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Dispersed Sedimentary Organic Matter in Albian - Cenomanian Sediments from the Cape Three Points 1 (CTP-1) Well, Tano Basin, Western Ghana: Constraints on Age, Palynofacies and Source Rock Maturity

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Abstract

A palynological study of 84 cutting samples from Cape Three Points 1 (CTP-1) well in the Tano basin allows the identification of three biozones based on the First Appearance Datum (FAD) and Last Appearance Datum (LAD) of stratigraphically significant sporomorphs taxa recovery. These are *Elateropollenites jardinei - Reyrea polymorphus* Zone, *Elaterocolpites castelainii - Afropollis jardinus* Zone, and *Cretacaeiporites polygonalis – Classopollis classoides* Zone, which permit an age assignment of early – middle Albian, late Albian – early Cenomanian and late Cenomanian respectively.

The diagnostic miospores from the samples are characteristic of the Albian-Cenomanian Elaterate paleofloral Province in a semi-arid to arid climate, with sediments yielding mixed kerogen assemblage which reflects a marginal marine or nearshore environment.

Four palynofacies assemblages (P-1 to P-4) and kerogen types identified indicate deposition under marginal dysoxic-anoxic basin (kerogen type III), shelf to basin transition (kerogen type III/II), a distal suboxic- anoxic basin (kerogen type II>I) and distal dysoxic-anoxic shelf (kerogen type II) conditions respectively. Thermal maturity values obtained from colour changes of psilate spore (*Deltoidspora, Cyathidites*) reveal that samples from P-1 and P-2 are within immature phase and P-3 and P-4 are mature.

Keywords: *Palynofacies; Ghana; Cretaceous; Thermal maturity; Palynology; Kerogen.*

1. Introduction

The Tano Basin is located on the easternmost portion of the Cote d’Ivoire Basin. It is bounded by the Saltpond Basin in the east and the St. Paul Fracture Zone in the west. The Tano Basin covers an area of about 3000km^2, with an onshore extent of about 1165km^2 [1]. The basin is part in the Gulf of Guinea Province which also includes the Saltpond, Cote d’Ivoire, Keta, the Benin Basins and the Dahomey Embayment in the northwestern part of the Gulf of Guinea (Fig. 1). The Gulf of Guinea according to [2] was formed at the culmination of Late Jurassic to Early Cretaceous tectonism that was characterized by both block and transform faulting. This faulting was superimposed on an extensive Paleozoic basin during the breakup of Africa and South American paleocontinents. The province has thus, undergone a complex tectonic history which is divided into pretransform (Late Proterozoic – Late Jurassic), syn-transform (Late Jurassic – Early Cretaceous), and posttransform (Late Createaceous – Holocene) stages of basin development. These tectonic complexes or stages have also been referred to as pre-rift, syn-rift and post-rift stages by [3]. [2] posited that the structural basins within the provinces are aligned in east-west direction, with boundaries delimited by an east-west transform fault system and north-south structural arches.

The Tano basin is a typical transform margin basin which originated during the early Cretaceous (Albian) at the onset of the separation of the Africa Plate from the South American Plate. [4] reported that movement along a series of transform faults including major east- west oceanic transform faults in the Romanche Fault Zone and the St. Paul fracture zone during the continental separation led to the development of the large rift basin in the Tano area of Ghana. These movements resulted in the formation of the rift basin around the Aptian - early Albian time. The prevailing conditions at the time which formed a continuous –anoxic seaway in the late Albian to Turonian were apt for the deposition of organic rich shales. [5] were of the view that the large ancestral River Tano in western Ghana may have drained extensive areas to the north during the early post transform period and deposited large amounts of clastics sediments during the Cenomanian. [5] have also stated that seismic data indicate large turbidites channels developed in the basin during the Maastrichtian and their presence supports the interpretation that the large fans or detached sandstone bodies may lie in deeper parts of the basin.

This aim of the study is to establish biostratigraphic zonation based on stratigraphic distribution of palynomorphs, to evaluate the use of marker palynomorph species to assign the age of the sediments from the CTP-1 well and the application of palynofacies associations to interpret the depositional environment of the sediments. The hydrocarbon potential of samples is evaluated based on the thermal maturity levels of the organic matter using visual assessment of spore coloration and organic thermal parameters.

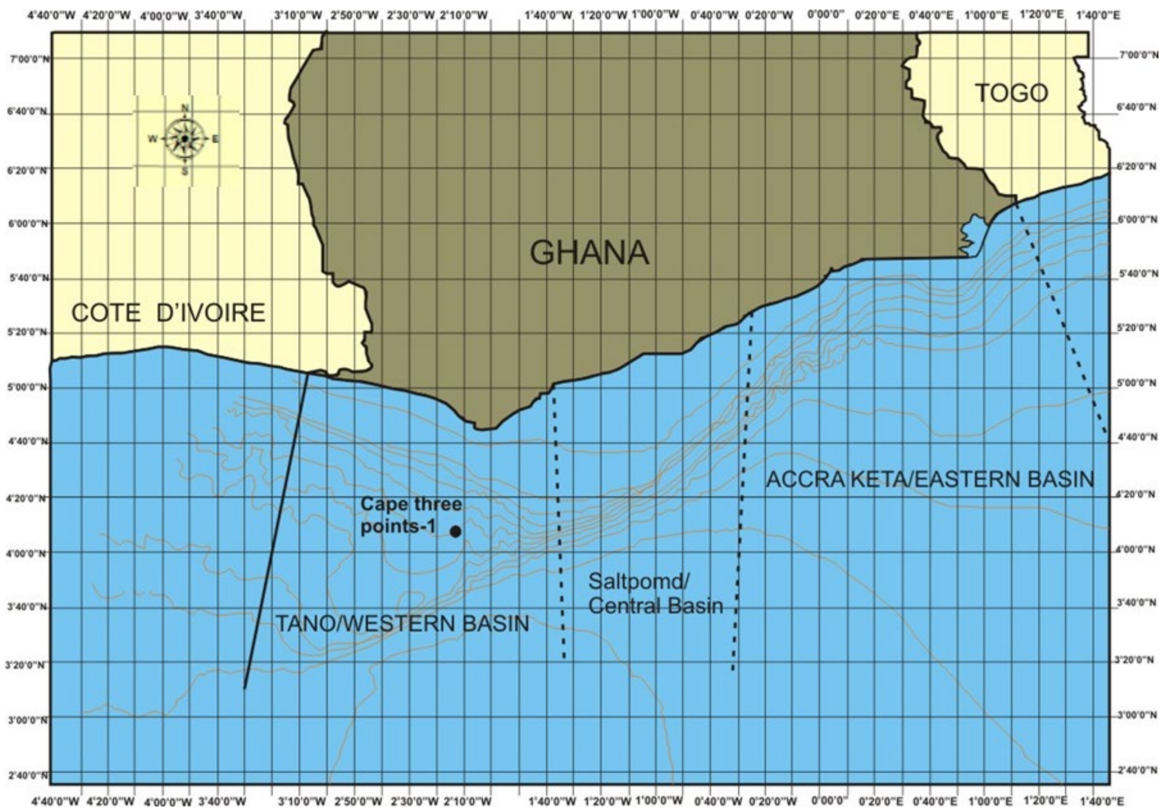

Fig. 1. Location map of CTP-1 well Offshore Tano Basin (modified after GNPC Report, [11]).

2. Geology and tectonic setting

[6] reported that the rocks of the Tano Basin are part of the Apollonian System of Cretaceous age. These rocks overlie the Precambrian basement rock (mainly schist, phyliite and volcanoclastics) of the Birimian system. [6] described the lithology onshore as consisting mainly of limestones with alternating clays and sands, with a general SSW dip direction and low dip angles. At depth, these sands and clays compact to form sandstones and shales.

Basin development in the Tano area suffered three important tectonic periods that influenced the structure and sedimentation rate; the Pre-rift, Syn-rift and Post-rift. The pre-rift stage according to [3], consist of Precambrian to Triassic rocks that outcrop in the Voltaian and Tano Basins of Ghana. In the Tano basin, the oldest pre-rift sequence is represented the

Elmina sandstone Formation of the Sekondian Group, which was encountered in the Cape Three Points 4-1 (CTP 4-1) well, and [1] assigned a Devonian age. This age, however, has been reviewed as palynological evidence point to a late Ordovician to early Silurian age [7]. Further offshore mixed siliciclastic rocks, dated palynologically as early Carboniferous were penetrated in the Central Tano Structure 1 (CTS 1) [8]. These rocks succeed the Paleozoic rocks further eastward which can be seismically interpreted to underlie the Carboniferous section encountered in CTS 1 well [8].

According to [9] and [10], data on age of volcanic intrusives associated with initial block faulting in Liberia, southern Sierra Leone and Ghana, indicate that the syn-rift stage started no later than the middle Jurassic. The syn-rift sedimentation was tectonically controlled and took place in small rotated fault blocks trending northwest –southeast. The lowermost Cretaceous syn-rift sediments in the basin were deposited during continental conditions [8,10]. According to them, however, during the late Aptian – early Albian times, the environment became mostly marine, resulting in sequences of alternating sandstone and shales and shales with some black, coarse sandstone, conglomerate, and minor limestone. Uplifts and tilting of the syn-rift sequences characterized the end of syn-rift stage during the late Albian with subsequent faulting and erosion. This episode resulted in a major unconformity, which separated it from the marine post-rift rocks of the latest Albian and Cenomanian [5,9-10].

The post rift period in the Tano basin has a similar tectonic and stratigraphic history with the Cote I'voire Basin [3]. They also reported that the post-rift continental margin tectonism was driven by thermal subsidence from Cenomanian with the first transgression into the Gulf of Guinea [10]. [8] reported that the Cenomanian rocks include sandstone, shale, siltstone, mudstone and limestone; black shales and limestone were deposited on the crest of the horst, whereas turbidites accumulated in the graben. The Turonian to Maastrichtian rocks include marine sandstone, shale, limestone and minor conglomerates and major unconformities bound the Cenomanian to Maastrichtian rocks in the basin [10].The overlying unconformable Cenozoic or Tertiary rocks consists of marine sandstone, shale, and limestone and the regional Oligocene unconformity is present in the basin separating the Miocene from the Eocene rocks.

3. Materials and methods

A total of 84 cutting sample slides between intervals 6020ft-13780ft from CTP-1 well, offshore Tano Basin [11] (Fig. 1) were obtained from the Core Laboratory of the Ghana National Petroleum Corporation (GNPC). Palynological samples were prepared using the standard acid–based (HCl/HF) palynological extraction techniques [12]. The organic residues were sieved using 20 µm and 10 µm nylon meshes. The residues were not oxidized since this would hinder the study of the kerogen particles and spore colouration. The particulate organic matter (POM) and palynomorphs were examined qualitatively and quantitatively using Leica DMEP 750 microscope fitted with an AmScope Toup View 3.2 digital camera for microphotography. For palynofacies analysis, a total of 400 particulate organic matter (POM) was counted for each sample to determine the relative abundance in percentage of POM at each studied depth. In order to establish the ratio of sedimentary organic matter grouping (palynomorphs, phytoclasts and amorphous organic matter (AOM)), cluster analysis (Q-mode) using the IBM SPSS Statsistics 25 program (Ward's method) was employed. The AOM-Palynomorphs-Phytoclasts (APP) ternary plot of [13] was used to reveal the depositional environments of the various palynofacies assemblages.

For the purpose of estimating thermal maturity, optical examination of the exine colours of the thin-walled psilate spore (*Deltoidspora, Cyathidites*) was used. The colours were compared with [14] spore/pollen colour chart to obtain the numerical thermal alteration index (TAI) of the samples. Equivalent vitrinite reflectance (Ro %) values were obtained using the correlation chart of [15]. All slides used for the study are stored in the Palynological Laboratory of GNPC.

4. Results and Discussions

4.1. Palynostratigraphy

The miospore (spore and pollen) ranges have been utilized for the biozonation purposes with dinoflagellate cysts providing additional supporting evidence where applicable. Biozonation and age assessment of sediments was based on the vertical distribution by the First Appearance Datum (FAD) and the Last Appearance Datum (LAD) of stratigraphically important miospore taxa.

4.1.1. Elateropollenites jardinei- Reyrea polymorphus Zone

This zone is recognized in the deepest part of the CTP-1 well between the intervals 13350 – 80ft. (4,045 - 55 m) to 10,780 – 90 ft (3,266 – 3,270 m) (Fig. 2). This zone is defined by the FAD and LAD of the stratigraphically important taxa *E. jardinei,* and *R. polymorphus* respectively

The general characteristics of this zone includes the presence of *E. klaszii, E. protensus, E. verrucatus,* common to highly abundant angiosperm pollen species including *Crybelosporites pannuceus*, *Classopollis classoides, C. perplexus, Ephedripites* spp., (straight and twisted ridges of *Ephedripites barghoornii-staplinii-jansonii* form group), *Reyrea polymorphus*, *Afropollis jardinus*, *Callialasporites dampieri*, *Araucariacites* spp. Some *Psila/Retitricolpates* pollen are observed in this zone, however, in lower quantities. Pteridophytic spores of the *Cyathidites*, *Concavisporites*, *Deltoidspora, Cicatricosisporites* form group are also present. Marine dinocysts include *Oligosphaeridium, Subtilisphaera, Florentina, Cyclonephylium, Coronifera.*

Elateropollenites jardinei, the first elater pollen has been recorded in early Albian – middle Albian in Brazil [16-20], middle Albian in Senegal and Côte d'Ivoire [21]. It has not been recorded from post-middle Albian sediments [19]. [22] reported that, stratigraphically important taxa that have their last occurrence in the middle Albian include *Elateropollenites* spp, *Reyrea polymorphus* and *Ephedripites irreguaris.* [17] described *Reyrea polymorphus,* an inaperturate grain of unknown affinity from the lower to middle Albian in Brazil and so did [20] from Venezuela. In Africa, however, it has been reported from sediments which range in age from late Barremian to early Cenomanian [23-29].

Crybelosporites pannuceus one of the seven stratigraphically terrestrial miospore species for dating the mid-Cretaceous strata in Egypt [29] has a stratigraphic distribution from Albian to Cenomanian. It has also been reported for the same interval by [17,26,30-33] also reported it presence in the Albian of Brazil.

Elaterosporites klaszii, is widely accepted to mark the base of the middle Albian in the Elaterate Phytogeographical Province [34]. [35] reviewing the distribution of elaterate pollen from Peru and Colombia, recorded *E. klaszii* from the late Albian – early Cenomanian. It has been reported from Albian – Cenomanian of Libya [36] late Albian – early Cenomanian of northern Sudan [37-38] late Albian in Nigeria [39] early Albian - early Cenomanian of Brazil [18] early Albian – early Cenomanian of Eygpt [40] middle Albian – middle Cenomanian [29] middle Albian – late Cenomanian in Gabon [41] and Senegal [42].

Based on the FAD of *E. jardinei* and LAD of *R. polymorphus* just above the FAD of *E. klaszii,* an early to middle Albian age is assigned to this interval.

4.1.2. Elaterocolpites castelainii - Afropollis jardinus Zone

This zone is defined by the FAD of *Elaterocolpites castelainii* and the LAD of *Afropollis jardinus* between the sample intervals of 10670 – 700 ft. (3,233 – 3,242 m) and 6950 – 80 ft. (2106 - 2115 m) respectively (Fig. 2). The general characteristics of this zone is the common occurrences of *Afropollis jardinus. E. klaszii, E. protensus, E. acuminatus*, *E. verrucatus, Elaterocolpites castelainii, Sofrepites legouxae, Galaecorna causea, Cyberosporites pannaceus, Classopollis classoides, Ephedripites* spp*. Araucaricites* spp, *Inaperturopollenites* spp*.* There is also the presence of spores of the *Cyathidites*, *Concavisporites*, *Deltoidspora, Cicatricosisporites* form group. Dinocysts are rare and include *Oligosphaeridium, Subtilisphaera, Florentina, Cyclonephylium, Coronifera.*

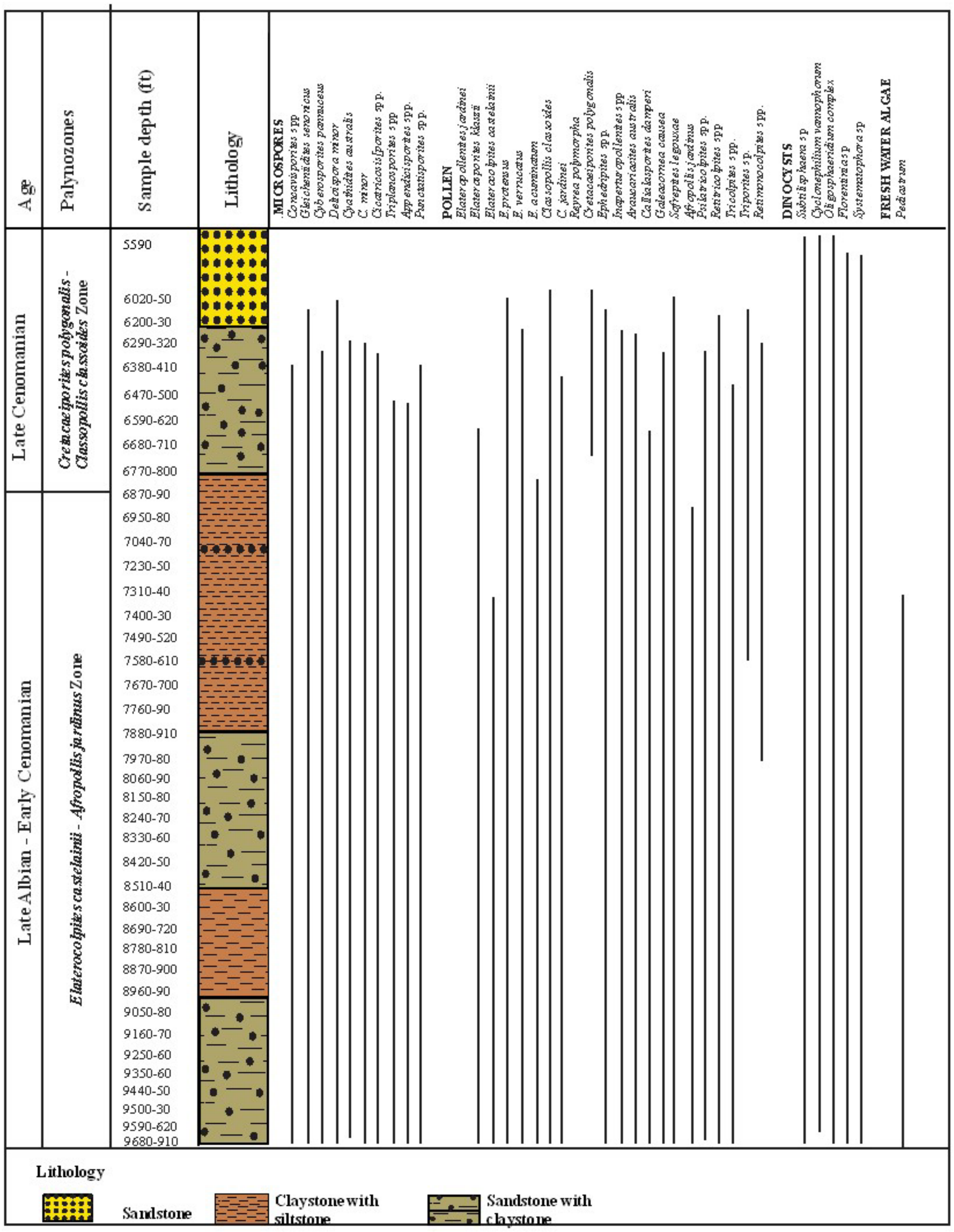

Fig. 2a. Lithologic column and palynomorph ranges in the CTP-1 well.

E. castelainii is reported to have appeared first in late Albian – early Cenomanian sediments [43]. It has also been reported from late Albian – early Cenomanian in Gabon and Senegal [17-18,21,37,42]. [19] have also reported *E. castelainii* from the late Albian – middle Cenomanian in Brazil. Elater-bearing pollen in the ASA region has been reported from the early Albian - late Cenomanian [18,44]. [42] reported earlier forms of *Elaterosporites klaszii, Elaterosporites verrucatus, Elaterocolpites castelainii* and *Elateroplicites africaensis* as being restricted to the Upper Albian of the Lower Benue Trough in Nigeria. *Elaterosporites klaszii, Elaterosporites protensus* and *Elaterosporites verrucatus* recovered from this interval have also been reported from Middle to Upper Albian sediments in Senegal, Côte d'Ivoire and Gabon [42]; from middle Albian rocks of Brazil [17-18] and from the CIG transform margin [27]. [45] states that the cooccurrences of *E. klazsii, E. castelain*ii, *G. causea*, points to an early Cenomanian age. According to [37], *E. klaszii* and *E. castelainii* have a short stratigraphic range and are restricted to the middle Albian – Cenomanian in the ASA region.

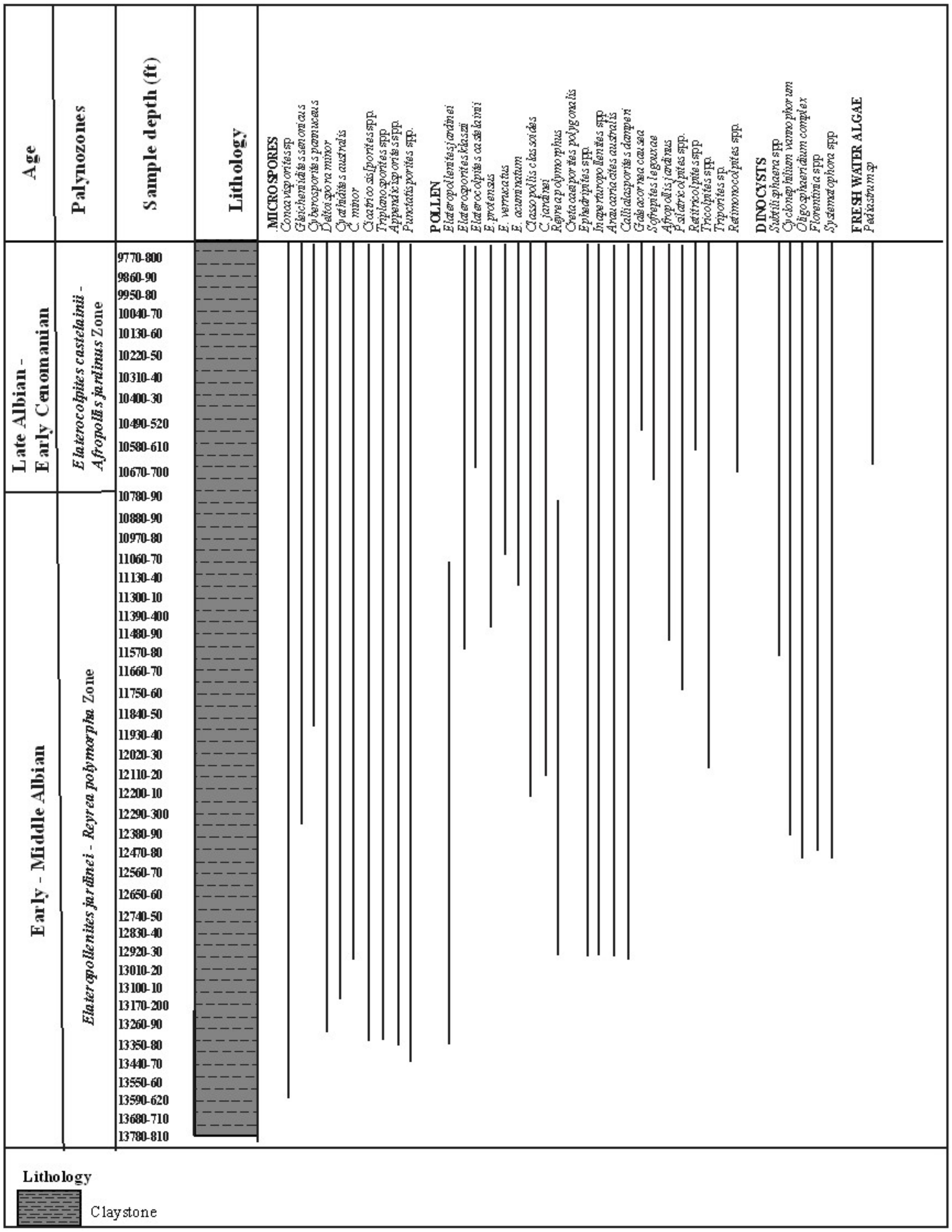

Fig. 2b. Lithologic column and palynomorph ranges in the CTP-1 well.

[18] reported that *Sofreipites legouxae* is an index fossil in the late Albian – early Cenomanian strata in Brazil. It has, however, been reported from the late Albian – middle Cenomanian of Brazil and Ecuador [19]. The species has also been reported from the late Albian – early Cenomanian in Senegal and Gabon [20-21,26,34,42,45,47-48].

Galaecornea causea has been reported from late Albian – Cenomanian of Brazil [17-18,26,49] and from Senegal and Portuguese Guinea [50], late Albian – early Cenomanian of Senegal and Gabon [21,42], late Albian – early Cenomanian of Egypt [38,51-53], late Albian – late Cenomanian of Brazil and Ecuador [19]. [46] have intimated that *G. causea* is a late Albian – early Cenomanian marker, which appears above *E. klaszii* as recorded from sediments of the ASA region (equatorial Africa, NE Brazil, Nigeria, Senegal, and Egypt).

Afropollis jardinus has been recorded from the Late Albian in Senegal [21], middle/late Albian - middle Cenomanian of Northern Gondwana. [54], in late Albian to early Cenomanian of Brazil [17-18], Sudan [37,55], Colombia [35]; middle Albian – middle Cenomanian of Egypt [56].

The FAD of *E. castelainii*, together with *G. causea, S. legouxae,* and the LAD of *A. jardinus,* in this interval suggests a late Albian to early Cenomanian age.

4.1.3. Cretacaeiporites polygonalis – Classopollis classoides Zone

This zone is characterized by the FAD of *Cretacaeiporites polygonalis* at sample point 6770-80 ft (2052 – 2055 m) and the LAD of *Classopollis classoides at* the sample point 6020-50 ft. (1842 – 1833 m) (Fig. 2). The zone has moderate to common occurrences of triporate/tricolpate pollen. Also present are the elater-bearing forms which disappear just below the LAD of *C. classoides.* Dinoflagellates are few and are mainly *Oligosphaeridium, Subtilisphera, Florentina*.

Cretacaeiporites polygonalis has been reported from late Albian – late Cenomanian in Senegal [21], Brazil [18], late Albian – Turonian in Sudan [55], Gabon [57-58], Nigeria [59], Cameroon, Congo and Angola [60]. [61] reported also that common representatives of angiospermic pollen belonging to *Cretacaeiporites* and *Hexaporotricolpites* appeared in the late Cenomanian. [34] in their compilation of ranges of important Cretaceous marker species in different phyt ogeographic provinces in north and west Africa, north South Africa, put the range of *C. polygonalis* from late Albian – late Cenomanian.

The stratigraphic ranges of *Classopollis classoides* and its other forms put together by [55] from West African coastal basins, straddles from the Aptian to late Cenomanian. [61] and [22] established that the quantitative important elaterates and *Classopollis* disappeared at the Cenomanian/Turonian boundary. These two bioevents have been observed in this section of the CTP 1 well.

The FAD of *Cretacaeiporites polygonalis* and LAD of *Classopollis classoides* and the elaterate pollen and common occurrence of triporate/tricolpate suggests a late Cenomanian age for this zone.

5. Palynofacies analysis and kerogen types

Palynofacies is a powerful analytical tool that can be applied in the determination of kerogen types and their abundance, provide indications of depositional environment and hydrocarbon potential. [62] intimated that palynofacies analysis entails the integrated study of all aspects of the palynological organic matter assemblage, which include the identification of individual particulate components, assessment of their absolute and relative proportion, article size and their preservation states. The palynofacies assemblage proposed in the study are based on the quantitative analysis of the recorded palynofacies constituents, AOM, opaque phytoclast, translucent phytoclast and palynomorphs. Cluster analysis (Q mode) revealed four discrete groupings (Fig. 3). These are Clusters P-1, P-2, P-3 and P-4, which are indicative of palynofacies type 1, 2, 3 and 4 respectively.

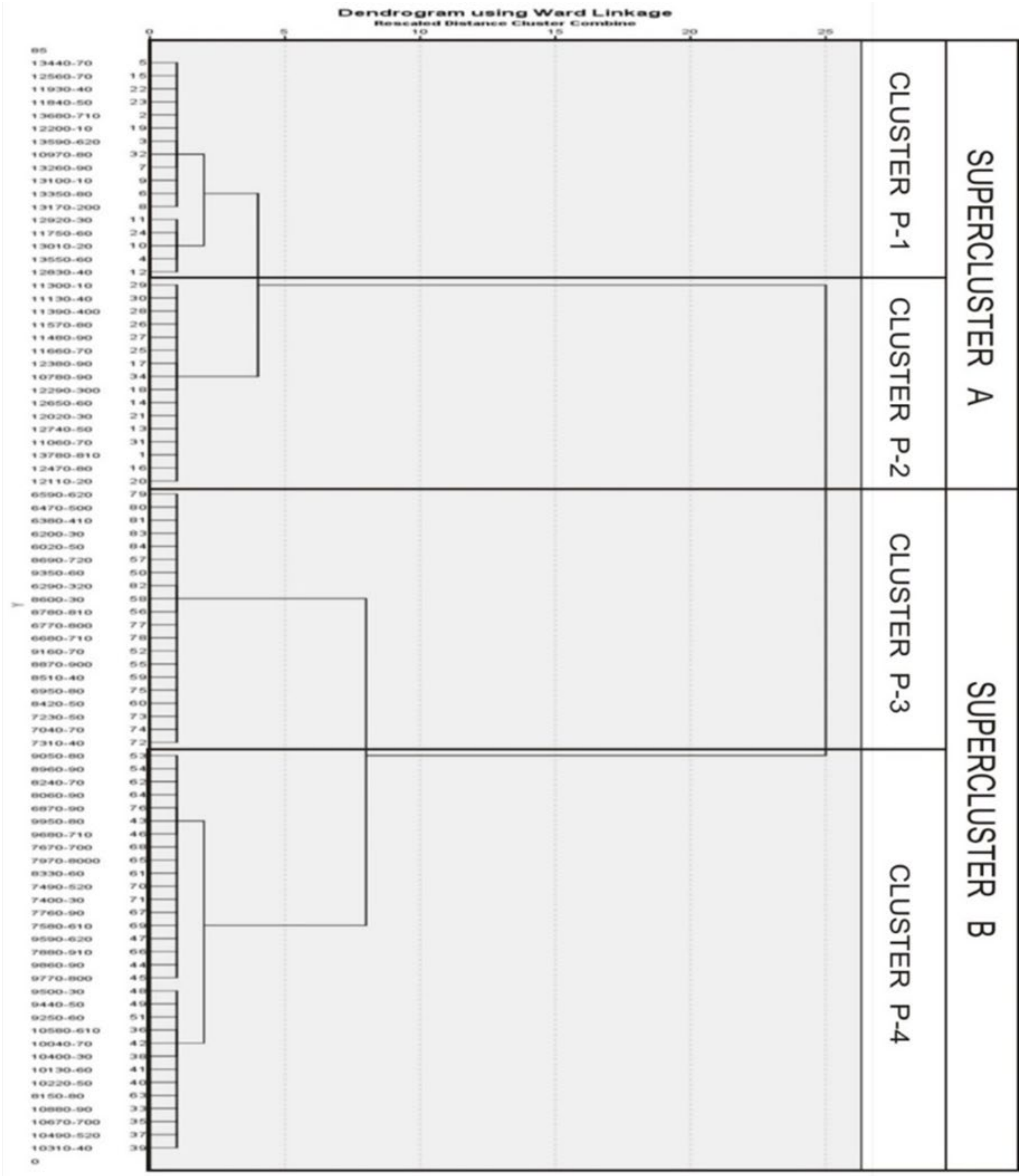

Fig. 3. Dendogram by Q-mode of CTP-1 well showing the grouping of samples.

5.1. Palynofacies 1 (P-1): [*Phytoclasts (PHY) and Opaques (OPA) -Equal Dominance*] (Plate 4; A, B)

This type of palynofacies is recorded mainly from samples between the interval 13680-710 ft (1,145 – 55 m) and 11750-60 ft. (3,560 – 64 m). It is characterized by relatively equal percentage of translucent phytoclasts (phytoclast) and opaques phytoclast (opaques) of up to 38% and 37% respectively. The AOM and palynomorphs also have almost equal abundances in this assemblage with a percentage abundance of 12% and of 13% respectively. The phytoclasts consists mainly pale brown and often well preserved structured plant fragments. Opaque phytoclasts (equant to lath-shaped fragments) are mainly products of oxidation of translucent woody material from prolonged transport or post-depositional alteration [63]. The

AOM is orange to brown in colour with often diffused edges. The palynomorphs are mainly of terrestrial origin and are yellowish to medium brown in colour.

Kerogen type: This facies represents kerogen Type III (gas – prone material), due to the abundance of translucent and opaque phytoclasts.

Palaeoenvironmental interpretation: This facies is characterized by high percentages of phytoclasts and opaques which are normally associated with relatively coarse grained, high energy, poor organic facies [13,64]. According to [65], a higher percentage of phytoclasts is usually found close to the fluvial source where they dilute any opaque phytoclasts, palynomorphs or AOM that are present. The dilution of the AOM by the phytoclasts suggests a shallow marine setting greatly influenced by runoff from and proximity to adjacent high landmass [38]. The common occurrence of *Classopollis* also supports this shallow marine condition [66]. The frequent occurrence of *Classopollis,* and *Ephedriptes* pollen which are produced by xerophytic plants in these intervals indicate a warm relatively arid to semi-arid local paleoclimatic conditions. Dinocysts are few and are of the *Subtilisphaera, Cyclonephelium* form group that supports a brackish condition in an inner shelf marine setting [33,67].

Redox condition: As deduced from the APP ternary diagram of [13] (Fig. 4), the studied samples are concentrated in the palynofacies field II indicating marginal marine dysoxic – anoxic basin.

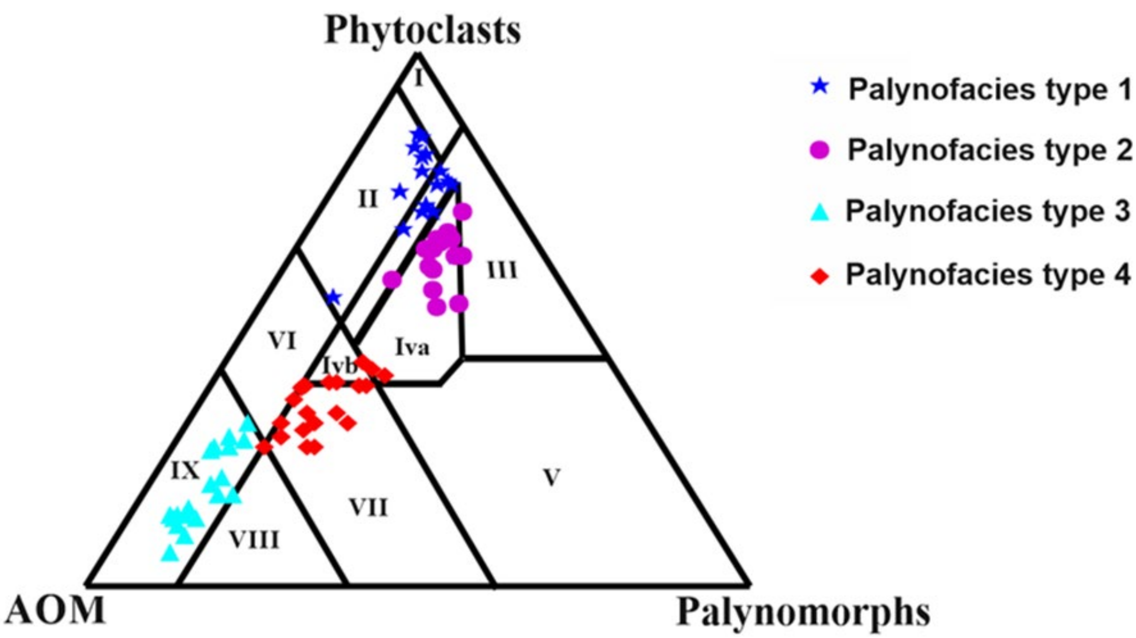

Fig. 4. Key to palynofacies field, kerogen types and corresponding environment of deposition in present study using the APP ternary diagram of [13]. II – Marginal dysoxic-anoxic basin (Type III kerogen), IV – Shelf to basin transition (Type III or II kerogen), IX – Distal suboxic-anoxic basin (Type II>I kerogen), VII – Distal dysoxic-anoxic 'shelf' (Type II kerogen).

5.2. Palynofacies 2 (P-2) [*Phytoclasts (PHY) Dominant*] (Plate 4; C, D)

Palynofacies 2 is recognized within the intervals 11,660-70 ft (3533 – 36 m) and 10,780-90 ft. (2,667 – 70 m) and is characterized by the dominance of phytoclasts of relative percentage abundance of 34%. The relative percentage abundances of AOM, opaques and palynomorphs (mainly terrestrial) for this assemblages are 16%, 29% and 22% respectively. AOM is the least preserved in this assemblage. They show mostly diffused edges and are orange to brown in colour. The phytoclasts are well preserved, with structured plant fragments composed mainly of tracheids and cuticles. The opaques are well preserved, equant to lath shaped fragments of different sizes.

Kerogen type: The dominant phytoclasts with relatively high amounts of opaques and terrestrial palynomorphs points to Kerogen Type III (gas-prone materials) for Palynofacies 2.

Paleoenvironmental Interpretation: Palynofacies 2 is characterized by high abundance of translucent phytoclast which dilutes the other palynofacies elements. Palynomorphs are predominantly terrestrial with high numbers of spores compared to pollen. Dinocysts occur in low numbers similar to that of P 1, but dominated by *Subtilisphaera* (restricted inner-shelf cysts) reflecting low salinity water during sea level fall [68]. The admixture of high terrestrial material of large clasts and low marine elements indicates deposition in a fluvio-deltaic to marginal marine (inner shelf) environment.

Redox conditions: As inferred from the APP ternary plot (Fig. 4), the samples plot in field IVa pointing to a shelf to basin (dysoxic – suboxic) transitional environment.

5.3. Palynofacies (P- 3) [*Amorphous Organic Matter (AOM) Dominant*] (Plate 4; E, F)

The bulk of palynofacies 3 occurs between intervals 10,670-700 ft (3233 – 42 m) and 7,400-30 ft. (2242 – 51 m). It is made up mainly of AOM with a relative percentage of 73%. Phytoclasts contributes (13%), opaques (6%) and palynomorphs (8%) to this assemblage. The facies consists of AOM with fluffy appearance and often uniformly granular. [69] and [13] established that a high percentage of AOM simply indicates a dysoxic-anoxic conditions where depositional site was located relatively further from high terrestrial organic matter input and with prevailing reducing conditions that must have enhanced AOM preservation. Phytoclasts are pale brown to medium brown, with the opaque being equant and lath-shaped. The palynomorphs (pale brown to dark brown) are mainly terrestrial in origin (90% of total palynomorphs).

Kerogen type: Kerogen Type II>I (oil prone material) is suggested for the facies due to the abundance of AOM.

Paleoenvironmental interpretation: The higher relative percentages of the AOM with moderate terrestrial phytoclasts, suggests slightly deeper marine setting during deposition [70] and [71]. Marine elements though few and sporadic include *Florentinia, Spiniferites*, and *Oligosphaeridium* which are middle shelf cysts. Low counts of opaques compared to phytoclasts have been suggested by [63] and [72] to represent low salinity due to close proximity to active fluvio-deltaic sources. This facies also contains higher numbers of the freshwater *Pediastrum.* [73] in [33] have reported that, *Pediastrum* represents an allochthonous component carried by rivers and streams from freshwater catchment areas. [74], assumed that the occurrence of *Pediastrum* and other algae in such marine deposits reflect the predominance deposition of fluviatile sediments related to the discharge of rivers into shelf seas. The abundance of both the freshwater algae (*Pediastrum*) and AOM in these samples maybe related to high terrestrial influx of freshwater algae brought in by rivers or from deltaic sources. The composition of palynomorph data and palynofacies elements suggests a shallow marine environment (inner-middle neritic)

Redox condition: As deduced from the APP ternary plot of [13] (Fig 4), the studied samples plot in the field IX which represents deposition in distal suboxic-anoxic basin.

5.4. Palynofacies (P-4) [*Amorphous Organic Matter (AOM) relatively dominant with Phytoclasts (PHY)*] (Plate 4; G, H)

This palynofacies assemblage is recorded between sample depths between 7310-40 ft (2215 – 24 m) and 5020-50 ft. (1521 – 1530 m). It is characterized by a dominance of AOM and with phytoclasts of relative percentage abundance of 48% and 22% respectively. Opaques contribute 13% of POM whilst palynomorphs contribute 17%. The AOM is mainly diffused at the edges, well preserved and pale yellow to orange in colour. The phytoclasts are pale brown, moderately to well - preserved structured plant fragments. Opaques are equant and lath-shaped, the palynomorphs are medium to dark brown in colour and are mainly of terrestrial origin (about 80% of total palynomorphs). Marine dinoflagellate cysts are few.

Kerogen type: Kerogen Type II (oil - prone material) is assigned to this facies due to the abundance of AOM and common phytoclasts and few marine dinocysts.

Paleoenvironmental interpretation: This environment is characterized by high abundance of AOM and translucent phytocalsts along with palynomorphs of terrestrial origin. Opaques are recorded in less abundance and marine dinoflagellate cysts are few to rare.

Based on the integration of palynomorph data and palynofacies signals i.e dominance of terrestrial palynomorphs (*Deltoidspora*, *Cyathidites*, *Triplanosporites*, *Classopollis, Ephedripites, Cyberosporites* etc), and phytoclasts over few brackish water dinocysts (*Subtilispheara, Cyclonephylium, Systematophora*) a marginal marine setting is suggested for this environment.

Redox condition: From sample plots in the APP diagram (Fig 4), the studied samples are mainly concentrated in the palynofacies field VII pointing to a distal dysoxic to anoxic shelf condition.

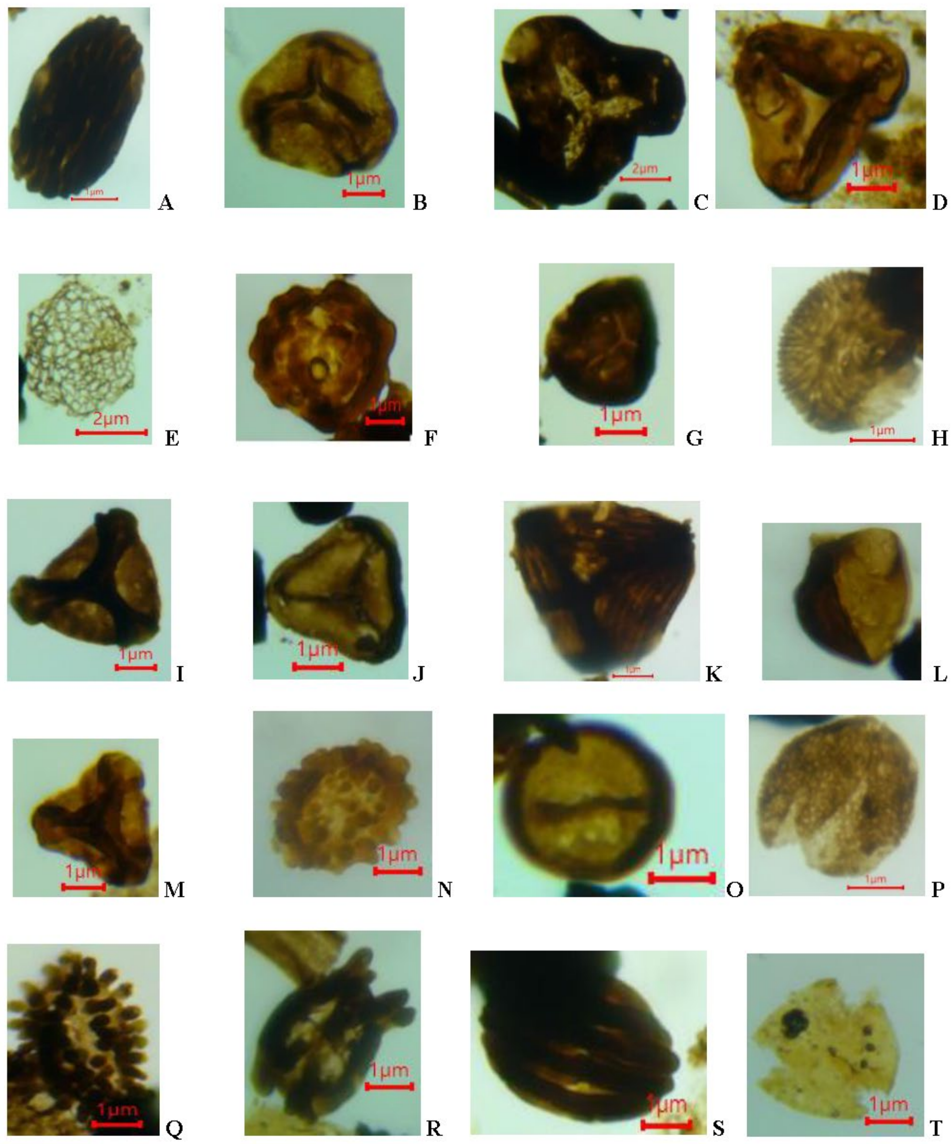

Plate 1. **Fig. A**. *Ephedripites elsikii* Herngreen, 1975; **Fig. B**. *Matonisporites crassiangulatus* (Balme) Dettman, 1963; **Fig C.** *Deltoidospora mesozoica* (Theigart) Schuuram, 1977; **Fig. D.** *Deltoidospora* sp; **Fig. E.** *Afropollis jardinus* (Brenner) Doyle, Jardine & Doerenkamp, 1982; **Fig. F.** *Verrutriletes* sp.; **Fig. G.** *Deltoidspora minor* (Couper) Pocock, 1970; **Fig. H.** *Classopollis spinosus* Herngreen, 1973; **Fig. I.** *Deltoidospora toralis* (Leschik) Lund, 1977; **Fig. J.** *Deltoidospora psilostoma* Rouse, 1953 *;* **Fig. K.** *Cicatricosisporites* sp.; Fig. L. *Triplanosporites* sp.; Fig. M. *Cibotiumspora jurienensis* (Balme) Filatoff, 1975; **Fig. N.** *Leptolepidites* sp.; **Fig. O.** *Classopollis obidosensis* Groot & Groot, 1962; **Fig. P.** *Retimonocolpites variplicatus* Shrank and Mahmoud, 1998; **Fig. Q.** *Reyrea polymorphus* Herngreen, 1973; **Fig. R.** Dyad of *Sofrepites legouxiae* Jardine, emend Boltenhagen, 1982; *Fig. S. Ephedripites* sp.;Fig. T. *Tricolpites* sp.

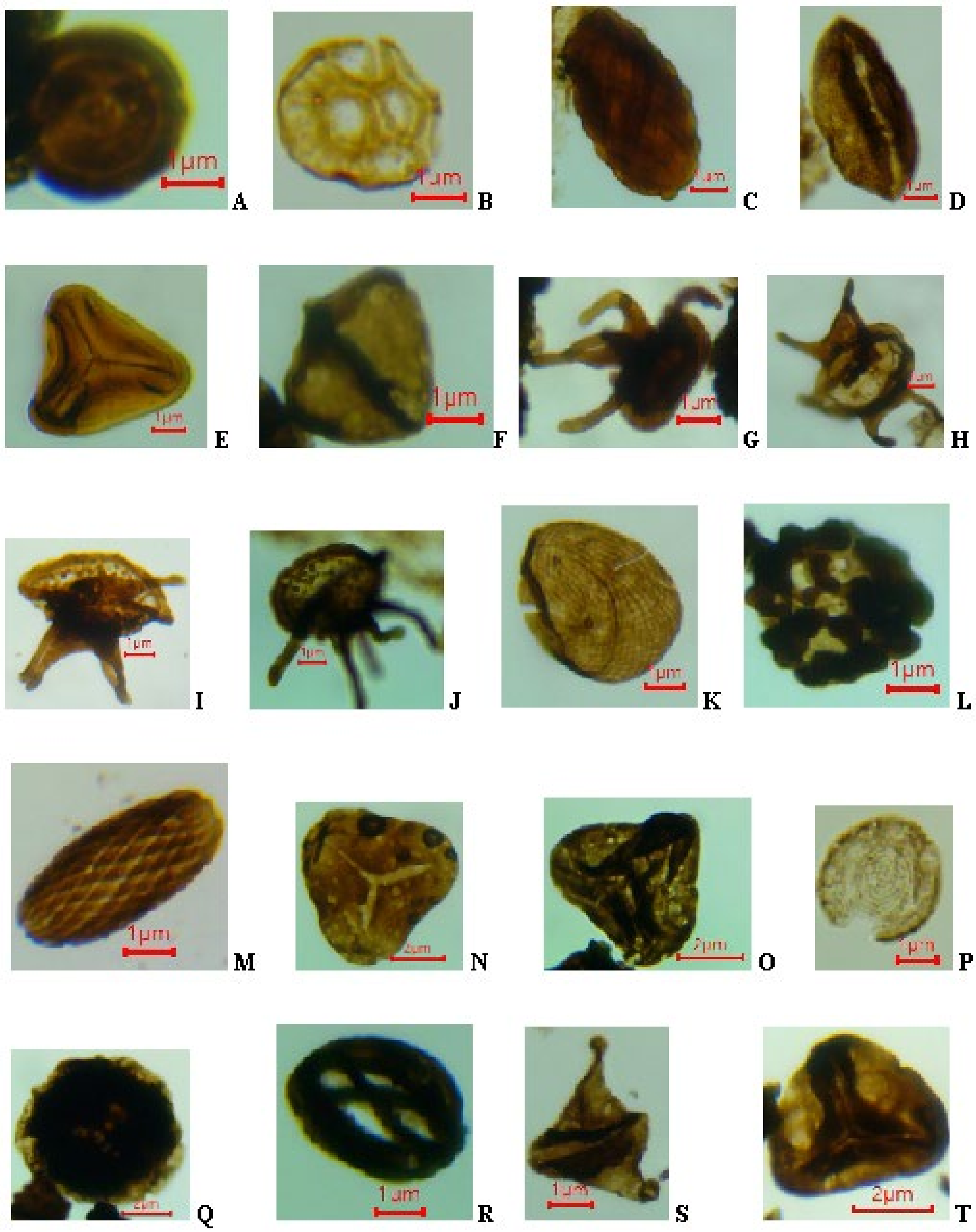

Plate 2. **Fig. A.** *Classopollis torosus* (Reissinger) Balme, 1957; **Fig. B.** *Cretacaeiporites polygonalis* (Jardine & Magloire) Herngreen, 1973; **Fig. C.** *Gnetaceaepollenites* sp. *;* **Fig. D.** *Cycadopites* cf. *carpentieri* (Delcourt & Sprumomt) Singh, 1964; **Fig. E.** *Gleichenidiites senonicus* Ross emend. Skarby, 1964; **Fig F.** *Triplanosporites sinuosus* Thomson and Pfung, 1953; **Fig. G*.*** *Elaterosporites acuminatus* (Stover) Jardine, 1967; **Fig. H*.*** *Elaterosporites klaszii* (Jardine & Magloire) Jardine, 1967; **Fig. I.** *Elaterosporites protensus* (Stover) Jardine 1967; **Fig. J.** *Elaterosporites verrucatus* (Jardine & Magloire) Jardine, 1967; **Fig. K*.*** *Classopollis classoides* Pfung, 1953; **Fig. L*.*** *Leptolepidites psarosus* Norris 1969; **Fig. M*.*** *Ephedripites jansonii* (Pocock) Muller, 1968; *Fig. N. Cyathidites australis* Couper, 1953; **Fig. O*.*** *Cyathidites* sp.; **Fig. P.** *Chomotriletes minor* (Kedves) Pocock, 1970; **Fig. Q.** *Crybelosporites pannuceus* (Brenner) Srivastava, 1977; **Fig. R*.*** *Galeacornea causea* Stover 1963; **Fig. S.** *Elateropollenites jardinei* Herngreen, 1973; **Fig. T*.*** *Murospora* sp.

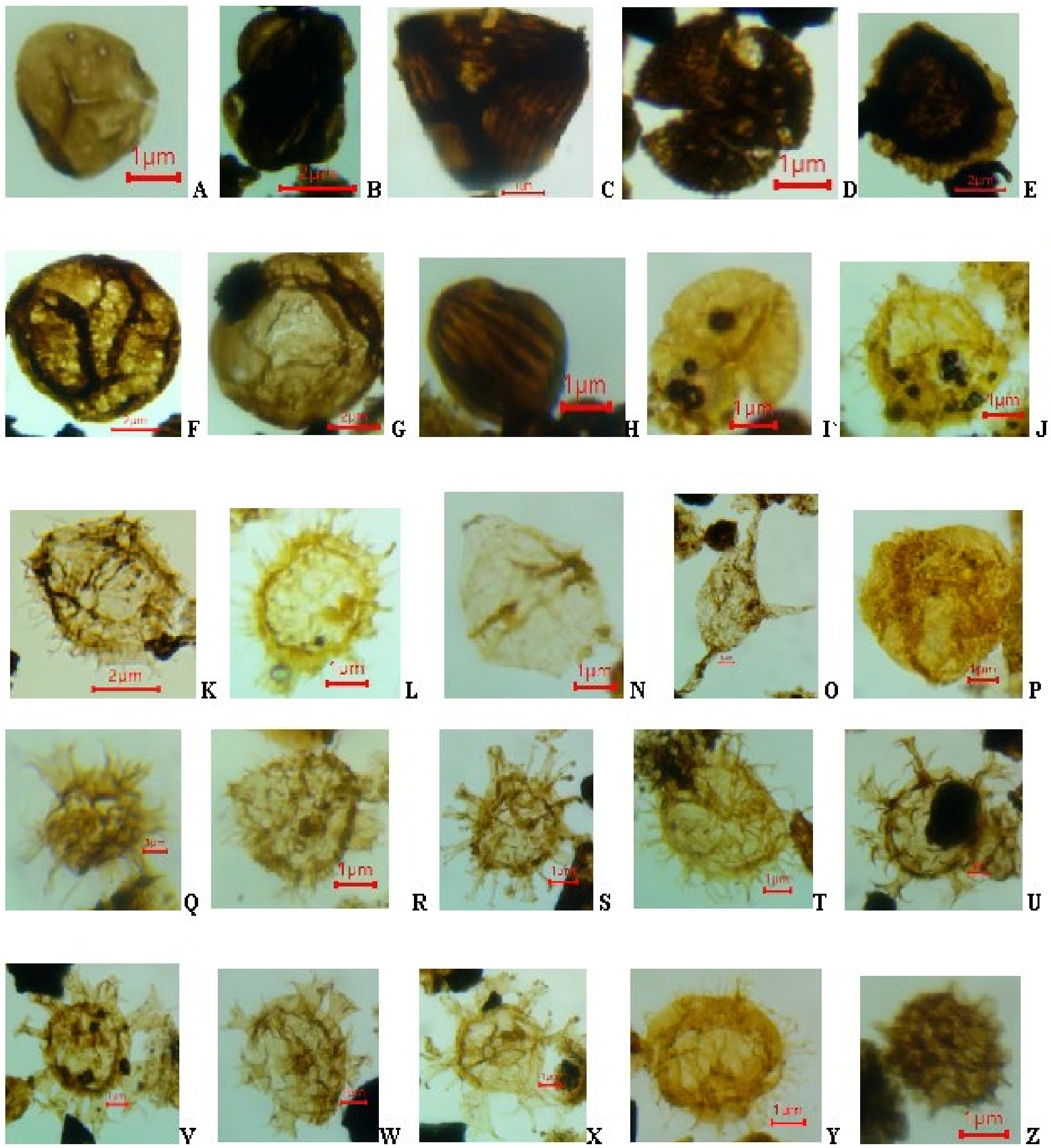

Plate 3. **Fig. A.** *Dictyophyllidites harrisii* Couper, 1958; **Fig. B.** *Ephedripites irregularis* Herngreen, 1973 **Fig. C.** *Cicatricosisporites australiensis* (Cookson) Potonie, 1956; **Fig. D.** *Tricolpites vulgaris (Pierce)* Srivastava, 1969; **Fig. E.** *Aequitriradites spinulosus* (Cookson & Dettman) Cookson & Dettman, 1961; **Fig. F.** *Araucariacites australis* Cookson ex Couper, 1953; **Fig. G.** *Inaperturopollenites dubius* (Potonie & Venitz) Thomson & Pflung, 1953; **Fig. H.** *Ephedripites ovalis* Muller, 1968; **Fig. I.** *Striopollenites* sp.; Fig J. *Coronifera tubulosa* Cookson & Eisenack, 1974; **Fig. K.** *Spiniferites multibrevis* (Davey & Williams) Below, 1882; **Fig. L.** *Coronifera oceanica* Cookson & Eisenack, 1958; **Fig. M.** *Systematophora* sp.; **Fig. N.** *Subtilisphaera senegalensis* Jain & Millepied, 1973; **Fig. O.** *Odontochitina operculata* (Wetzel) Deflandre, 1946; **Fig. P.** *Cyclonephilium vannophorum* Davey, 1969; **Fig. Q.** *Florentinia laciniata* (Davey and Verdier) Below, 1982; **Fig. R.** *Coronifera tubulosa* Cookson & Eisenack, 1974 ; **Fig. S.** *Florentinia berran* Below, 1982; **Fig. T.** *Spiniferites ramosus* (Ehrenberg) Loeblich & Loeblich, 1966; **Fig. U.** *Oligosphaeridium complex* (White) Davey and Williams, 1966; **Fig. V.** *Oligosphaeridium pulcherrimum* (Deflandre & Cookson) Davey and Williams, 1966; **Fig. W.** *Oligosphaeridium poculum* Jain, 1977; Fig. X. *Oligosphaeridium perforatum* (Gocht) Davey & Williams, 1969; **Fig. Y.** *Spiniferites* sp cf. *S. fluens* (Hansen) Stover & Williams, 1987. **Fig. Z.** *Pediastrum* sp.

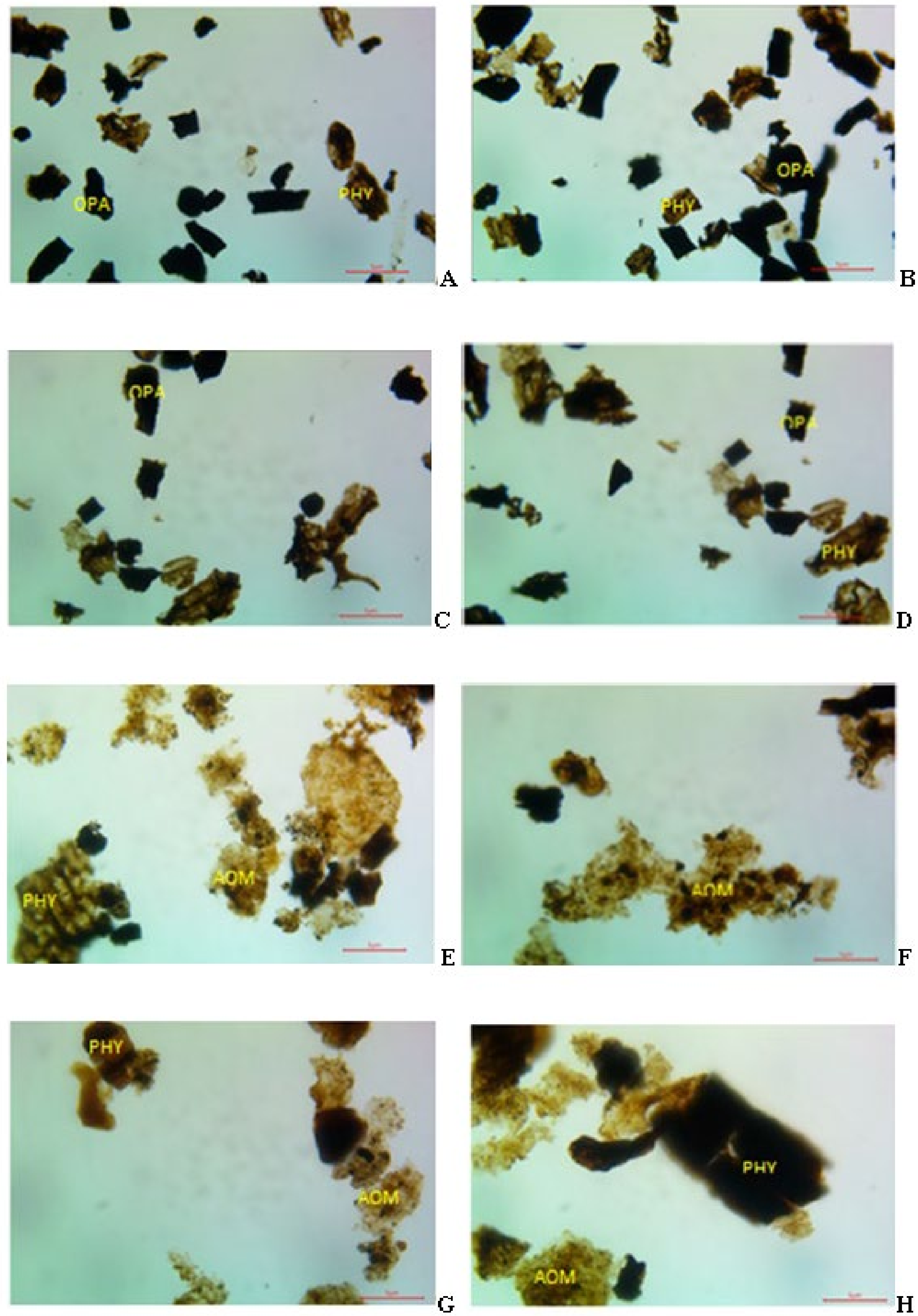

Plate 4. Fig. A, B. Photomicrograph showing recorded palynofacies assemblage P-1; **Fig. C, D.** Photomicrograph showing recorded palynofacies assemblage P-2; **Fig. E. F.** Photomicrograph showing recorded palynofacies assemblage P-3; **Fig. G, H.** Photomicrograph showing recorded palynofacies assemblage P-4.

6. Organic thermal maturation

Thermal maturity which is influenced by source rock organic matter type, the presence of excess free hydrocarbon, mineral matter, content, burial depth and age can be inferred from the degree of thermal alteration of organic matter due to prolonged heating [75,78].

[76-78] have reported that Vitrinite Reflectance (Ro) provides an overview of maturity distribution as it is the most reliable and commonly used maturity indicator. Ro values between 0.5 and 0.7 % are indicative of a low source rock grade. That between 0.7 to 1.0 % indicates a moderate source rock grade and values between 1.0 and 1.3 % refers to a high source rock grade.

In observations of spore colour and correlation of values to Thermal Alteration Index (TAI) and Ro values (Fig 5), the observed pollen colours of the simple thin – walled psilate spores (*Deltoidspora, Cyathidites*) ranged from yellow to yellowish orange with TAI values of 1+, 2, -2 and Ro values of 0.3 - 0.5 %. The values suggest immature stage (Kerogen Type III) which is gas-prone for Palynofacies 1 (P-1) and Palynofacies 2 (P-2).

For Palynofacies 3 (P-3) and Palynofacies 4 (P-4) the observed exine colours are from bright orange to brown/tan (TAI values 2+, 3-, 3) equivalent to Ro values of 0.5 - 0.9 %. The values infer a mature phase (Kerogen Type II) which is oil prone. The suggested kerogen types from palynofacies analysis corroborates that of the thermal maturity studies for the various assemblages.

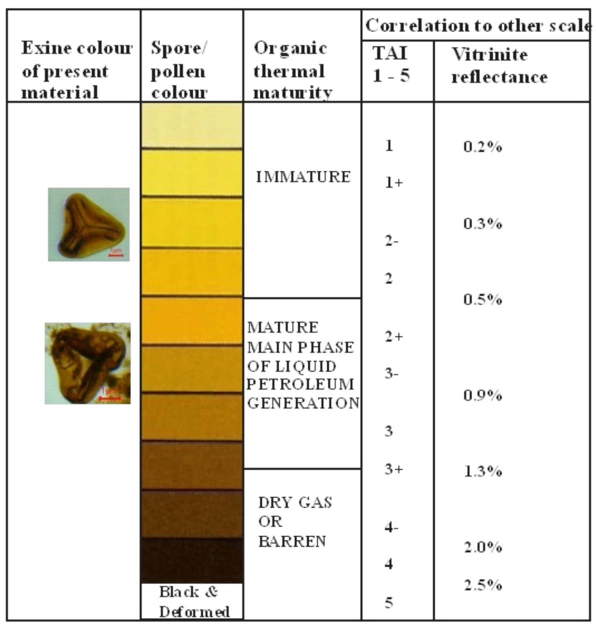

Fig. 5. Exine colour of spores in present study compared to the Pearson's spore/pollen colour chart. (modified after [78]).

7. Conclusion

The studied samples from well CTP-1 offshore Tano Basin, revealed that, the sediments are characterized by microfossil assemblage of abundant and diverse miospores and subordinate dinoflagellates. Three miospore assemblage zones have been proposed for the sediments based on the FAD and LAD of stratigraphically important species. These are: *Elateropollenites jardinei - Reyrea polymorphus* Zone, *Elaterocolpites castelainii - Afropollis jardinus* Zone and *Cretacaeiporites polygonalis – Classopollis classoides* Zone. These assemblage zones span from early Albian to late Cenomanian age. The miospores belongs to the Albian-Cenomanian Elaterate paleofloral Province with sediments deposited in a relatively warm and arid paleoclimate in a shallow marine environment.

Four palynofacies associations have been identified in the study. These are: P-1 deposited in a brackish condition in an inner shelf marine setting under marginal dysoxic-anoxic basin and characterized by Kerogen Type III (gas prone); P-2 reflects deposition in a fluvio-deltaic to marginal marine (inner shelf) environment under shelf to basin transition depositional conditions and characterized by Kerogen Type III or II (gas prone); P-3 suggests a shallow marine environment (inner-middle neritic) in a distal suboxic- anoxic basin environment with POM indicating Kerogen Type II>I (highly oil prone); and P-4 suggests a marginal marine setting characterized by distal dysoxic-anoxic shelf condition and indicative of Kerogen Type II (oil prone).

TAI values of 1+ to 2, -2, equivalent to 0.3 - 0.5 % Ro of palynomorph exines from P-1 and P-2 infers immature phase, while TAI values of 2+, 3-, 3, equivalent to 0.5 - 0.9 % Ro from P-3 and P-4 suggest mature stage.

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