise associated with subsidence as volumes of clastics were being transported into the basin. The multistory upward fining pattern commenced, building about four stories. Directly on top of the regressive sand in the sequence is the transgressive marine shale that is monotonous. The sequence is c apped by regressive coarsening upward sediments, with intercalated sands and shales exhibiting its parasequence set.

Sequence IX is the last observable depositional sequence in Gaibu-1 Well, the TST exhibit retrogradational parasequence set, then followed with a swift progradation parasequence set within the HST. Sequence IX could have been dominated possibly by allochthonous mechanism, the prograding sediments are moderately thickened relative to the retrograding sediment.

4.6   Chronological Sequences

In this study, electrosequence and biostratigraphic analysis helped in the delineation of nine (9) depositional sequences in line with the Global Cycle Chart of Haq *et al.* (1988) and Snedden and Liu (2010). The delineated sequences span through the Cenomanian and Maastrichtian (Figure 4 and 5).

4.6.1   Late Cenomanian Sequences

On the Global Cycle Chart of Snedden and Liu (2010), the Cenomanian age witnessed six cycles (transgression and regression) of deposition. The first major transgression occurred at its boundary with the Albian. In this work, the base of Cenomanian is assumed not reached, but four marine events were

recorded based on the biostratigraphic data, only two major events marked by (MFS I and II at 4300 m and 3810 m, respectively) could be recognized (Figure 5a). They are picked based on where a clink on the gamma ray log coincides with the occurrence of dinoflagellates (*Canningia capillata*)**.** These enabled the delineation of two sequences, sequence I and II.

Sequence I (4470 - 3960): This is an incomplete sequence characterised from the basal section with a candidate SB, below it is a HST and above is a TST that is capped by candidate MFS, which is overlain by a fairly thick HST. This sequence shows thick interdigitated signature pattern comprising thick shaly sand units in the well. The separation of the TST from the HST is based on the cyclic pattern of the resistivity log readings within the HST showing an overall progradational pattern. The candidate MFS coincide with the high abundance and diversity of the dinoflagellates at depth 4300 m (Figure 5a).

Sequence II (3960 - 3610): This sequence consists of log motif that is totally interdigitated suggesting thick shaly sand beds sequences within the TST and HST. The candidate MFS is picked based on the highest gamma - ray value within a coastal deltaic setting. The HST is clearly marked by a prograding log motif has a prograding thick body of thick shaly sands (Figure 5a).

4.6.2   Turonian – Coniancian Sequences
The Turonian – Coniancian boundary could not be distinguished in this study owing to the absence of diagnostic fossils and are therefore lumped together. During the Turonian – Coniancian five cycles of deposition are implied on the Snedden and Liu (2010) Chart. In this study, two major marine transgression events (candidate MFSs 3&4) could be recognized (Figure 5a). The candidate MFSs are bounded by two unconformities that enabled the delineation of sequences III and IV.

Sequence III (3610 - 3300): Absence of a complete wireline log within this interval makes interpretation to be based mostly on bio-data. Only the LST marked by a serrated pattern of log motif suggesting thick packet of aggrading sand unit with thin shale intercalation could be inferred on the available log. The MFS is picked based on the occurrences of palynomorphs (dinoflagellates) that are marine indices at depth 3400 m (MFS 3).

Sequence IV (3300 - 2850): Definition of this sequence was based on the occurrence of dinoflagellates, particularly in the picking of the candidate MFS at depth 3050 m. The candidate SB at the base and the top were picked by abrupt decrease in palynomorps.

4.6.3   Santonain – Campanian
The Santonain – Campanian boundary could not be defined in this study, hence they are lumped together. In Snedden and Liu (2010) Chart, 12 cycles of deposition was recognized during these two stages, beside the flooding events at their boundaries with the Coniancian below and the Maastrichtian above. Only one (candidate MFS 5) of the surfaces could be picked within Gaibu–1 Well using fossil occurrences (*Cyclagelosphaera rotaclypeata, Cylindralithus serratus, Spiniferites ramosus* and *Spiniferites* spp.). The absence of the

remaining could be as a result of widely reported exhumation events following the Santonian squeeze in the basin (Petters, 1979). In essence, only one sequence (Sequence V) could be picked within the two stages (Figure 5a).

Sequence V (2850 – 2490 m): A sharp based sand body at depth 2475 m suggests the candidate SB surface that marks the top of this sequence. The occurrence of dinoflagellate guided in picking of the candidate MFS (Figure 5a). The upper boundary of this sequence laps on the Maastrichtian sequences, marked by a relatively abundant occurrence of palynomorphs at depth 2490 m. The marine events inferred are taken to mark the onlapping event at the boundary of these two ages.

4.6.4   Maastrichtian
Two onlapping events are recognized on the Haq *et al.* (1987) Chart during the Mastrichtian as against five of Snedden and Liu (2010). Within the section dated Maastrichtian in this study, two horizons marked with log motifs and relative abundance of dinoflagellates indicate the maximum flooding events of Haq *et al* (op cit) that enabled the delineation of sequences VI and VII (Figures 3 and 5b). In addition, several other peaks are recorded on the dinoflagellate chart, which could be the minor flooding events relative to that of Snedden and Liu (2010).These are however not marked in this study.

Sequence VI (2490 - 2175): The LST is absent while the sequence consists of thick body of shales and thin sands characterised with prograding to retrograding patterns. The TST exhibits a huge thickness with a mix of prograded and retrograded sediments until the MFS is reached. The occurrence of dinoflagellates and log signature guided the picking of the candidate MFS 6. The HST has a prograding thick body of shale (Figure 5a and b).

Sequence VII (2175 - 1625): In this sequence the LST appear absent based on the log signature, while the TST consists of stacked thick sand bodies and thin shales with the sands aggrading until the maximum flooding surface is reached (Figure 5b). The candidate MFS 7 is picked based on the occurrence of dinoflagellates indicating marine event. The HST consists of stacked thin shale with thick shaly sand beds (Figure 5b).

4.6.5   Tertiary
Sequel to the biostratigraphic data, these horizons are construed to be deposited mostly during the Tertiary with relative abundance of Tertiary palynomorphs. Sequence VIII and IX are deduced based on the interpreted electrofacies within the section of the well (Figure 5b).

Sequence VIII (1625 - 725): This is a complete sequence observed in the well, consist of the three systems tracts. The LST-SF (slope fan complex) was recognized in the well, and characterised by cresent shapes of individual levee channel units, thickening and thinning upward of individual overbank sandstone from a sharp base. This is essentially a sand-rich proximal slope fan deposit exhibiting parasequence set of spiky log motifs indicative of sand-shale interbedding. In a vertical facies relationship using the parasequence sets,

the successively base parasequence set contains more shale and higher percentages of sediments deposited in deeper – water marine environments than the overlying parasequences. Meanwhile, the younger parasequence sets are composed entirely of retrograded sediments deposited on the shelf, marked by boundary traced (diagnostic resistivity signature) of the shale that characterise the transgressive surface. The TST consists of stacked thick aggraded shale of a fluvial floodplain or storm dominated shelf with thin sands that grade into retrogradation to lap on the maximum flooding surface. The HST is characterised by a progradational parasequence set, consisting of prograding thick sands and shales capped by a candidate sequence boundary.

Sequence IX (725 - 50): This is the last deducible sequence in Gaibu-1well and only the TST and the HST are clearly defined on the log. The TST consists of stacking pattern made up of an interbedded sequence of aggrading sands and shale units until it reached the candidate maximum flooding surface within shale bed. The HST has stacking patterns exhibiting progradational and retrogradational parasequences, composed of shales and sands until it reached the candidate sequence boundary.

4.7   Petroleum System Identification
Each systems tract has a predictable set of associated reservoirs, which are the main exploration targets. The use of resistivity signatures in conjunction with gamma ray logs, suggests presence of hydrocarbon bearing (reservoir) intervals (Adepelumi *et al.*, 2012). The deductions made in this study are based on the premise that relatively high resistivity log motif within sand bed suggests presence of hydrocarbon. From the electrosequence analysis carried out within the Gaibu–1 Well section. It is observed that the following depth intervals signal presence of hydrocarbon; the LST of sequence III (3500 – 3600 m) and sequence VIII (1350 – 1625 m), the TST (650 – 700 m) and the HST (325 – 375 m) of sequence IX (Figures 5a and b). These depth intervals are labelled potential reservoir A – D respectively.

Quite a number of sand beds within the lowstand systems tract do contain large quantities of hydrocarbon (Kingston *et al.*, 1983). The lowstand systems tract in sequence VIII (reservoir B), consist of sand and shale bounded below and above by a thick sequence of shale of transgressive and highstand systems tract respectively (Figure 5b). The high resistivity motif suggests presence of hydrocarbon, the reservoir thickness appear thick but relatively the above shale could serve as a seal. Although this applicable to reservoir A, is deposited within shallow marine environment with crescentic curve (Figure 5a), enclosed below and above (from lithological examination) by a thick marginal marine shale that could serve as the source rock and seal. The thin shale above probable reservoir C & D (Figure 5b) may not have good capacity as a seal that could have led to a secondary migration of hydrocarbon.

The TST and the HST of both sequence VI (2175 – 2500 m) and sequence IX (50 – 275 m) (Figure 5b), show indication of hydrocarbon reflection. The organic

rich shales that are commonly associated with the transgressive marine shales may provide a petroleum source rock as well as regional seal, while the transgressive sands and highstand sands characterised with boxcar/irregular shape and funnel shape respectively could be served as a reservoir. The black shale within interval (925 – 1350 m) could be a potential source rock, while the sand packets within depth interval (2500 – 2575 m) with high resistivity could be a potential reservoir. Lithologically, the physical properties of the selected intervals above, add some clues to the highlighted hydrocarbon potentials within the studied well as in terms of source and reservoir rocks (Table 1). This study is of the view that the lower section of the well could be a potential source rocks and create a sealing effect for the sand beds enclosed, while the upper section could be potential reservoirs.

5.0   CONCLUSION
The integrated analyses of the downhole log signatures, the lithic chracterisation and the recouped abundance and diversity of palynomorphs has helped to elucidate the bio–sequence stratigraphic framework of southern Bornu Basin. The lithic characteristics show different composition of siliciclastic rocks (Shales, Sands and Silts) penetrated by Gaibu-1 Well. The palynozones established are: *Triorites africaensis*, *Cretacaeiporites scabratus – Odontochitina costata*, *Droseridites senonicus* and *Syncolporites/Milfordia* spp. Assemblage Zones. Thus, describing the chronostratigraphic framework and paleo - biostratigraphical events of the siliciclastic facies to span through Late Cenomanian to Maastrichtian (younger).

The delineated nine (9) depositional sequences chronologically bounded within age range of about 96.28 Ma to 70.07 Ma comprising of ten (10) candidate sequence boundaries and nine (9) candidate maximum flooding surfaces with their respective systems tracts elucidating the lithofacies characterisation and depositional trend of the well. The palaeoenvironmental proxies depict environmental settings ranged from continental, marginal marine to open marine. The alternation of sands and shales within the sequences possibly provides the combination of source, reservoir and cap rocks that are essential for hydrocarbon generation, accumulation and trapping. The Shales consisting most of the candidate MFSs could be suggestive of seals and potential source rocks, thus indicating presence of stratigraphic traps for hydrocarbon if all criteria are met. Moreover, the high resistivity values from the log suggest potential good reservoirs.

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