Late Cretaceous Palynostratigraphy of Subsurface Sediments of Southern Bornu Basin, Nigeria: Implications For Depositional Environments And Palaeoclimate.

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Abstract

Presented in this study are the findings of a cross-examination of the subsurface stratigraphic successions (1500-4600 m) penetrated by the Gaibu-1 well, Bornu Basin, NE Nigeria to understand the palaeoenvironmental settings and the palaeoclimatic conditions of the sediments. Sedimentological/textural description, lithological identification and palynological analysis were carried out using standard laboratory procedures and wireline (gamma-ray and SP) logs. The sediments consist predominantly of sandstone, siltstone, sandy shale, and shale. The sandstones range from fine-coarse, angular to sub-rounded, moderate to poorly sorted, and are texturally immature. Five (5) stratigraphic sub-divisions; the Bima, the Yolde, the Gongila, the Fika (Upper, Middle and Lower members) and the Gombe formations were identified. The palynozonation enabled four distinctive zones: (i) A (1) *Triorites africaensis* Assemblage Zone, (ii) A (2) *Cretacaeiporites scabratus / Odontochitina costata* Assemblage Zone, (iii) A (3) *Droseridites senonicus* Assemblage Zone, A (4) *Syncolporites/Milfordia spp.* Assemblage Zone. These suggest the well penetrated Cenomanian – Maastrichtian (younger) successions, interpreted to have been deposited in a series of continental to marginal marine environments. The sediments are characterised by palynofloral assemblages that are indicative of a tropical to subtropical climate condition that is warm and humid, which correspond to the late Cretaceous Palmae Province of Africa – Southern America.

Introduction

The Bornu Basin (Fig. 1), which occupies the north-eastern area of the Nigeria crustal mass has attracted significant research attention following the need and efforts of the Nigerian government to expand the nation's hydrocarbon reserve (e.g., Adegoke et al. 1978, 1986; Adepelumi et al. 2011; Alalade and Tyson, 2010; Avbobvo et al. 1986; Odusina et al. 1983; Olugbemiro, 1997). Despite these research efforts, the stratigraphic relationship of the sequences within the basin is yet to be well-understood (see Fig. 2). Documented palynological studies were locally interpreted (Adegoke et al. 1973; Adegoke, 2012; Boboye, 2012; Ola-Buraimo, 2013a, 2013b; Ola-Buraimo and Boboye, 2011; Ola-Buraimo and Oluwajana, 2012). Hence, there are still gaps for holistic conclusions to be reached. Previous biostratigraphic studies were mainly concentrated in the northern part of the basin (e.g., Adegoke, 2012; Boboye, 2012; Ola-Buraimo, 2012; Ola-Buraimo and Boboye, 2011; Ola-Buraimo and Oluwajana, 2012). Therefore, inferring the biostratigraphic signatures of the southern segment from these findings could be misleading, owing to the significant distance between the two reaches. This study is an attempt to enhance the current understanding of the litho-characteristics and chronostratigraphic framework of the southern part of the basin. Specifically, the study described the lithological characteristics of the penetrated sequences, detailed the stratigraphic age and framework with their respective palaeoenvironments of deposition as well as predicts the prevailing palaeoclimatic conditions of sediments encountered in the southern Bornu Basin, Northeastern, Nigeria.

Geological Framework Of The Bornu Basin

The Bornu Basin (Bornu sub-Basin of Nwajide 2013) represents the southern axis of the mega Chad Basin (Adekoya et al. 2014; Alalade and Tyson, 2013; Obaje et al. 2004) that lies exclusively within the north-eastern Nigeria landmass. It is approximately one-tenth of the Chad Basin, and underlies the entire landmass of the Bornu State, a portion of Yobe, Gombe, and Bauchi States in Nigeria (Obaje, 2009). The Cretaceous-Tertiary rift systems in Chad, Niger and the Central African Republic (CAR) constitute a significant portion of the "West and Central African Rift System" (WCARS) (Fairhead, 1986; 1988; Genk, 1993; Popoff, 1988). The evolution of WCARS is linked with the 120–130 Ma fragmentation of the Gondwanaland, and the subsequent openings of the South Atlantic and the Indian Oceans (Burke, 1976; Fairhead, 1986; Guiraud and Maurin, 1991; 1992; Genk, 1993). It is segmented into two coevals of substantially disconnected yet intrinsically related rift subsystems: The West African Rift Subsystem (WARS) and Central African Rift Subsystem (CARS).

The regional stratigraphical framework and tectonic development of the Cretaceous - Tertiary rift basins across the crustal landmasses in Niger, Chad and the CAR, as postulated by Genik (1992) support the earlier proposed concept of Fairhead (1986). The extension of laterally displaced oceanic crust into the African plate occasioned the orthogonal extension that initiated the Niger and Sudanese rifts (Ibid). Tectonically, the Chad Basin evolved during the development of the WARS basins, and the process involved four distinctive phases (Ibid). The consensus among earlier workers is that the WCARS was produced by rifting and strike-slip displacement (see Avbovbo et al. 1986; Hartley and Allen, 1994; Wilson and Guiraud, 1992). The persistence of the WARS rift basins and their genetic connectivity to the CARS have been the subjects of different geophysical investigations (e.g., Avbovbo et al. 1986; Ofoegbu and Okereke, 1990). Notably, Cratchley et al. (1984) indicated that the rift system of the Benue Aulacogen extends through the Gongola Arm to the Lake Chad region (Fig. 1).

Though highly controversial, the stratigraphy of the Bornu Basin is subdivided into groups and formations that range from Albian to Holocene (Fig. 2; Adegoke et al. 1978; Okosun, 1995; Ola-Buraimo and Oluwajana, 2012; Omosanya et al. 2011; Petters, 1981; Whiteman, 1982). Figure 2 presents the major consensus that is also partly validated in this current study. The Cenomanian marginal marine and sparsely fossiliferous Bima Formation, which is lithologically composed of sandstone, shale, and clay unconformably overlies the Precambrian basement rocks. The Bima Formation is generally documented to be overlain by calcareous shales and sandstones of the Gongila Formation, which alludes the onset of the marine incursion into the Bornu Basin (Obaje et al. 1999, 2004; Olugbemiro et al. 1997; Moumouni et al. 2007). The Yolde Formation identified in between the Bima and the Gongila in this study was hardly reported earlier workers (Fig. 2). The overlying marine Fika Formation comprises of shales and sands and possesses some complexity in its lithofacies that enables its differentiation into three subdivisions (Fig. 2). The overlying mid-late Maastrichtian deltaic-estuarine successions of the Gombe Formation were merged with the underlying Fika Formation by Okosun (1995) in a review. However, the successions in the Gaibu-1 alludes to the presence of the Gombe Formation in the basin, in agreement with earlier workers (see Fig. 2). Though, lumped with the underlying Palaeocene Kerri-Kerri Formation by Avbovbo (1986), the Pliocene-Pleistocene lacustrine Chad Formation dominated by clayey lithologies is generally regarded uppermost litho sequence in the basin (Fig. 2).

Materials And Methods

The vertically drilled Gaibu-1 Well bored through a total depth of 4620 m of dominantly siliciclastic detritus. Recovered ditch cuttings, self-potential and gamma-ray logs from the Gaibu-1 were used for this study. A total of two hundred and ten (210) ditch cuttings retrieved from the depth interval of 1500–4600 m of the well were serially arranged and washed in distilled water to remove possible drilling mud/contaminants. Lithological description of samples was done using a binocular microscope as aid, following the method of Ola and Adepehin (2017). The standard textural comparator of Western Atlas was used to guide the textural descriptions; colours, lithologies, grain sizes, degrees of roundness or angularity, sorting, ferruginous content, fossil contents, and accessory minerals. Carbonate contents in the ditch cuttings were tested using dilute hydrochloric acid (HCl).

Palynological analysis was conducted on selected ditch cuttings at 30 m intervals of the Gaibu-1 Well. The samples were washed through a 5µm polyester sieve with distilled water to remove chemical contaminants that were perchance bypassed by the earlier washing. The washed samples were dried in a preset (50^{o}C) oven for 24 hours. Ten grams of the dried samples were thereafter digested using 10% HCl to remove carbonates. The dried samples were soaked in 60% Hydrofluoric acid (HF) for 24 hours to digest the silica content. The dissolved solution was sieve washed using a 5µm sieve in a running tap, and then oxidised in Schulze solution for 30 minutes. At the expiration of 30 minutes, 10% Potassium hydroxide was used to wash the samples before zinc bromide (Zn_2Br_4), a heavy liquid was used for separation through the process of centrifugation. Polyvinyl alcohol was used to disperse the aliquots, which was thereafter dried and then mounted on glass slides with the aid of Norland mountant. The microscopic examination involved the identification and counting of pollens, spores, dinoflagellates, and algae for subsequent chronostratigraphic biozonation and analysis. Nikon P6000 digital camera was used to photograph imperative palynomorphs (see Appendix 1).

Results And Discussion

4.1. Sedimentological and Lithofacies Descriptions

The lithological units encountered between 1500 m to 4600 m interval of the well are summarised in Fig. 3. Five main lithounits were identified; these include, sand-shale heterolith, sand, shale, gypsiferous shaly sand, and silty clay. The heterolithic unit is very thickly bedded and of similar characteristics to those described by Odusina et al. (1983), Avbovbo et al. (1986) and Olugbemiro (1997) in Kanadi and Albarka wells, Ola–Buraimo and Boboye (2011) in Tuma – 1 well, and Ayinla et al. (2013) in Kemar – 1 well. The shale constituent is brownish to greyish, while the sand component is fine to coarse-grained, angular to subrounded shape and poorly sorted grains, with varying shale/sand ratio at different intervals. The occurrence of the unit is limited to the lower and the middle horizons of the well, at the 4450–4600 m, 3750–3850 m, and 2700–2850 m intervals (Fig. 3).

The sand lithofacies occurs as a medium to thickly bedded units, distributed within the stratigraphic intervals of the well and often intercalated with other facies (Fig. 3). It is fine to very coarse-grained, subangular to rounded in shape and moderate to poorly sorted, generally characterised by off white to reddish-brown colouration. The shale lithofacies are very prominent within the penetrated sequences of the Gaibu – 1 well, this facies is more predominant in the middle part of the well (Fig. 3). Thick to very thick-bedded black shale is present within 1620–2660 m and 2760–2900 m intervals. Shale lithofacies at 3450–3520 m and 2660–2750 m intervals of the well are medium to thickly bedded, greyish to brownish, fissile, and relatively ferruginised.

The gypsiferous sandy-shale is not common in the stratigraphic section of the well, its occurrences are mainly within the 3500–3600 m and 2450–2580 m intervals (Fig. 3). The lithofacies is characterised by frequent pale greyish to blackish pigments on the shaly components whereas the sandy parts are of fine to coarse grains, angular to subangular and poorly sorted. Estimated percentage of sand/shale/gypsum ratio in this unit is 31:59:10. The silty clay lithofacies is fairly present at the lower and upper part of the well and typified by brownish coloured grains, and some ferruginisation imprints. The lithofacies occurs at depths of 3450–3460m, 1650–1710m and 1540–1590 m, and as rare intercalations with shale beds (Fig. 3). Presented below are the detailed descriptions of the encountered lithostratigphic intervals based on lithology, palynomorphs' distribution and bioevent charts (Figs. 3–5).

4.1.1. Bima Formation

This is the oldest stratigraphic unit in the study area, and it represents the basalmost penetrated unit by the Gaibu-1 well. It occurs within the 3700 to 4600 m interval with an estimated 900m thick unit (Fig. 3). The Bima Formation primarily consists of shaly sandstone and sand-shale heterolith. The sands are brownish, poorly sorted, fine to coarse-grained and moderate to largely supported by the fissile shale units. The ferruginised clay units at the upper end (3700 to 3790 m) of the formation in this study occur as intercalation with greyish sand – shale heterolith units. The sand grains are predominantly medium-grained and sub-angular to subrounded at the lower end (Fig. 3). This interval consists of some land derived forms (*Cyathidites minor*) with the sparse occurrence of marine species such as fungal and dinocyst indeterminate (see Fig. 4–5). Thus, suggesting, a distinct continental to brackish setting. This formation correlates to the Middle - Upper Bima subdivisions of Guiraud (1990), and the Bima Sandstone of Okosun (1995).

4.1.2. Yolde Formation

This formation represents transitional deposit that conformably overlies the Bima Formation. It occurs within the depth interval of 3350–3700 m (Fig. 3) in the Well. The Yolde Formation is predominantly characterised by interbeds of brownish-greyish sands, siltstone, and thin-bedded reddish shale with the occurrences of subordinate carbonaceous and ferruginous materials. The sands are medium to coarse-grained, moderately to poorly sorted, angular to sub-angular in shape. The depositional environment of the lithofacies is interpreted to range from lagoonal estuarine to marginal marine environments due to the occurrence of non-marine palynomorphs, such as *Laevigatosporites spp*, and *Cyathidites minor* (see

Fig. 4). *Botryococcus braunii*, fungal spore and dinocyst indeterminate, which are major marine palynomorphs found in the overlying successions were not found within the analysed detritus of the Yolde Formation (Figs. 4 and 5). Yolde Formation has not been frequently mentioned in the stratigraphy of the Bornu Basin (Fig. 2). However, the presence of this lithofacies in the Gaibu-1 Well, attests to its presence in the southern Bornu Basin. The lithological characteristics of this interval correlates to Akande et al. (1998)'s description of the Yolde Formation in the contiguous Gongola Arm of the Northern Benue Trough (see Fig. 1). The naming of this Formation in other exploration wells (e.g.,, Kinasar-1, Saa-1, Wadi-1, Murshe-1, Ziye-1) drilled in the southern Bornu Basin by Adekoya et al. (2014) further attest to its presence in the sedimentary successions of the Southern Bornu Basin.

4.1.3. Gongila Formation

The Gongila Formation occurs between 2950–3350 m in the well. It overlies the Yolde Formation. It consists of reddish-brown, ferruginised sandy shale sequences with minute occurrence of carbonaceous detritus (Figs. 3 and 4). This 400 m thick greyish shale contains very thin interbeds of sands. The sands are fine to medium grain, sub-angular in shape. The formation is characterised as a marginal marine to inner shelf deposit based on the occurrences of non-marine taxa (*Cyathidites spp., Cyathidites infectus, Longaperities marginatus*) and marine palynomorphs (*Spiniferites membranceous, Botryococcus braunii, Odontochitina costata*). It is remarkable that volcanic intrusive independently reported by Alalade and Tyson (2013), Ilozobhie et al. (2015) and Okosun (1995) in the Gongila Formation is not seen in the studied Well. Thus, the intrusion must have been localised to the northern and northeastern parts of the basin.

4.1.4. Fika Shale

The Fika Shale spans the depth of 1620–2950 m with an estimated thickness of 1330 m, it lies conformably on the Gongila Formation (Figs. 3 and 4). Careful sedimentological description of ditch cuttings within this interval revealed that the formation is not entirely shaly as previously documented by earlier authors based on wells from the northern segment of the basin (see Okosun, 1995; Olugbemiro et al. 1997), but rather shows intercalation with essentially siliciclastic sandstone and silty materials (Moumouni et al. 2007). We subdivided the Fika Shale into three (3) units based on observed physical and textural characteristics. The depth interval of 2550–2950 m marked the lowermost part of the sequence that contains greyish, coarse-grained, poorly sorted, and vividly angular shaly sand with off-white sandstone (Fig. 2).

The middle part of the sequence is characterised by black sandy shale deposited between 1900 and 2550 m, with the sands characterised by medium to coarse-grained, subangular, and poorly sorted materials. The uppermost part comprises of thick greyish to brownish shale unit between intervals 1620–1900 m. It consists of minute brownish, medium to coarse-grained, subrounded geometry and moderately sorted sandstone/sand. The unit is capped by ~ 30 m of calcareous siltstone (Figs. 3 and 4). Gypsum sporadically occurs as an accessory mineral. The palaeoenvironment of deposition of the formation is suggested to be mainly marginal marine due to the presence of palynomorphs such as *Cyathidites ssp,* *Psilatricolporites triangulates, Psilatricolpites spp., Retimonocolpites spp* with the occurrence of *Odontochitina costata* and *Botryococcus* that are marine-derived forms (Figs. 4 and 5). However, transporting medium might be of relatively high energy and erosive in nature (turbidity currents) which might be responsible for the presence of coarser particles in the shale during deposition. The recorded thickness conforms with earlier workers (see Carter et al. 1963; Moumouni et al. 2007; Okosun, 1995; Olugbemiro, 1997).

4.1.5. Gombe Formation

The Gombe Formation occurs within the interval 1500–1620 m with an estimated thickness of 120 m (Figs. 3 and 4). The formation consists of a basal sandstone unit intercalated with thin beds of shale at the lower part of the interval (Fig. 3). The sand is reddish-brown in colour, medium to coarse in grain size, sub-angular to angular in shape and poorly sorted. Significant amounts of reddish sands are distributed within the interval. The interplay between the colour composition of the sediments and the visible grain sizes,in addition to the presence of palynomorphs such as *Milfordia spp, Monosulcites spp., Oligosphaeridium spp Longapertities marginatus, Periretisyncolpites spp, Monoporites annulatus* characteristically suggest an environment of deposition indicative of distal continental to proximal fluviatile (Figs. 4 and 5). The Gombe Formation was recorded missing in some selected wells (including Gaibu-1) by Moumouni et al. (2007). However, our data has shown that the formation is present in the Gaibu-1 Well.

4.2. Palynological Assessment and Palynostratigraphy

Recovered palynomorphs are fairly preserved and the miospore recovery is moderate to barren at different intervals (Figs. 4 and 5). The species that are of well-known stratigraphic ranges in other contemporaneous basins of Western Africa (see Lawal and Moullade, 1986; Deaf et al., 2014) and Northern South America (see Herngreen, 1973; Germeraad et al. 1968) were used as a guide in deducing the biozones (Fig. 6). Recovered palynomorphs were classified into four major groups based on their botanical affinity, which are, (i) angiosperm pollen, (ii) gymnosperm pollen, (iii) spores, and (iv) dinoflagellate cysts. These, respectively represent an estimated 48.40%, 26.39%, 16.97% and 8.24% of the total recovered taxa (Fig. 7A). Constructed palynomorphs' frequency distribution chart (Fig. 7B) indicated that angiosperm pollens dominated the recovered forms across the five stratigraphic intervals (formations), having its peak in the 2950–3350 m interval, which corresponds to the Gongila Formation (see Figs. 3 and 7B). Like the angiosperm, the gymnosperm, and spores both peaked at the 2950–3350 m interval. Though it is generally of lesser frequency compared to the other three palynomorph groups, the dinocysts show an uphole increment, thus indicating possible marine influence in the Fika (1620–2950 m) and Gombe (1500–1620 m) Formations (Fig. 7B)

Figure 8 shows the overall frequencies of recovered taxa associated with the four identified botanical affinity. *Tricolporopollenites* spp. (69) and *Psilatriporites* spp. (30) are the angiosperms with the highest frequencies (Fig. 8A). The gymnosperm pollens generally recorded lower frequencies of ≤ 6 except for *Podocapidites* spp. (63), *Alnus vera* (48), and *Inaperturopollenites* spp. (22), compare to their angiosperm counterparts (Fig. 8B). Spore count ranges from 1 in *Polypodiaceoisporites caperatus* to 32 in *Laevigatosporites* spp. (Fig. 8C). The counts of dinoflagellate cysts are generally low ranging from 2 to 7 (Fig. 8D). Palaeoconditions that favoured the abundance of angiosperms and rare incursions of marine can be construed from the high frequencies of angiosperm pollen taxa (Fig. 8A) and the low counts of the dinoflagellates (Fig. 8D), respectively.

Palynozonation interpretation was generally based on the evolution of the miospores, their extinction and their relative frequencies depend on the ecology and other environmental factors (Brenner, 1968; Deaf et al., 2014). Thus, four palynozones denoted as Zones A1 – A4 (Figs. 5 and 6), were erected base on the assemblages of diagnostic forms that were confirmed from earlier researchers (Jardine and Magloire, 1965; Lawal and Moullade, 1986; Williams, 1975; 1977). These palynozones are discussed below.

Zone A (1): *Triorites africaensis* Assemblage Zone

Interval: 3420–4600 m

Age: Late Cenomanian

Characteristics:

This is the oldest palynozone encountered in the studied well (Fig. 5). It represents the deepest horizon penetrated by the well (total depth = 4600 m). This assemblage zone was proposed earlier as a major palynological zonation across the West Africa basins (Blotenhagen, 1980; Jardine and Magloire, 1965; Lawal and Moullade, 1986) and North-South America (Muller, 1981; Regali, 1989) to date the late Cenomanian. The top of the interval is placed at 3420 m based on the appearance of *Cicatricosisporities* spp. co-existing with the presence of *Classopollis* spp. and *Triporate* spp., following Jardine and Malgloire, (1965) and Deaf et al. (2014). However, the presence of *Triorites* spp. and first downhole occurrence (FDO) of *T. Africaensis* (Abubakar et al. 2006; Deaf et al. 2014; Jardine and Magloire, 1965) support the top interval to be of late Cenomanian (Fig. 5).

The microfloral assemblages present within this zone include *Cyathidites* spp., *Verrucatosporites* spp., *Polypodiaceiosporities* spp., *Retimonocolpites* spp., *Triporate* spp., *Retitricolpites* spp., *Cyathidites minor*, and *Retitricolporities* spp. This assemblage interval is characterised by few associated elaterate pollen grains and noticeable triporate angiosperm pollens, which could have allowed this interval to be named *Afropollis jardinus* sub-zone of the pollen PO – 304 assemblage zone in the Northern Benue Trough (Lawal and Moullade, 1986). This can be inferred into the southern part of the Bornu Basin. Nevertheless, the reference point of *Afropollis jardinus* implies that its stratigraphic importance based on its associated taxa are delimited to middle Cenomanian in some other works around Africa (Deaf et al. 2014; Jan Du Chene et al. 1978; Said et al. 1994). Thus, this assemblage zone can be correlated with zone VI of Schrank and Ibrahim (1995) and zone I of El Beialy et al. (2011) as indicative of late Cenomanian.

Zone A (2): *Cretacaeiporites scabratus - Odontochitina costata* Assemblage Zone

Interval: 2940–3420 m

Age: Turonian

Characteristics

The top of the zone coincides with the FDO of *Odontochitina costata* and *Cupanieidites reticularis* at 2940 m (Fig. 4) while the base corresponds to the disappearance of *Proxapertities* spp, which was classed by Lawal and Moullade (1986) with *Gnetaceaepollenites* sp. 1 as an Upper Cenomanian index species. This zone is likened to the acme zone of Lawal and Moullade (1986), which is characterised by the dominance of *Cretacaeiporites scabratus* (Herngreen, 1975) and *Cretacaeiporites mulleri*.

Odontochitina costata recorded by Moustafa and Lashin (2012) from the western desert of Egypt, as an important Turonian index form with the presence of other associated dinoflagellate cysts. The abundance of *Odontochitina costata*, and the last downhole occurrence (LDO) of *Botryococcus* (Chlorococcalean green algae) in the present zone is coeval to the characteristic of *tricolporate* – *triporate* – *Cretacaeiporites mullerii* Assemblage Zone (Fig. 4). A major zone of northern Kordofan (Schrank, 1994a) chronologically, and the upper part of the Chlorococcalean green algae interregnum zone from the lower Turonian of the northwestern Desert of Egypt (Ibrahim, 1996). Other species in this zone are *Inaperturopollenites* spp, *Cyathidites* spp., *Psilatricolporites triangulates, Psilatricolpites* spp., *Psilatricolporities* spp., *Monosulcites* spp., *Verrucatosporites* spp. and *Retimonocolpites* spp. These assemblages are indicative of Turonian.

Zone A (3): *Droseriidites senonicus* Assemblage Zone

Interval: 2500–2940 m

Age: Santonian – Campanian

Characteristics

This zone was first proposed as an acme zone by Lawal and Moullade (1986), the details of this zone are provided in Abubakar et al. (2011) work. The top of the interval is characterized by FDO of *Buttinia andreevii*. Other palynomorphs within this interval include *Canningia capillata, Proteacidites sigalii*, *Polypodiaceoisporites retitrugatus*, *Cyathidites infectus, Monocolpites* spp, *Verrucatosporites* spp., *Tricolporopollenites* spp. and *Spiniferites ramosus*. The base of this zone is characterized by the highest occurrence of *Tricolporopollenites* spp. The presence of *Proteacidites sigalii* shows that this section of the well is pre-Santonian (Fig, 5). Owing to the paucity of miospore, particularly marker species within this section, the Santonian – Campanian boundary could not be defined. This zone is assigned pre – Santonian to Campanian (Fig. 5). The associated assemblages for this zone are similar to the foraminifera – controlled Coniacian – Santonian successions (Deaf et al. 2014) discussed by Lawal and Moullade (1986) in northeast Nigeria, Morgan (1978) in the Angola Basin and Schrank and Ibrahim (1995) in early Santonian sediments from Egypt.

Zone A (4): *Syncolporites / Milfordia* spp Assemblage Zone

Interval: 1500–2500 m

Age: Maastrichtian -? Younger

Characteristics

The FDO of *Cyathidites infectus* and LDO of *Bombacacidites* spp. mark the base of the interval (Fig. 5). The interval is characterised by the appearances 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 wall lining. This interval is composed of assemblages of palynomorphs that are depictive of Maastrichtian to Early Tertiary (Fig. 5).

4.3. Palynofacies and Palaeoenvironments Interpretation

The application of quantitative and qualitative palynomorphs in this section provide insights on the environments of deposition (Figs. 4–5). Several studies have demonstrated the usefulness of palynofacies analysis and palynomorph assemblages in providing reliable and useful information on the depositional environments of sedimentary detritus (e.g., Traverse, 1994; Tyson, 1995; Ibrahim, 1996; Herngreen et al, 1996; Schrank and Mahmoud, 1998, Dino et al., 1999; Schrank, 2001). The general composition of the palynomorphs in the Gaibu-1 well indicates mixed pteridophyte – gymnosperm – angiosperm vegetation (Figs. 4–5). The sparse occurrence of marine/dinoflagellate cysts and much presence of some terrestrial microflora (represented by thick-walled pollens and smooth trilete spores) (Fig. 5) implies the deposition of the Cenomanian sediments (3420–4600 m) took place in continental/coastal environment with fluctuation of brackish water.

The Turonian to Campanian sediments (2540–3420 m) are interpreted to have been deposited in a fluctuating system of lagoonal estuarine to marginal/shallow marine environment alongside freshwater incursion. This interpretation was based on the presence of thick-walled spores, thin-walled pollens, the occurrence of fungal spore and *Botryococcus braunii*, coupled with the presence of fern spores such as *Cyathidites and Cicatricosisporites* probably reflects local pteridophyte vegetation growing on wetlands (Schrank and Mahmoud, 1998).

The Santonian-Maastrichtian sediments are interpreted to have been deposited under the influence of anoxic condition, as deduced from the moderate occurrence of glauconite in the lithologic unit. According to Rull (1997) and Germeraad et al. (1968) the presence of *Pachydermites diederexi*, *Verrucatosporites spp* and *Laevigatosporites spp*., indicate a swampy freshwater or brackish water environment, these species with *Polypodiaceiosporites spp.*, are common in the upper section of the well.

The Maastrichtian sediments (1500–2500 m) are characterised by the common occurrences of dinocysts (*Spiniferites, Oligosphaeridium*), microforaminiferal linings with fungal spore and *Botryococcus braunii*, suggesting incursions of marine events into the interpreted distal continental to proximal fluviatile depositional setting in the Maastrichtian (see Sect. 4.1.5). The uphole increment in distribution and frequency of *Botryococcus* and other algae in this study (Fig. 5) is suggestive of the influence of marine influx or water depth fluctuations. Taking clues from Fig. 6, the late Cenomanian section is certainly sparse of dinoflagellates and marine index palynomorphs, whereas the Maastrichtian is typified by more occurrences of dinoflagellates. The abundance of chlorococcalean green algae (*Botryococcus braunii*) alongside the highest occurrence of dinocysts (Figs. 4 and 6) *vis-à-vis* the dominantly shale-sand intercalations of sediments (Figs. 2–3) within this succession further justify intermittent marine incursions.

4.4. Palynofloral Provinces and Palaeoclimate Interpretation

Sequential palynofacies record is of importance in constraining ecosystem and their respective climatogenic conditions (Poumot, 1989). Akande et al. (2005) and Chateauneuf (1980) have demonstrated climatic variation across the earth is responsible for differential vegetation at various geological times Herngreen and Chlonova (1981) established eight palynofloral provinces: (i) the pre-Albian West Africa – South America province (WASA), (ii) the Boreal lower Cretaceous province of the northern hemisphere, (iii) the middle Cretaceous (Albian to Cenomanian) Africa – South America province (ASA), (iv) the late Cretaceous Normapolles province, (v) Aquillapollenites province, (vi) the late Cretaceous Palmae province of Africa and Northern South America, (vii) the Gondwana province and the (viii) Senonian Northofagidites province.

The palynofloral assemblages recovered from the Cretaceous sediments in the Gaibu-1 Well contains a reasonable occurrence of Palmae type monocolpate and tricolpate pollen taxa, such as *Acrostichum aureum, Spinizonocolpites, Proxapertites, Longapertites, Retimonocolpites* and *Retitricolpites* (Fig. 5), which have affinities to modern palms (see Muller, 1968; Thanikaimoni et al. 1984; Schrank, 1987; El Beialy, 1995). Referred to as Nypa by Atta-Peters and Salami (2006), these pollens are reliable indicators of coastal to mangrove environments in the humid tropics (Adebanji, 2012; Herngreen, 1998; Schrank, 1987). These monocolpate pollen taxa have been locally recovered from Maastrichtian sediments such as the Patti Formation of the southern Bida subbasin (Ojo and Akande, 2004; Ojo 2009), Nkporo Shale in the Calabar Flank (Edet and Nyong, 1994), Ojo-1 Well in the Dahomey Embayment (Jan Du Chene et al. 1978), Araromi Shale and Abeokuta Formation in the Dahomey Basin (Salami 1982; 1988), and the Anambra Trough (Salami 1990) in Nigeria. Similarly, these taxa correlate with the Palmae Province of Senegal and Ivory Coast (Jardiné and Magloire, 1965), Brazil (Herngreen, 1975), Northern Somalia (Schrank, 1994b), Egypt (El Beialy, 1995; Schrank, 1987), and other areas stated by Atta-Peters and Salami (2004).

Dino et al. (1999) stressed the inappropriateness of inferring palaeoclimate based on the presence of pollen and spore plants alone in sedimentary terrains. This is because factors, such as physiographic/biotic processes exert significant controls on their distributions, owing to the interplay of sedimentary materials/successions and vegetation. However, sorting recovered palynomorphs into their botanical affinity groups or associations is a veritable and acceptable means to constrain prevailing palaeovegetation zone and palaeoclimate condition during sediment deposition (see Dino et al. 1999; Jianguo et al. 2015). Thus, the classification of palynomorphs based on botanical affinities in Sect. 4.2. was adopted to aid palaeoclimate interpretation (Figs. 7–8).

The domination of angiosperm pollens over other botanical groups of palynomorphs in tropical forest is an indicator of less seasonal, wetter, and cooler climate (Boyce et al. 2010). Taking clues from the documented predominance of angiosperm (*ca.* 48.40 %) as indicated in Figs. 5 and 7, vis-à-vis the high occurrences of taxa such as *Tricolporopollenites, Triporate, Triorites, Retimonocolpites* and *Psilatriporites* (Figs. 5 and 8) in the studied succession is thus alluding to a wet or humid tropical climate. This agrees with Herngreen (1998), and consequently indicate that the successions in southern Bornu Basin encompass the wet lowland forest that is associated with the Nypa mangrove zone. The late Cretaceous Palmae Province is implied from this elevated habitat and suggestive of a tropical - subtropical climate system (T-SCS). According to Vakhrameev (1991), the T-SCS is typified by assemblages that are indicative of a warm (e.g., *Classopollis* spp., *Alnus ve*ra etc) and humid (*Inaperturopollenites* spp. *Proxapertites* spp., *Spinizonocolpites baculatus* etc) climate as recorded in this study (see Fig. 8). Similarly, Jianguo et al. (2015) narrated that *Cupaniedites* (regarded as Sapindaceae), and *Proteacidites* (of proteaceous origin) (see Figs. 5 and 8) have their modern representatives as trees and shrubs known to inhabit and flourish in the tropical and subtropical climate, and arid conditions, respectively. Although, the taxa recorded few incidences in the studied successions (Fig. 8A), their presence reasonably buttressed a palaeoclimate system affiliated to tropical, subtropical, and warm – temperature zones (*Ibid*).

The Cenomanian in the studied succession is typified by a low diversification and sparse occurrence of sporomorphs with an accompanied rarity of dinoflagellates (see Fig. 4). This, in addition to the inferred continental/coastal environment of the upward coarsening, generally angular, and brownish sediment successions (Fig. 4) signify a warm arid to semi-arid palaeoclimate condition. Though very rare, the occurrence of the gymnosperm pollen, *Classopollis* (Fig. 8B), which is presumably an autochthonous fossil plant, is indicative of mid-dry zones (semi-arid) under warm climate (Dino et al. 1999). The nonattendance of elaterate pollens together with its associated palynomorphs within the Cenomanian interval of the Gaibu – 1 Well suggests the interval does not belong to the Albian–Cenomanian African–South America (ASA) palynofloral province (see Herngreen, 1974; Dino et al. 1999).

The upper section (Turonian - younger) of the studied well yielded increasing occurrences of dinoflagellate cysts (see Figs. 4 and 7B) that could reflect increasing marine tendencies uphole, and by implication implying possible progressive semi-arid with a humid condition. The Campanian – Maastrichtian brownish shale and sands in this study contain mangrove palms of Nypa vegetation such as *Acrostichum aureum* (Figs. 4 and 8C), *Spinizonocolpites, Proxapertites*, and *Longapertites* (Figs. 5 and 8A) that are related to those from northern South America and West Africa. Their existences in the studied successions also indicate tropical to subtropical climate (Dino et al. 1999; Schrank 1987). The Nypa vegetation is a prominent component of the mangrove environment in humid tropics (Herngreen, 1998; Schrank, 1987). It is thus deducible that the sequences penetrated by the Gaibu-1 Well were deposited apt into the late Cretaceous Palmae Province of Africa – northern South America (Herngreen and Chlonova, 1981; Herngreen et al. 1996) that typifies the documented palynologic complexes of Equatorial (palm) region of western Africa and South America (Vakhrameev, 1991). This is substantiated by the appreciable frequency of taxa attributed to the Palmae (e.g., *Proteacidites* spp., *Psilatricolpites* spp., *Spinizonocolpites baculatus*), and the concomitant dearth of Normapolles – group of pollens (Atta-Peters and Salami, 2004).

Conclusion

The studied succession of the southern Bornu Basin, NE Nigeria consists of five main lithounits identified as sand-shale heterolith, sand, shale, gypsiferous shaly sand, and silty clay. The Bima Formation is the oldest of the sequences, and it is dated Cenomanian. It is sequentially overlain by the Yolde (late Cenomanian to early Turonian), Gongila (Turonian), Fika Group (lower-Turonian to Santonian, mid-Campanian, and upper-Campanian to Maastrichtian) and Gombe (Maastrichtian) formations. The succession is categorised into four palynozones; (i) the Cenomanian *Triorites africaensis* assemblage zone, (ii) the Turonian *Cretacaeiporites scabratus / Odontochitina costata* assemblage zone, (iii) the Santonian–Campanian *Droseridites senonicus* assemblage zone and, (iv) the Maastrichtian-Palaeocene *Syncolporites/Milfordia* spp. assemblage zone. Spores and pollens predominate recovered palynomorphs in across the five formations/ intervals, whereas dinocysts range from rare in the deepest horizon to common in the shallow intervals. Integrated of sedimentological and palynomorph datasets construed the depositional environments to range from a continental - brackish - marine system. The late Cretaceous successions of the southern Bornu Basin were deposited in a tropical -to- subtropical climate system, evidenced by assemblages that are indicative of warm (e.g., *Classopollis* spp., *Alnus vera* etc) and humid (*Inaperturopollenites* spp. *Proxapertites* spp., *Spinizonocolpites baculatus* etc) climates. Conclusively, the presented datasets show that the penetrated sequences belong to the late Cretaceous Palmae Province of Africa and northern South America.

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Figures

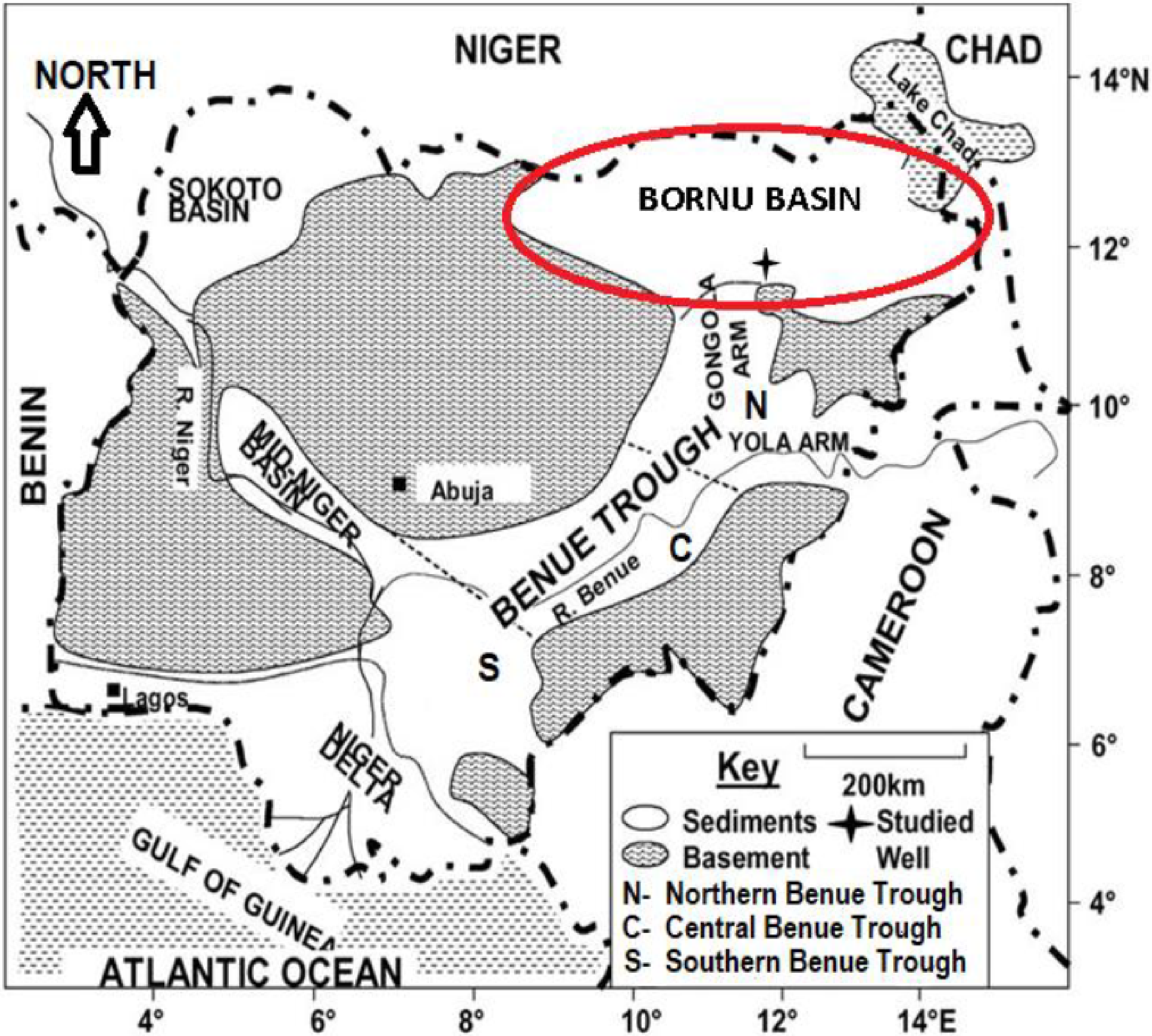

Figure 1

Generalised geological map of Nigeria showing the Bornu Basin (encircled in red) and the location of Gaibu−1 Well marked by the cross sign (Modified from Abubakar et al., 2006).

AGE	LITHOLOGY	This Study		Carter et al. (1963)	Avbovbo et al. (1986)	Okosun (1995)	Deposition Environment
Pliocene – Pleistocene	Clay, Sand	Not Investigated		Chad FM	Kerri – Kerri FM	Chad FM	Continental
Paleocene	Sandstones, Claystones	Not Investigated		Kerri – Kerri FM		Kerri – Kerri FM	Continental
Maastrichtian	Shaly Sandstones, siltstone	Gombe FM		Gombe FM	Gombe FM	Fika Shale	Deltaic, Estuarine
	Sandy Shales, Sandstones	Upper	Fika FM	Fika Shale	Fika Shale		Marine
Campanian		Middle					Marine
Santonian		Lower					Marginal Marine
Coniacian							
Turonian	Sandstones, Shales	Gongila FM		Gongila FM	Gongila FM	Gongila FM	Marginal/ Shallow Marine
	Sandstones, Shales, Calcarous sands	Yolde FM					
Cenomanian	Sandstones, Shales, Clay	Bima FM		Bima FM	Bima FM	Bima FM	Marginal Marine
Crystalline Basement							

Figure 2

Correlational stratigraphic panel, palaeoenvironments and thickness of rock successions in the Bornu Basin as postulated by various authors vis-à-vis current research findings

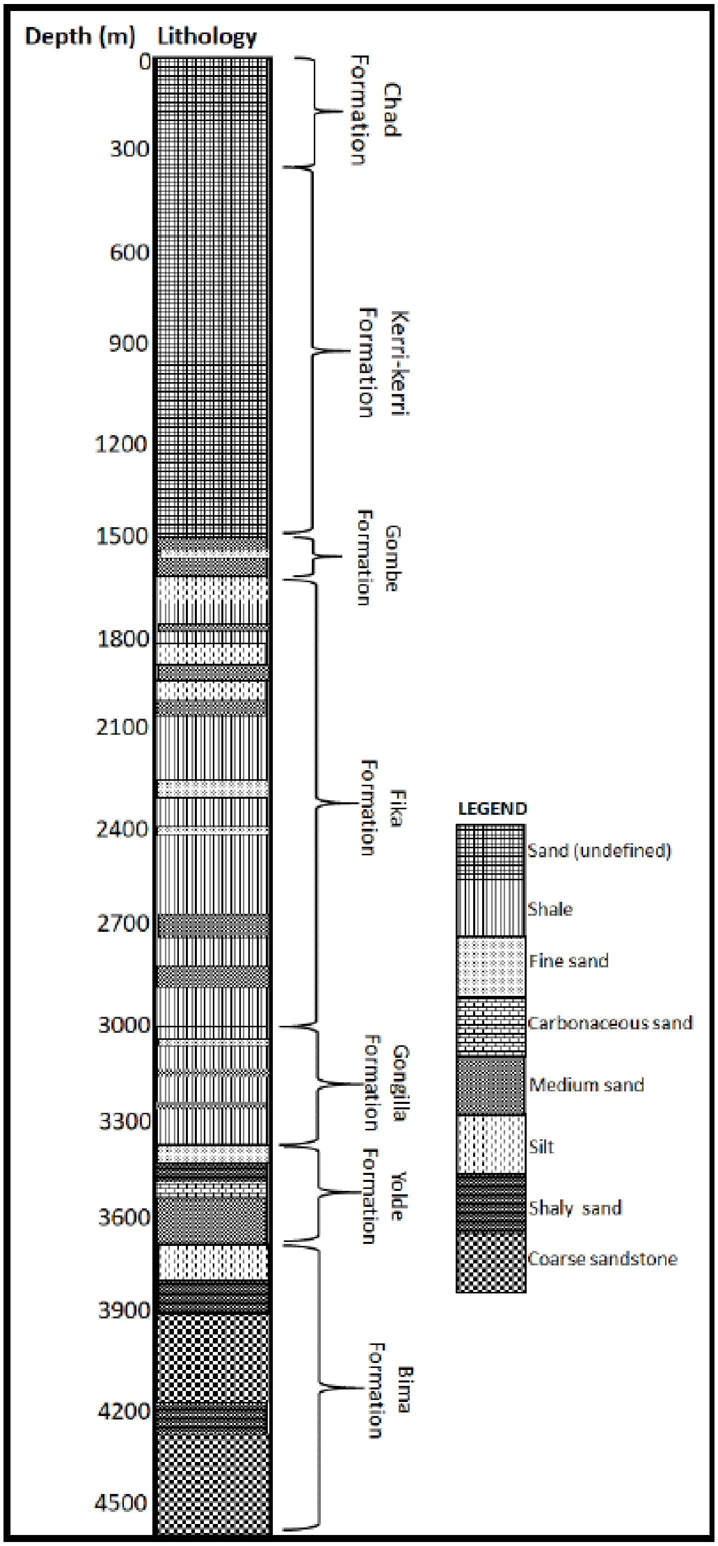

Figure 3

Lithologic sequence in Gaibu – 1 well. Note that the lithounits in the Kerri-kerri and Chad formations were interpreted based on gamma ray log, and formational thicknesses of the duo were obtained from Okosun (1995)

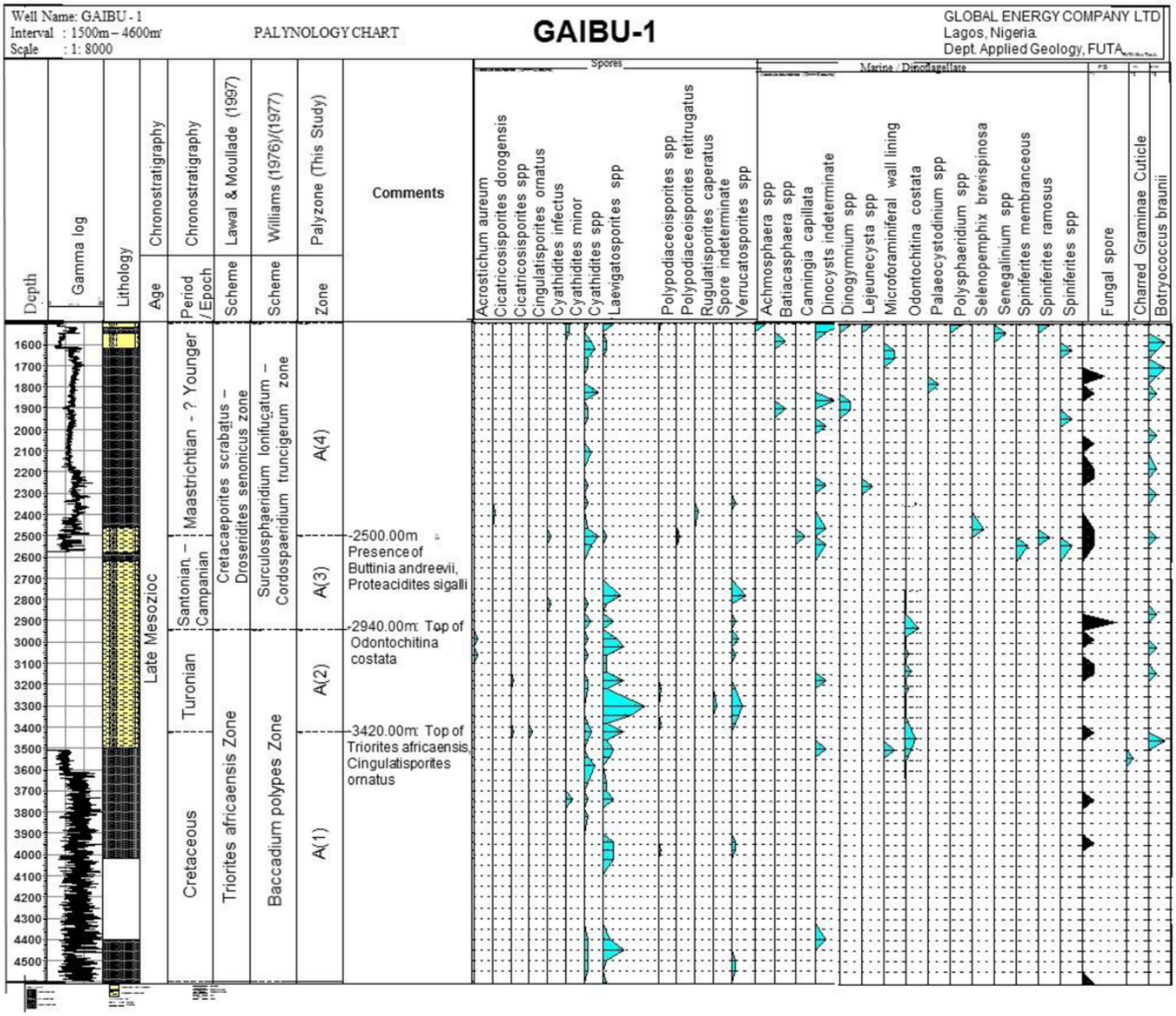

Figure 4

Spores and Dinoflagellate distribution and bioevents in Gaibu – 1 well, Bornu Basin, Nigeria.

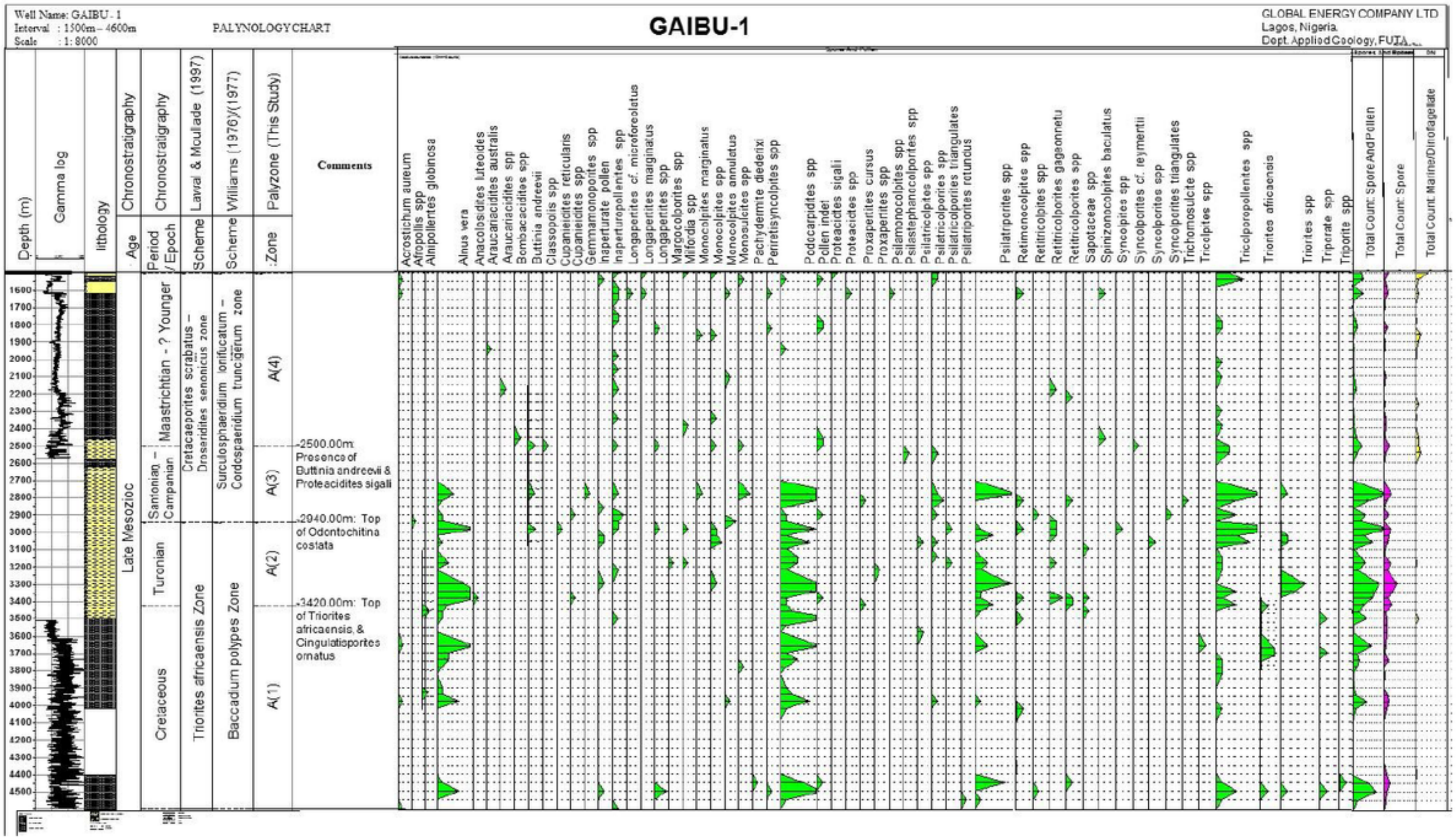

Figure 5

Palynomorphs distribution and bioevents in Gaibu – 1 well, Bornu Basin, Nigeria.

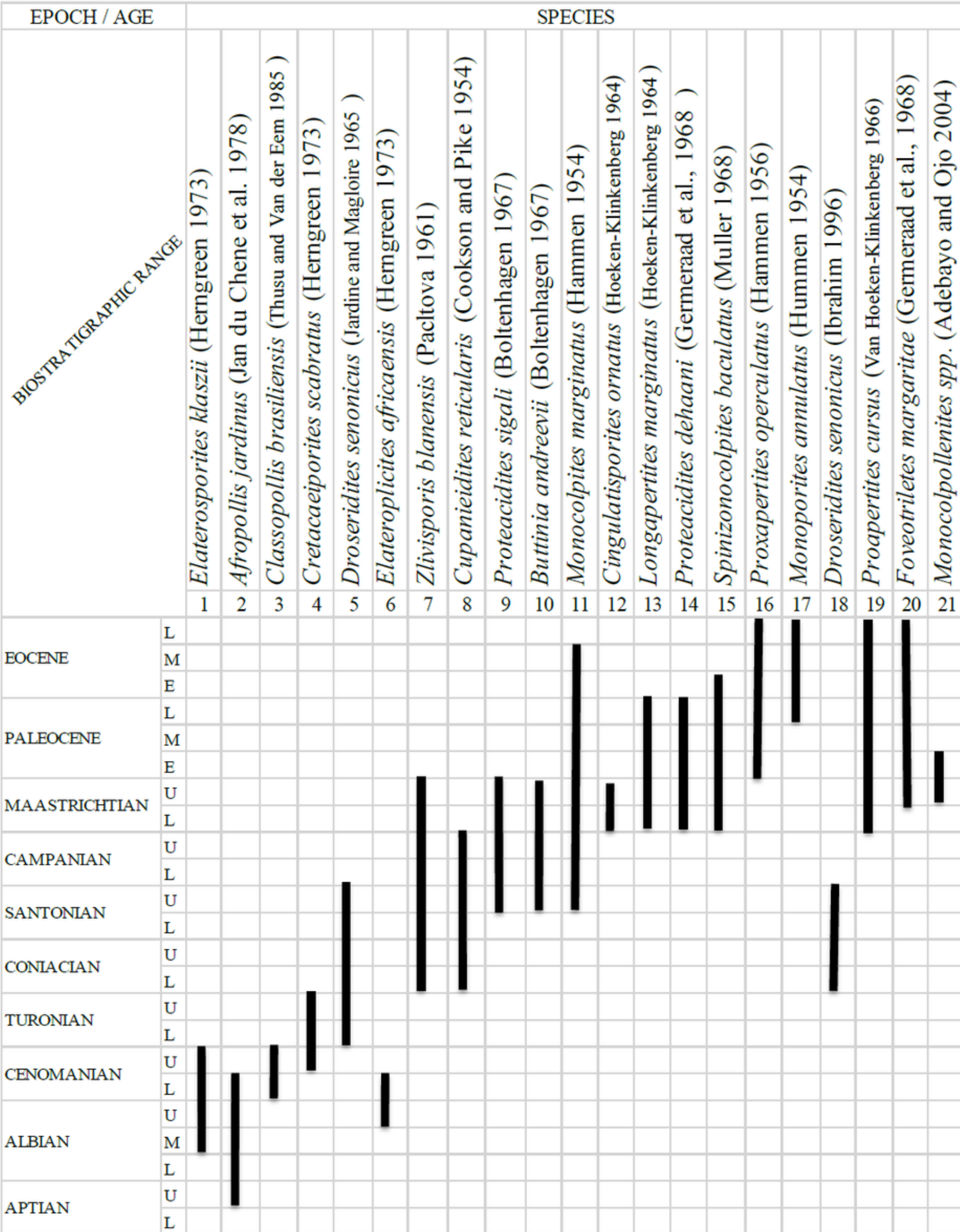

Figure 6

Species of well – known stratigraphic ranges in other contemporaneous basins of West Africa and Northern South America (African range of Tethyan ranges and the Northern South American range of independently dated).

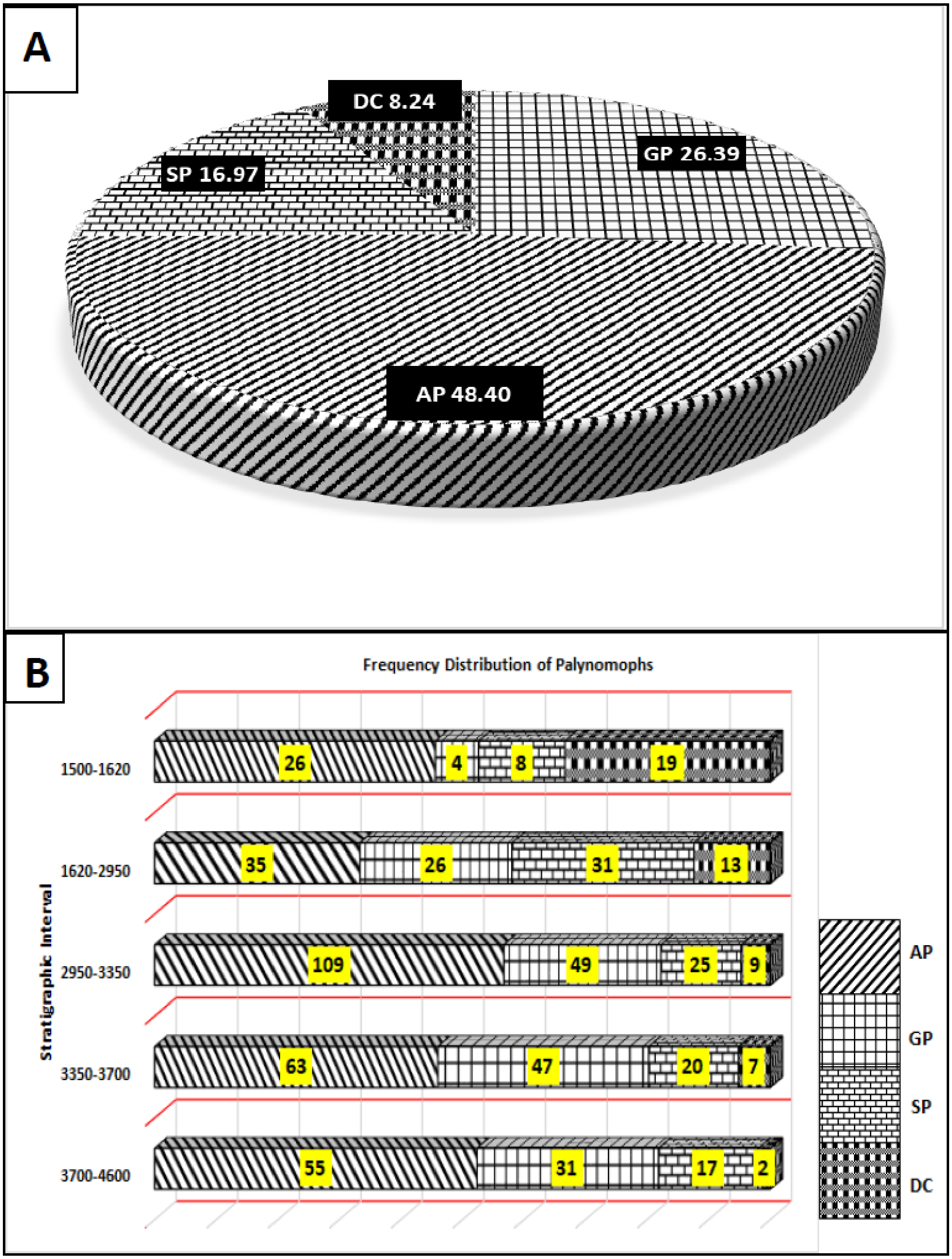

Figure 7

(A) Classification of recovered taxa based on their botanical affinities; (B) frequency distribution plot of palynomorphs group in Gaibu-1 Well showing downhole occurrences and variation of pollens, spores and dinocysts. Note that AP, GP, SP, and DC connotes angiosperm pollens, gymnosperm pollens, spores, and dinoflagellates cysts (dinocysts), respectively.

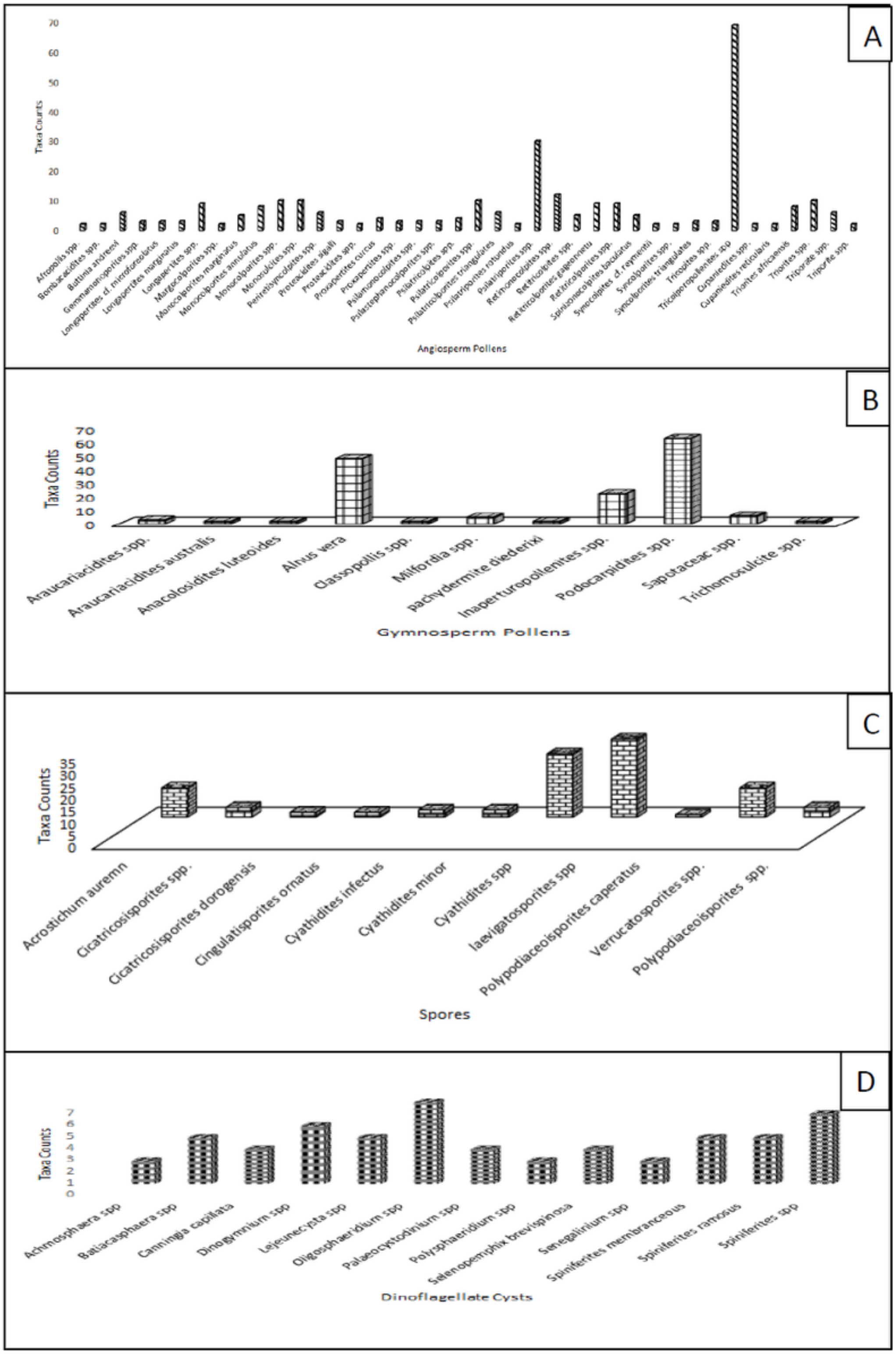

Figure 8

Taxa counts of major palynomorphs recovered from the studied succession. (A) angiosperm pollen (B) gymnosperm pollen (C) spore, and (D) dinoflagellate cysts (dinocysts). Note low taxa counts in dinoflagellate cysts compared to other plotted palynomorphs.

Supplementary Files

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- APPENDIX1.docx