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RESEARCH ARTICLE

Palynostratigraphy, palynofacies, and organic thermal maturity of the Cretaceous sediments of Kobnaswaso - 1 Well, onshore Tano basin (Ghana)

Palinoestratigrafía, palinofacies y maduración térmica orgánica de los sedimentos cretácicos de Kobnaswaso – Pozo 1, Cuenca de Tano (Ghana)

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Key point:

Biostratigraphy revealed five informal sporomorph units, which reflects sedimentation in a relatively nearshore to shallow marine settings under humid to arid conditions.

Four palynofacies types were identified, with PF-1 being oil-prone rocks, while PF-2, PF-3 and PF-4 are dominated by gas-prone rocks.

Observed TAI, and Ro indicate that, samples PF-1 are thermally matured, whereas those of PF-2 to PF-4 are immature.

ABSTRACT

Particulate organic matter from sediments in the Kobnaswaso-1 well, onshore Tano Basin, Ghana was subjected to palynological analysis. Palynomorphs recovered allow for the identification of five informal biozones: *Afropollis operculatus* Total Range Zone (PZ-I) (?late Aptian), *Elateropollenites jardinei - Sofrepites legouxiae* Interval Zone (PZ-II) (early Albian to early Cenomanian), *Triporites* sp - *Classopollis brasiliensis* Interval Zone (PZ-III) (mid-late Cenomanian), *Droseridites senonicus* Interval Zone (PZ-IV) (late Turonian-Santonian), and *Senegalinium laevigatum - Cordosphaeridium inodes - Andalusiella dubia* Assemblage Zone (PZ-V) (early Campanian). PZ-I, PZ-II, and PZ-III suggest sediment deposition in relatively shallow marine habitats with vegetation growing in coastal local wetlands under semi-arid/arid climatic conditions. PZ-IV indicates the presence of rainforest trees under humid climatic conditions. PZ-V reflects sedimentation in mangrove environment under a warm humid tropical to subtropical climate. Palynofacies analysis revealed four palynofacies types: PF-1 (inner neritic zone with proximal suboxic-anoxic shelf condition), PF-2 (marginal marine setting with marginal dysoxic-anoxic basin redox condition), PF-3 (fluvio-deltaic and mud-dominated oxic shelf), and PF-4 (nearshore to shallow marine environment with dysoxic-anoxic redox condition). PF-1 is dominated by oil-prone materials (kerogen type II), while PF-2, PF-3, and PF-4 are dominated by gas-prone materials (kerogen type III). Observed Thermal Alteration Index (TAI), and Vitrinite Reflectance (Ro) indicate that, samples associated with PF-1 are thermally mature, whereas those of PF-2, PF-3, and PF-4 are considered thermally immature.

Keywords: Palynostratigraphy; Palynofacies; Thermal maturation; Cretaceous; Tano Basin.

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Puntos clave:

La bioestratigrafía reveló 5 unidades informales de esporomorfos, indicando sedimentación en ambientes marinos someros cercanos a la costa, bajo condiciones húmedas a áridas.

Se identificaron 4 tipos de palinofacies: PF-1 con potencial petrolífero, mientras que PF-2, PF-3 y PF-4 tiene potencial gasífero.

Los valores de TAI y Ro indican que las muestras PF-1 presentan madurez térmica, mientras que las de PF-2 a PF-4 son inmaduras.

RESUMEN

Se realizó un análisis palinológico de la materia orgánica particulada de los sedimentos del pozo Kobnaswaso-1, en la cuenca de Tano, Ghana. Los palinomorfos recuperados permitieron identificar cinco biozonas informales: Zona de Distribución Total de *Afropollis operculatus* (PZ-I) (¿Aptiense tardío?), Zona de Intervalo *Elateropollenites jardinei - Sofrepites legouxiae* (PZ-II) (Albiense temprano a Cenomaniense temprano), Zona de Intervalo *Triporites sp - Classopollis brasiliensis* (PZ-III) (Cenomaniense medio-tardío), Zona de Intervalo *Droseridites senonicus* (PZ-IV) (Turoniense tardío-Santoniense) y Zona de Asociación *Senegalinium laevigatum - Cordosphaeridium inodes - Andalusiella dubia* (PZ-V) (Campaniense temprano). Las zonas PZ-I, PZ-II y PZ-III sugieren la deposición de sedimentos en hábitats marinos relativamente someros con vegetación en humedales costeros locales, bajo condiciones climáticas semiáridas/áridas. La zona PZ-IV indica la presencia de árboles de selva tropical en condiciones climáticas húmedas. La zona PZ-V refleja la sedimentación en un ambiente de manglar bajo un clima tropical a subtropical cálido y húmedo. El análisis de palinofacies reveló cuatro tipos: PF-1 (zona nerítica interna con condiciones de plataforma proximal subóxicas-anóxicas), PF-2 (ambiente marino marginal con condiciones redox de cuenca marginal disóxica-anóxica), PF-3 (plataforma fluvio-deltaica y óxica dominada por lodo) y PF-4 (ambiente costero a marino somero con condiciones redox disóxicas-anóxicas). La zona PF-1 está dominada por materiales con potencial para generar petróleo (querógeno tipo II), mientras que las zonas PF-2, PF-3 y PF-4 están dominadas por materiales con potencial para generar gas (querógeno tipo III). El Índice de Alteración Térmica Observado (TAI) y la Reflectancia de Vitrinita (Ro) indican que las muestras asociadas con PF-1 son térmicamente maduras, mientras que las de PF-2, PF-3 y PF-4 se consideran térmicamente inmaduras.

Palabras clave: Palinoestratigrafía; Palinofacies; Maduración térmica; Cretácico; Cuenca de Tano.

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1. Introduction

The Tano Basin is regarded as a large petroliferous basin in West Africa. It is situated in the southwestern region of Ghana and consists of offshore and nearshore sections, which are known for their significant hydrocarbon resources (Atta-Peters & Achaegakwo, 2016). The basin represents an eastward extension of the Cote d'Ivoire-Ghana Basin, located along a significant transform fault and forms part of the Gulf of Guinea Province. The Tano Basin is bounded to the north by the Ghana and Cote d'Ivoire mainlands, to the west by the St. Paul transform zone, to the east by the Romanche fracture zone, and to the southwest by the Atlantic Ocean's mid-oceanic ridge. (Davies, 1989; Brownfield & Charpentier, 2006; Atta-Peters *et al.*, 2013; Atta-Peters & Garrey 2014; Bempong *et al.*, 2019). The water depth within this region varies, spanning from 91 to 125 meters (Atta-Peters & Kyorku, 2013). The basin is known to have an area of about 3000 km², with an estimated onshore area of 1165 km². (Kesse, 1985; Garry *et al.*, 2016). It is also estimated to have an onshore total thickness of approximately 3048 meters, with 1768 meters being offshore (Garry *et al.*, 2016).

The Tano Basin has a petroleum system, where the Cretaceous sequences functioned as the source rock, and the significant reservoir units include sandstones and slope fan turbidite sandstones (Brownfield & Charpentier, 2006; Brownfield, 2016). Seals are marine shale and minor faults with both structural and stratigraphic traps (Adda, 2013). The migration pathway of hydrocarbon is minimal.

Oil and gas exploration particularly in the Tano Basin of Ghana has made well samples available for palynological and integrated research studies, which has yielded palynomorphs of biostratigraphic importance. Palynological and hydrocarbon potential studies of the Cretaceous subsurface succession of different wells in the Tano Basin by authors including Atta-Peters & Salami (2004), Atta-Peters & Salami (2006), Atta-Peters *et al.* (2013), Atta-Peters (2013), Atta-Peters & Kyorku (2013), Atta-Peters *et al.* (2015), Atta-Peters & Achaegakwo (2016), and Achaegakwo & Atta-Peters (2021) have generally focused their reports on relative age dating, palynofacies analysis, paleoenvironmental interpretation, and determination of kerogen types.

This current study, which documents the first palynological work of the Kobnaswaso-1 well, also demonstrate the use of palynofacies analysis and Thermal Alteration Index (TAI) as an excellent parameter for source rock evaluation as intimated by Aggarwal (2021). El Atfy (2021) reveals that palynofacies analysis provides more parameters than bulk geochemical data and allows interpreting petroleum source potential from direct information on biological sources and constituents of particulate organic matter.

The main objectives of the study are to: (a) establish informal palynozones for the succession based on qualitative and quantitative analysis of first and last occurrences of palynomorph species (b) describe and identify palynomorphs, palynofacies associations and their stratigraphic distribution (c) integrate palynomorphs with other sedimentary organic matter to evaluate paleoenvironment and kerogen types and (d) use spore colour to infer the hydrocarbon potential of the sediments.

1.1. Geology and stratigraphic setting

The Tano Basin has undergone a series of tectonically driven evolutionary stages that express a continental to oceanic rifting in a large-scale transform fault (Davies, 1986; Brownfield & Charpentier, 2006; Atta-Peters & Kyorku, 2013; Atta-Peters *et al.*, 2013; Garry *et al.*, 2016; Brownfield, 2016; Bempong *et al.*, 2019). These tectonic evolutionary stages are highlighted by Brownfield (2016) into three main tectonic phases: the pre-rift, syn-rift, and post-rift.

The Pre-Rift phase involves the post-Hercynian opening of the North Atlantic and the separation of North America from Eurasia and Africa, which commenced in the late Permian-early Triassic period (Brownfield & Charpentier, 2006; Brownfield, 2016). Deposits range from the pre-Cambrian to the Triassic age and are exposed in the Voltaian and Tano Basins of Ghana (Brownfield, 2016).

The Syn-Rift phase involves the formation of transform faults between African and South American plates in Early Cretaceous times (Blarez & Mascle, 1988; Brownfield, 2016). The Aptian initial rifting was accompanied by a 130 km long NE-SW trending marginal ridge associated with fault lineament and later filled with lacustrine and fluvial facies (Davies, 1986; Blarez & Mascle 1988; Arthur *et al.*, 2003; Brownfield & Charpentier, 2006; Brownfield, 2016). Until the late Aptian - early Albian times, the first oceanic accretion was formed (Brownfield & Charpentier, 2006), followed by the final separation of the two continents in the middle to late Albian period as transform tectonism was active (Blarez & Mascle, 1988). This phase coincides with the end of syn-transform tectonism marked by major Albian - lower Cenomanian tectonic unconformity (MacGregor *et al.*, 2003; Brownfield, 2016).

According to Blarez & Mascle (1988), following the early Cenomanian period, the evolution of the Ivory Coast-Ghana margin was primarily influenced by thermal subsidence and an active transform contact between the margin and the neighbouring southern oceanic crust until Santonian times, which resulted in the formation of major oceanic crust and the marginal basins.

The Kobnaswaso Formation, primarily, comprises sandstones, limestones and shales. Despite the deepest well reaching 4,270 meters, the basement of this interval remains unexplored. Sediments of the Kobnaswaso Formation are estimated to be Upper Cretaceous (Davies, 1989). Notably, the South Tano region shows evidence of two distinct mega-sequences. Thus, dark grey to green shales interspersed with occasional beds of very fine sandstone and siltstone characterize the lower mega-sequences. Overlying these shales is the upper mega-sequence, composed of sequences of limestone that coarsen upward, often termed parasequences by Davies (1989).

2. Material and methods

A total of 69 sample slides of ditch cuttings between intervals of 67 - 70 m to 2011 - 2015 m from the Kobnaswaso 1 well, onshore Tano Basin (Figure 1), were obtained from the Core Laboratory of the Ghana National Petroleum Corporation (GNPC). The samples were prepared following the standard palynological extraction techniques including hydrochloric and hydrofluoric acid (HCl and HF) demineralization treatment (Phipps & Playford, 1984). No oxidizing reagents were employed. All slides were examined using a Leica DMEP 750 optical microscope equipped with an AmScope Toup View 3.2 digital camera. This process aimed to generate qualitative and semi-quantitative data on particulate organic matter (POM). A total of 500 palynofacies point counts were made traversing across each slide to determine the organic matter types in the sediments.

To establish grouping patterns among the samples, cluster analysis (Q-mode) was conducted using the IBM SPSS Statistics 25 program, employing Ward's method to generate evenly sized clusters. The AOM-Phytoclast-Palynomorphs (APP) ternary plot of Tyson (1995) and Microplankton-Spore-Palynomorphs (MSP) plot of Traverse (1988) were used to infer and determine kerogen types and depositional environments. Palynomorphs have been compared to similar middle - Late Cretaceous species recovered from other parts of the world, especially from the Africa - South America (ASA) region including Sudan, Nigeria, Egypt, Cote D'Ivoire, Senegal, Angola, Brazil, Venezuela, Columbia, Equador, and Peru. Five informal palynozones were erected from a distribution chart of the identified palynomorphs against their respective sample depths. The proposed palynozones (PZ-I – PZ-V) are based on the last occurrence (LO) or first downhole appearance of selected marker species. This is to eliminate inaccuracies introduced from caving processes associated with cutting samples which can affect first occurrence (FO), but unlikely to alter the last occurrence (LO). An area plot that shows the relative percentage abundances of sedimentary organic matter for each identified palynofacies association was established. For the purpose of estimating the thermal maturity of the samples, the exine colour of the spore *Triplanosporites* in transmitted light microscopy was used and compared with Pearson's (1990) colour chart to determine the numerical thermal alteration index (TAI) of samples.

Equivalent vitrinite reflectance (Ro %) values were obtained by referring to the correlation chart of Traverse (2007).

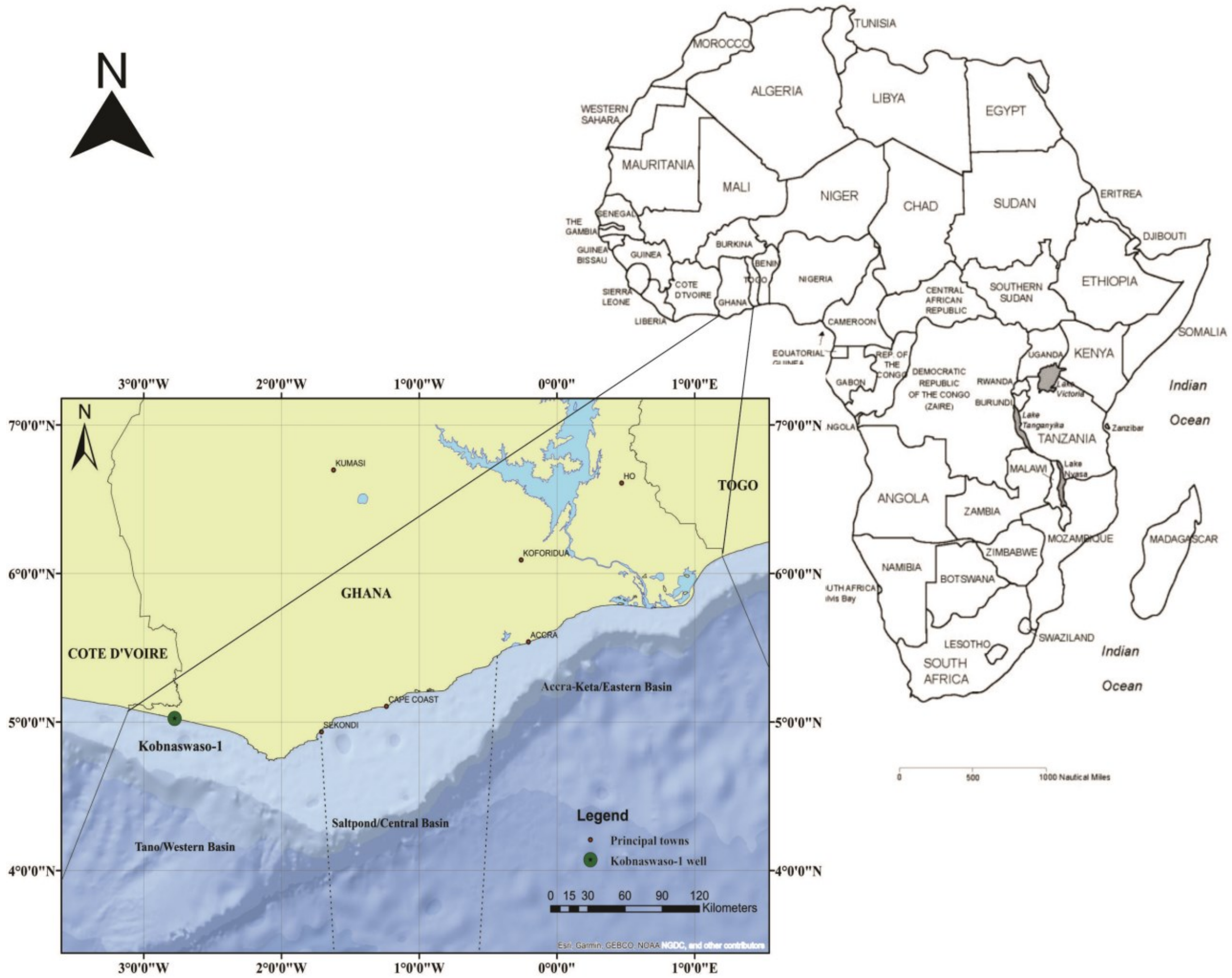


Figure 1. A map showing the location of the Kobnaswaso-1 well in the Onshore Tano Basin (Modified after the GNPC Report, 2010).

Figura 1. Mapa que muestra la ubicación del pozo Kobnaswaso-1 en la cuenca de Tano (Modificado a partir del Informe GNPC, 2010).

3. Results

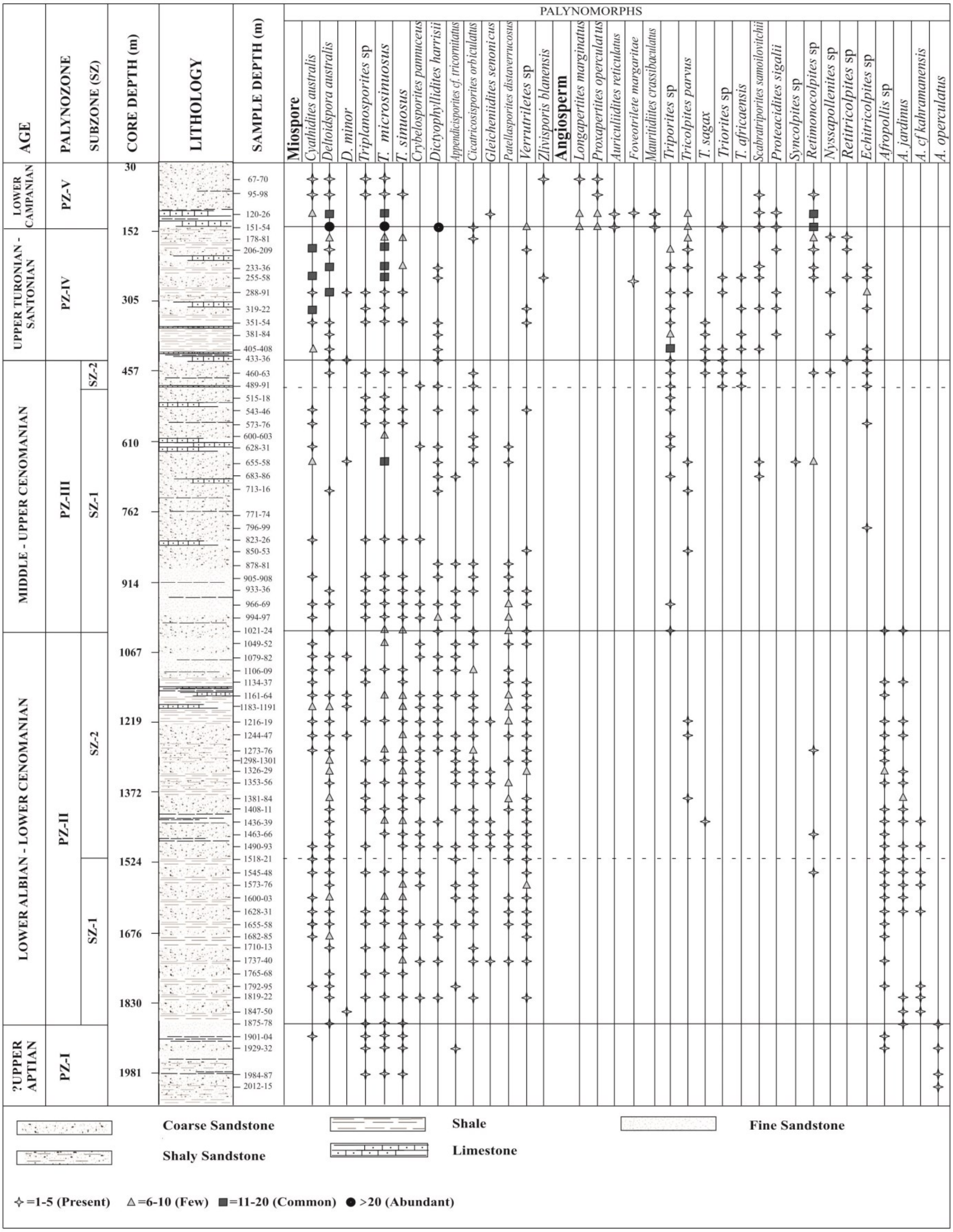
3.1. Palynostratigraphy

The sediments of the Kobnaswaso-1 well, were analyzed, and palynozones for the succession were erected. The spore and pollen have been used for biostratigraphical purposes with dinoflagellate cyst providing additional supporting evidence. The proposed zones are described in ascending order. Almost all of the sample slides examined contained well-preserved to fairly well-preserved and diverse assemblages of spores, pollen, and dinocysts in varying relative abundances. Micro-foraminiferal linings appeared infrequently.

3.1.1. Palynozonation

3.1.1.1. Palynozone I (PZ-I): Afropollis operculatus Total Range Zone

This palynozone is recognized at depth intervals between 2011 - 2015 m to 1875 - 1880 m (Figure 2).


AGE
PALYNOZONE
SUBZONE (SZ)
CORE DEPTH (m)
LITHOLOGY
SAMPLE DEPTH (m)
PALYNOMORPHS
Miospore
Cyathidites australis
Deltoidspora australis
D. minor
Triplanosporites sp
T. microsinuosus
T. sinuosus
Crybelosporites pannuceus
Dictyophyllidites harrisii
Appendicisporites cf. tricornitatus
Cicatricosisporites orbiculatus
Gleicheniidites senonicus
Patellasporites distaverrucosus
Verrutriletes sp
Zlivisporis blanensis
Angiosperm
Longapertites marginatus
Proxapertites operculatus
Auriculiidites reticulatus
Foveotriletes margaritae
Mauritiidites crassibaculatus
Triporites sp
Tricolpites parvus
T. sagax
Triorites sp
T. africaensis
Scabratriporites samoilovichii
Proteacidites sigalii
Syncolpites sp
Retimonocolpites sp
Nyssapollenites sp
Retitricolpites sp
Echitricolpites sp
Afropollis sp
A. jardinus
A. cf kahramanensis
A. operculatus
LOWER CAMPANIAN
PZ-V
UPPER TURONIAN - SANTONIAN
PZ-IV
MIDDLE - UPPER CENOMANIAN
PZ-III
SZ-2
SZ-1
LOWER ALBIAN - LOWER CENOMANIAN
PZ-II
SZ-2
SZ-1
?UPPER APTIAN
PZ-I
30
152
305
457
610
762
914
1067
1219
1372
1524
1676
1830
1981
67-70
95-98
120-26
151-54
178-81
206-209
233-36
255-58
288-91
319-22
351-54
381-84
405-408
433-36
460-63
489-91
515-18
543-46
573-76
600-603
628-31
655-58
683-86
713-16
771-74
796-99
823-26
850-53
878-81
905-908
933-36
966-69
994-97
1021-24
1049-52
1079-82
1106-09
1134-37
1161-64
1183-1191
1216-19
1244-47
1273-76
1298-1301
1326-29
1353-56
1381-84
1408-11
1436-39
1463-66
1490-93
1518-21
1545-48
1573-76
1600-03
1628-31
1655-58
1682-85
1710-13
1737-40
1765-68
1792-95
1819-22
1847-50
1875-78
1901-04
1929-32
1984-87
2012-15
Coarse Sandstone
Shale
Fine Sandstone
Shaly Sandstone
Limestone
=1-5 (Present)
=6-10 (Few)
=11-20 (Common)
>20 (Abundant)

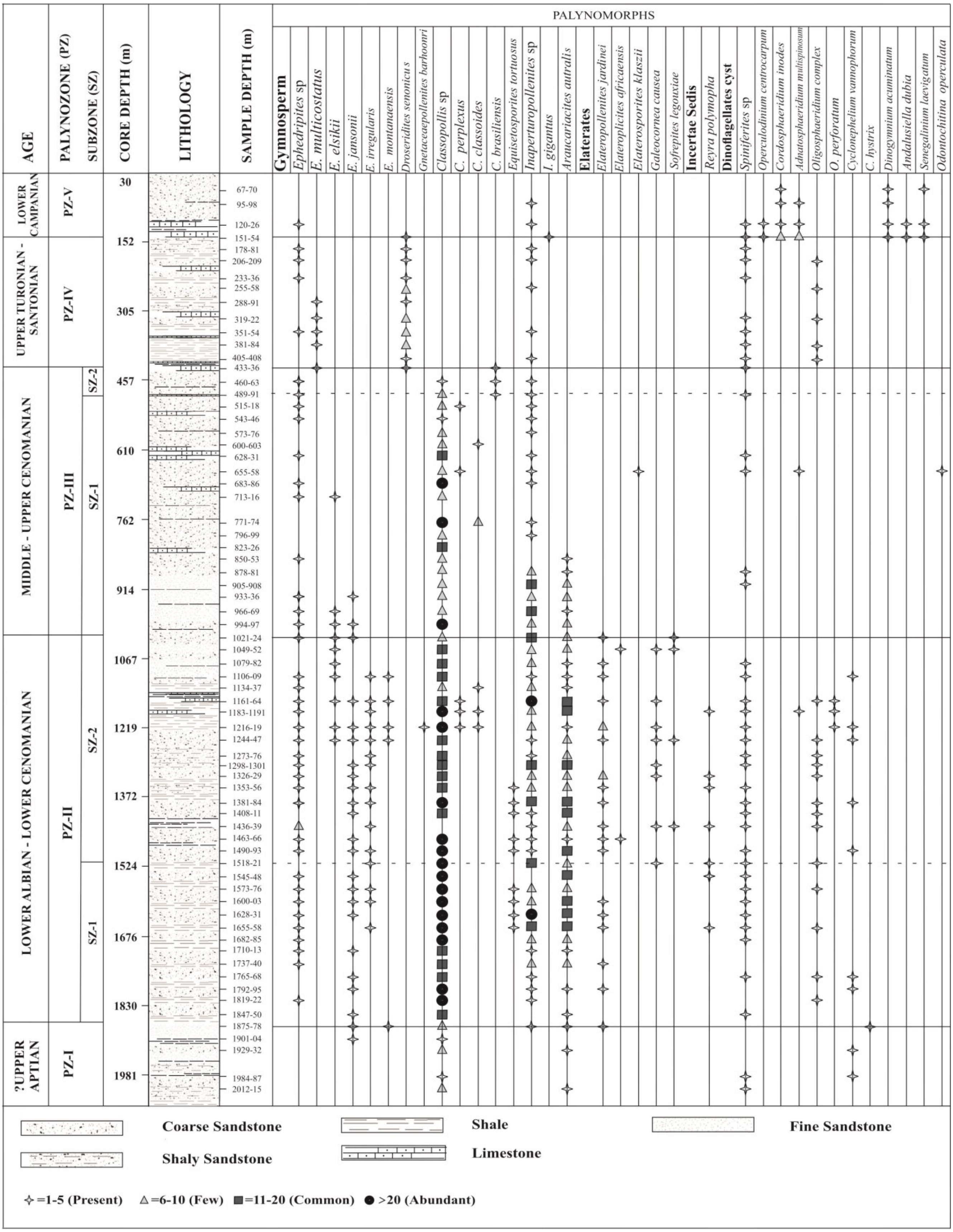


Figure 2. Semi-quantitative distribution of palynomorphs between intervals 67 - 70 m to 2012 – 2015 m in well Kobnaswaso-1.

Figura 2. Distribución semicuantitativa de palinomorfos entre los intervalos 67 - 70 m a 2012 - 2015 m en el pozo Kobnaswaso-1.

Definition of the zone: The top and base of this zone are marked by the LO and FO respectively of the *Afropollis operculatus.*

Associated taxa: Triplanosporites sinuosus, Cyathidites australis, Cicatricosisporites orbiculatus, Ephedripites jansonii, Araucariacites australis, Classopollis spp., Spiniferites spp., Cyclonephelium vannophorum (See Plate 1, 3 & 5).

Comments: This palynozone primarily consists of terrestrial palynomorphs, which are made up of dominant gymnosperm pollens with few angiosperm pollen grains and pteridophyte spores. Dinocysts are few to rare within this interval. Palynological assemblages within PZ - I show poor diversity but fairly preserved. The limited diversity of microflora prevents the precise dating of this interval. However, the presence of Afropollis operculatus is significant.

3.1.1.2 Palynozone II (PZ-II): Elateropollenites jardinei - Sofrepites legouxiae Interval Zone

This palynozone is recognized at depth intervals between 1875 - 1880 m to 1021 - 1024 m (Figure 2).

Definition of the zone: The base is defined by the FO of *Elateropollenites jardinei*, while the top coincides with the LO of *Sofrepites legouxiae.*

Associated taxa: *Afropollis. jardinus, A.* cf *kahramanensis, Galeacornea causea, Elateroplicites africaensis, Subtilisphaera* sp.*, Odontochitina operculata, Oligosphaeridium complex* (Plate 2, 4 & 5).

Comments: Terrestrial palynomorphs, predominantly gymnosperm pollen grains, dominate the taxa in this zone, with some recoveries of marine palynomorphs in most intervals of this zone. Sporomorphs are well-preserved with high diversity.

Subzone 1 (SZ-1) - *Elateropollenites jardinei - Galeacornea causea* Interval Zone from 488 - 490 m to 433 - 436 m (Figure 2) is defined by FO of the *Elateropollenites jardinei* for the base while the top of this zone coincides with the FO of *Galeacornea causea.*

Subzone 2 (SZ-2) - *Galeacornea causea, Elateroplicites africaensis and Sofrepites legouxiae* Assemblage Zone from 1875 - 1880 m to 488 - 490 m) (Figure 2) defined by FO of *Galeacornea causea* for the base and the LO of *Sofrepites legouxiae* for the top.

3.1.1.3. Palynozone III (PZ-III): Triporites sp - Classopollis brasiliensis Interval Zone

This palynozone is recognized at depth intervals between 1875 - 1880 m to 433 - 436 m (Figure 2).

Definition of the zone: The base is defined by the FO of the *Triporites* sp while the top is marked by the LO of *Classopollis brasiliensis.* (Figure 2).

Associated taxa: *Triorites africaensis, Classopollis classoides, C. perplexus, C. torosus, Inaperturopollenites* spp., *E. elsikii, Elaterosporites klaszii. Odontochitina operculata* (See Plate 2, 3, 4 & 5).

Comments: Recovered taxa are primarily composed of terrestrial palynomorphs, with sporadic occurrences of marine palynomorphs within specific intervals of this zone. Gymnosperms pollen grains dominate the sporomorph group but show low diversity together with the angiosperm pollen grains and pteridophyte spores. Palynozone III is subdivided into two subzones, designated as:

Subzone 1 (SZ-1) – *Triporites* sp - *Crybelosporites pannuceus* Interval Zone from 1875 - 1880 m to 488 - 490 m) (Figure 2) defined by FO of *Triporites* sp for the base and the LO of *Crybelosporites pannuceus* for the top.

Subzone 2 (SZ-2) - *Classopollis brasiliensis* Interval Zone from 488 - 490 m to 433 - 436 m (Figure 2) is defined by LO of the *Crybelosporites pannuceus* for the base while the top of this zone coincides with the LO of *Classopollis brasiliensis.* This zone is also recognized by the presence *Triorites africaensis.*

Plate 1

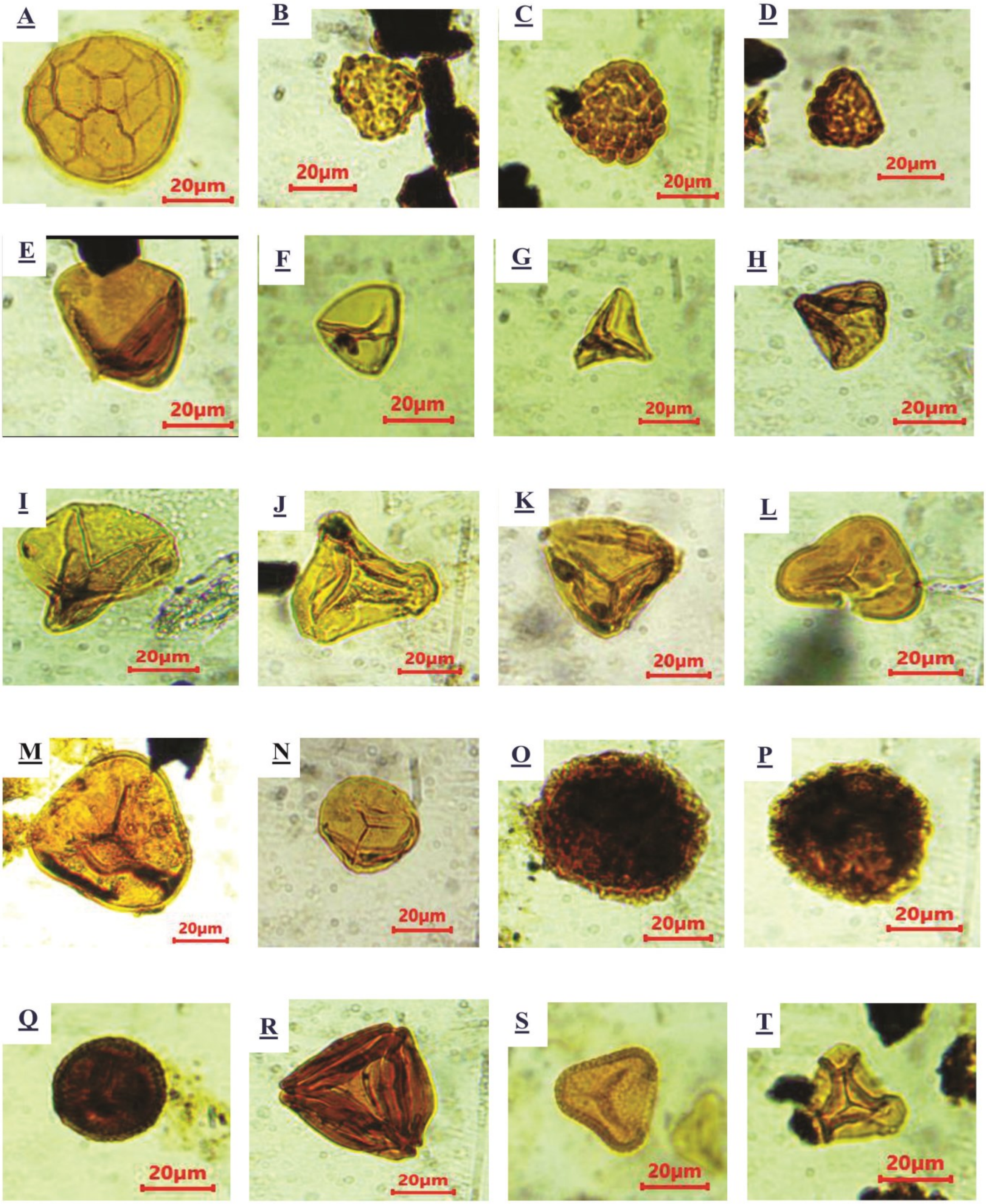


Plate 1. Photomicrograph of sporomorphs in samples from Kobnaswaso-1 well.

Placa 1. Fotomicrografía de esporomorfos en muestras del pozo Kobnaswaso-1.

Plate 2

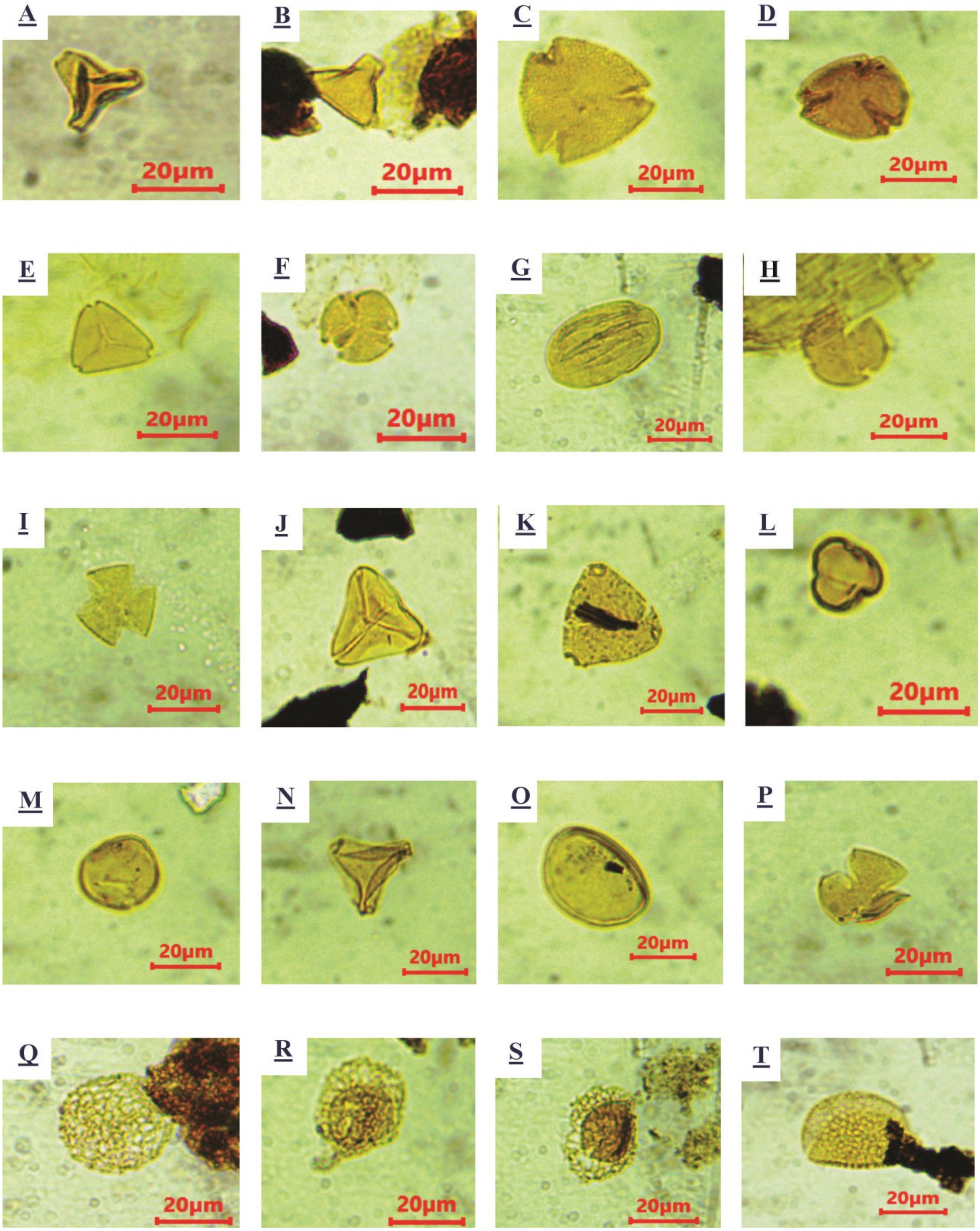


Plate 2. Photomicrograph of sporomorphs in samples from Kobnaswaso-1 well.

Placa 2. Fotomicrografía de esporomorfos en muestras del pozo Kobnaswaso-1.

Plate 3

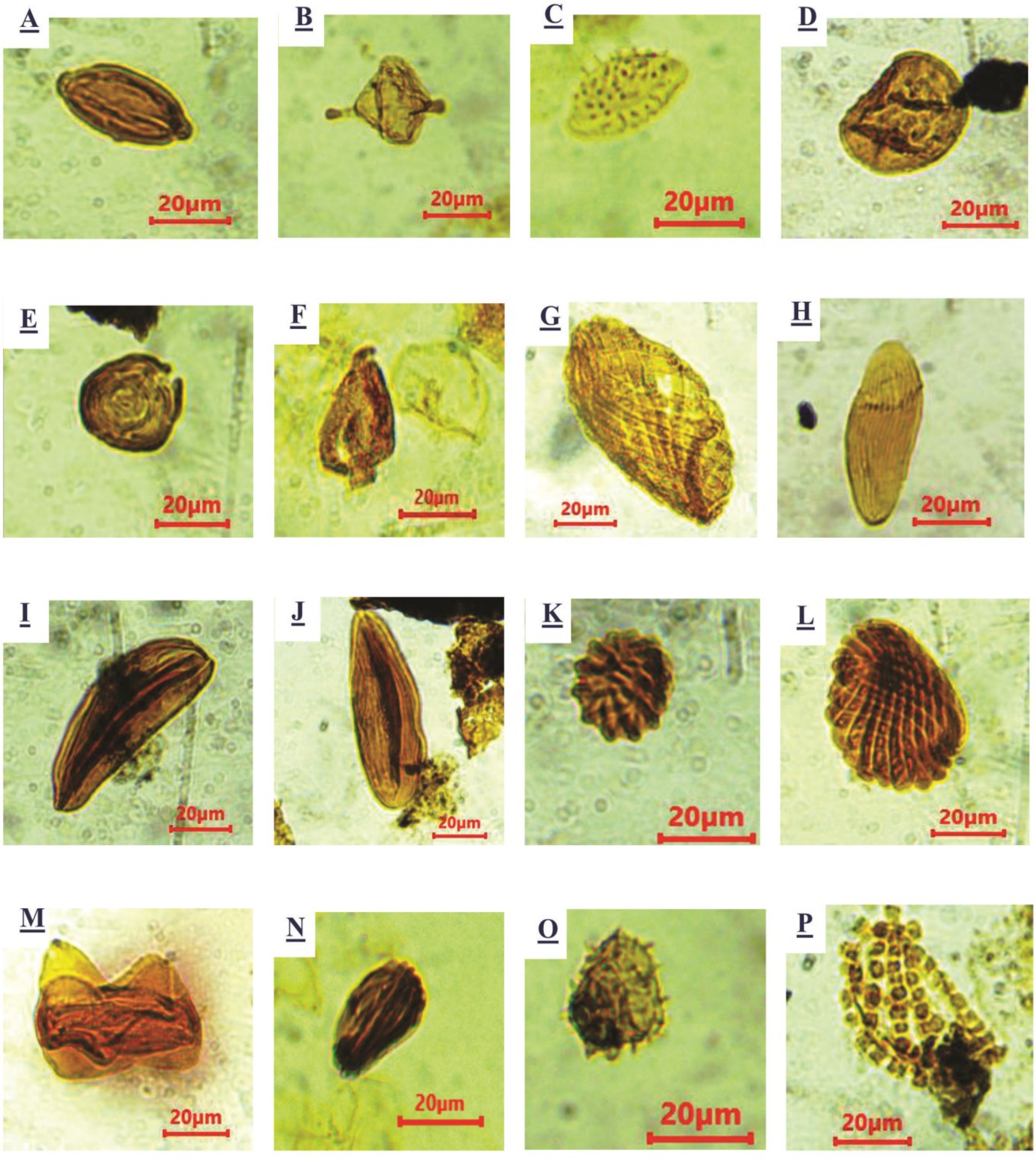


Plate 3. Photomicrograph of sporomorphs in samples from Kobnaswaso-1 well.

Placa 3. Fotomicrografía de esporomorfos en muestras del pozo Kobnaswaso-1.

Plate 4

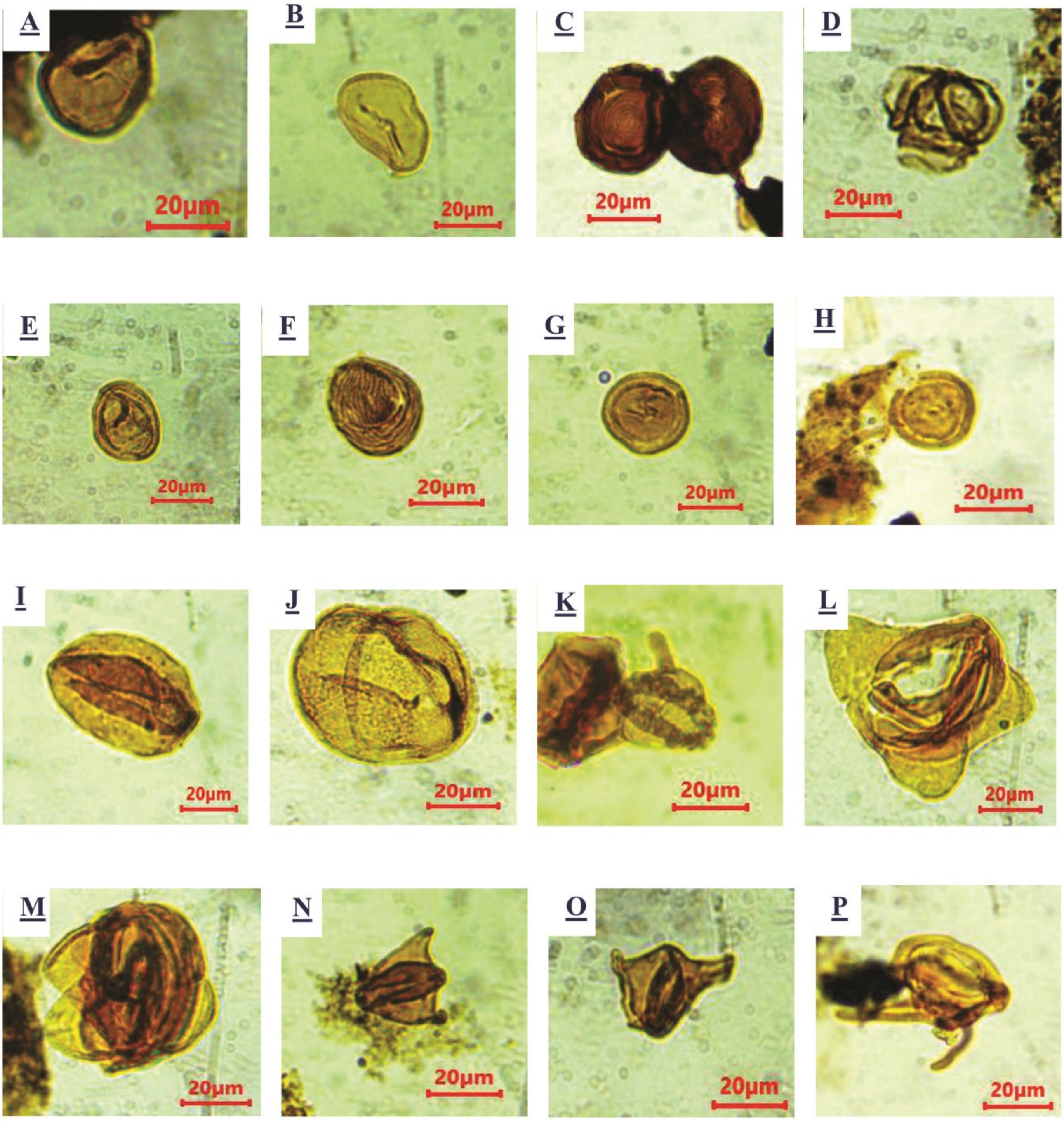


Plate 4. Photomicrograph of sporomorphs in samples from Kobnaswaso-1 well.

Placa 4. Fotomicrografía de esporomorfos en muestras del pozo Kobnaswaso-1.

Plate 5

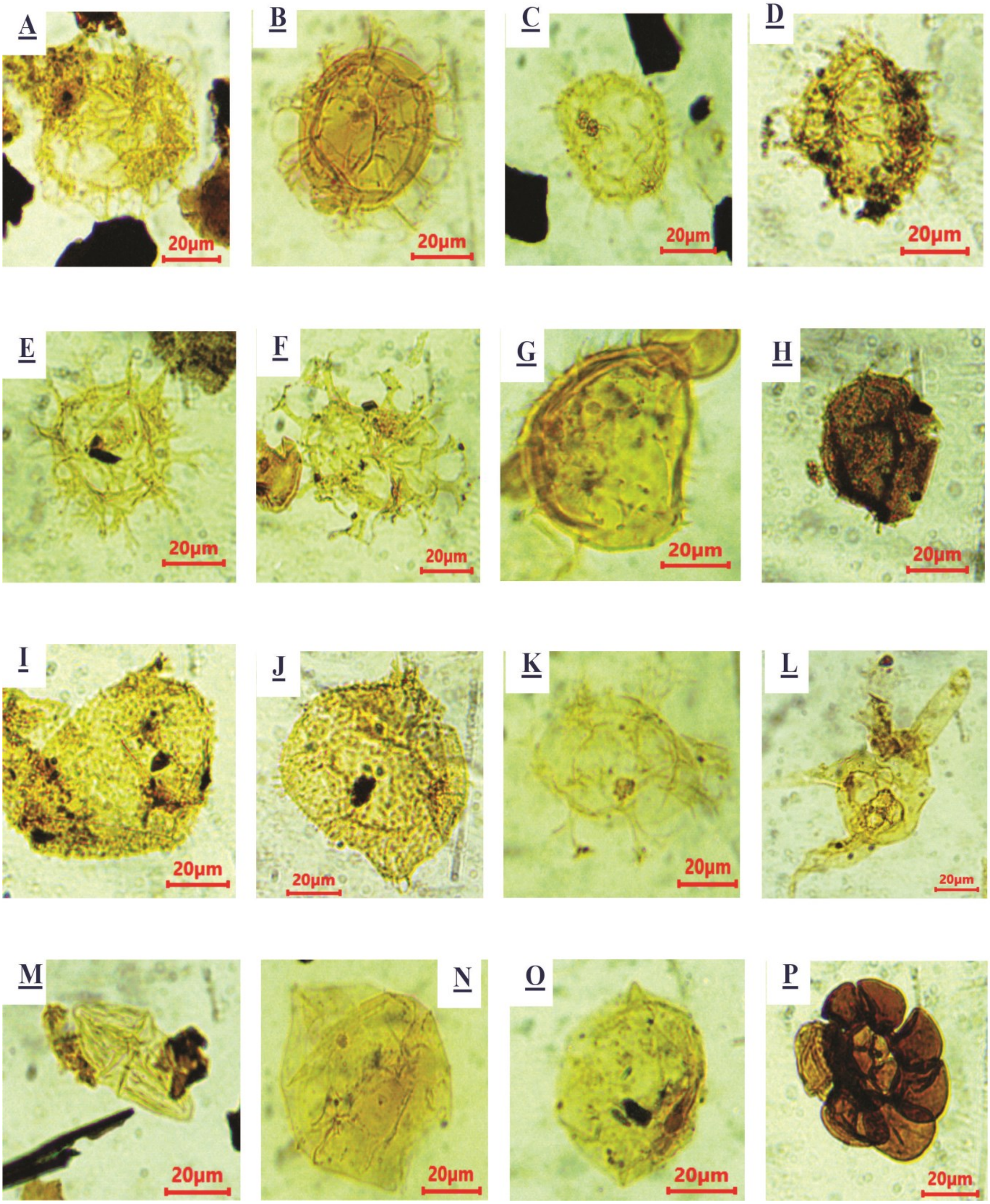


Plate 5. Photomicrograph of dinoflagellate cysts and the foraminiferal test lining in samples from Kobnaswaso-1 well.

Placa 5. Fotografía al microscopio de quistes de dinoflagelados y del revestimiento de la concha de foraminíferos en muestras del pozo Kobnaswaso-1.

3.1.1.4. Palynozone IV (PZ-IV): Droseridites senonicus Interval Zone

This palynozone is recognized between the intervals 432 - 436 m to 206 - 209 m (Figure 2).

Definition of the zone: The top is marked by the LO of *Droseridites senonicus* and the base coincides with the LO of *Classopollis brasiliensis.* (Figure 2).

Associated taxa: *Zlivisporis blanensis, Ephedripites multicostatus, Tricolpites sagax, Proteacidites dahaani, Scabratriporates samoilovitchii, Striatopollis dubius* (See Plate 1, 2 & 3).

Comments: The assemblage of this interval are characterized by angiospermic and gymnospermic pollen, which are well-preserved and diverse. There are also good counts of pteridophyte spores with few dinocysts.

3.1.1.5. Palynozone V (PZ-V) Senegalinium laevigatum - Cordosphaeridium inodes - Andalusiella dubia Assemblage Zone

This palynozone is recognized at depth intervals between 151 - 154 m to 67 - 70 m (Figure 2).

Definition of the zone: The top of the zone is not determined due to the uppermost part of the succession not sampled. The base is marked by the LO of *Droseridites senonicus* and the FO of *Senegalinium laevigatum, Cordosphaeridium inodes* and *Andalusiella dubia*.

Associated taxa: *Mauritiidites crassibaculatus, Auriculiidites reticulatus, Longapertites marginatus, Proxapertites operculatus, Retitricolpites* sp., *Adnatosphaeridium multispinosum, Dinogymnium acuminatum* (See Plate 3 & 5).

Comments**:** The palynofloral assemblage within this zone is dominated by angiosperm pollen grains with dinoflagellate cyst. Sporomorphs are diverse and well-preserved.

3.2. Palynofacies Analysis

The classification of organic matter follows that of Tyson (1993, 1995) which categorizes palynological matter into: (a) amorphous organic matter (AOM), (b) phytoclasts (translucent and opaque) and (c) palynomorphs. Cluster analysis (Q mode), enables us to distinguish four groupings or assemblages (A-D) (Figure 3). These assemblages reflect the four palynofacies associations PF-1 to PF-4 respectively (Table 1). The relative compositions of the palynofacies associations are shown in Table 2.

The AOM-Phytoclast-Palynomorphs (APP) ternary plot of Tyson (1995) show palynofacies associations plotting in field II, VI and V (Figure 4). Microplankton-Spore-Palynomorphs (MSP) plot of Traverse (1988) reveal a regressive trend of sequences from a shallow marine to deltaic environment (Figure 5).

3.2.1. Palynofacies types

3.2.1.1. Palynofacies type 1 (PF-1) - AOM dominant with opaques (Plate 6; Figure A and B).

PF-1 shows the dominance of AOM (53%) with opaques (30%). Palynomorphs and translucent phytoclasts contribute 8%, and 9% respectively (Table 2). The palynomorphs are dominated by pollen grains (85%) (See Appendix 3), with dinoflagellates and spores contributing 10% and 5% respectively. The AOM is pale yellow to light brown in colour with diffused edges. The phytoclasts show different sizes of pale-brown equant to lath-shaped fragments while the opaques are sub-equant and dark brown to black. (See Appendix 4 for samples intervals that fall in PF-1).

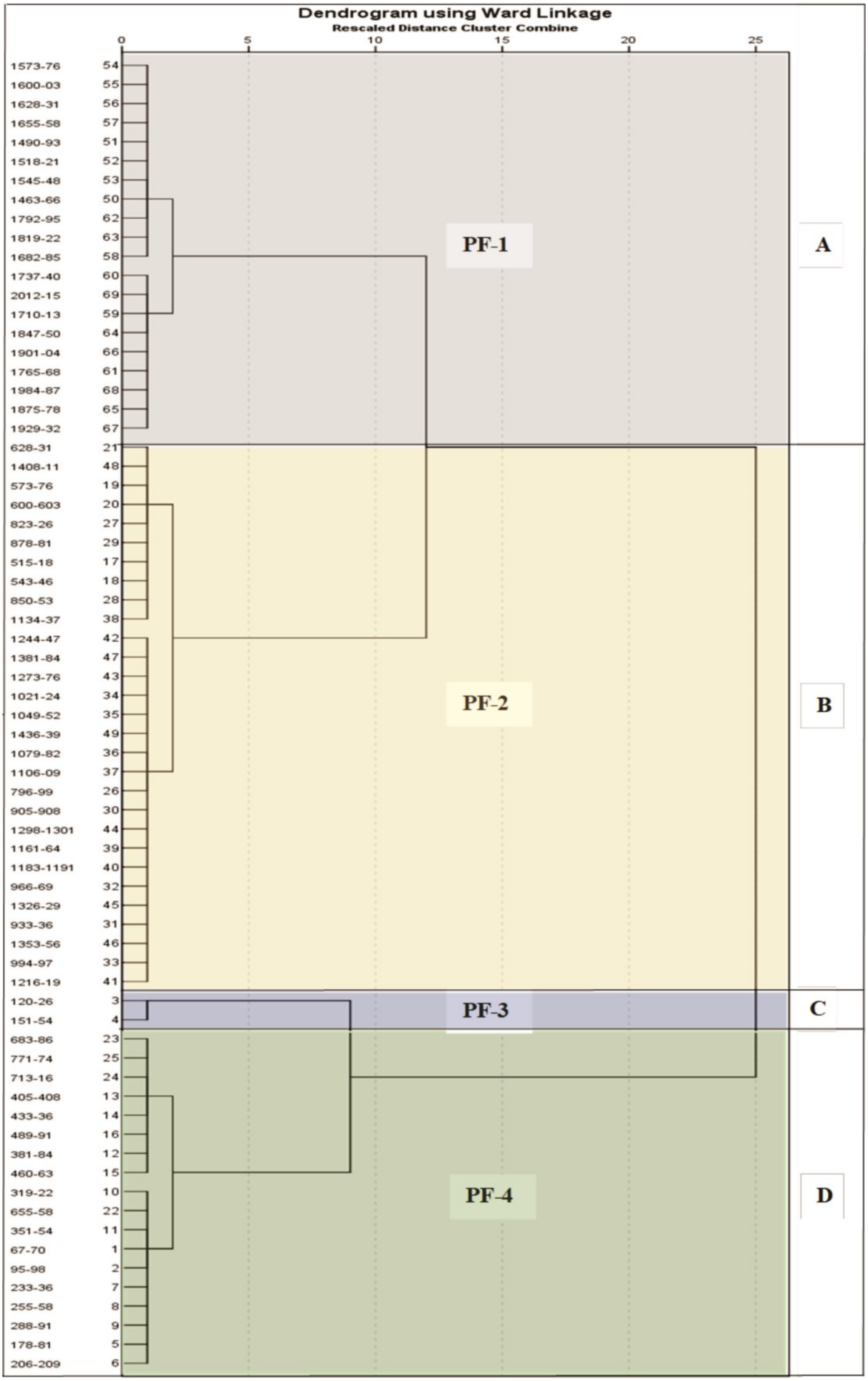


Figure 3. Q-mode dendrogram of Kobnaswaso-1 well showing the grouping of samples.

Figura 3. Dendrograma modo-Q del pozo Kobnaswaso-1 que muestra la agrupación de muestras.

Table 1. Palynofacies associations identified after cluster analysis.

Tabla 1. Asociaciones de palinofacies identificadas tras el análisis de *clusters*.

Palynofacies Associations	Description	Cluster
PF-1	AOM dominant with opaques	A
PF-2	Opaque phytoclasts dominant with moderate AOM	B
PF-3	Palynomorphs dominant with AOM	C
PF-4	Translucent Phytoclast dominant with opaques	D

Table 2. Palynofacies associations and their relative abundance of total kerogen in percentages.

Tabla 2. Asociaciones de palinofacies y abundancia relativa de querógeno total en porcentajes.

Palynofacies Associations	AOM	Translucent phytoclast	Opaque phytoclast	Palynomorphs
PF-1 (A)	53	9	30	8
PF-2 (B)	30	7	53	10
PF-3 (C)	25	12	14	50
PF-4 (D)	17	51	21	11

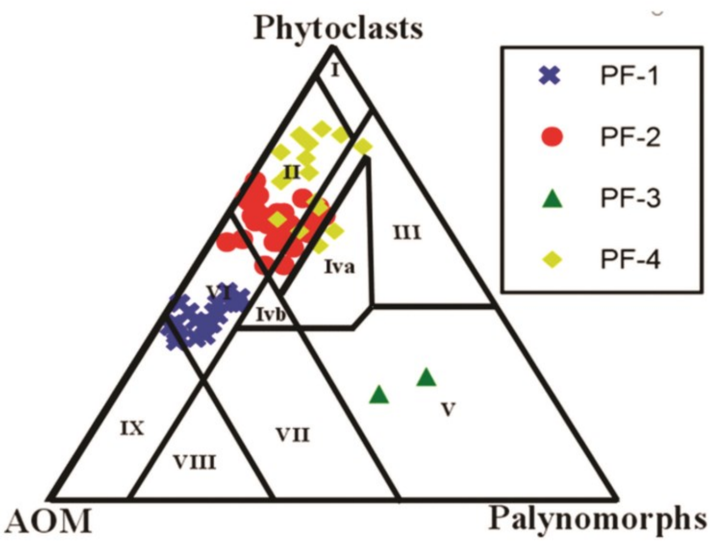


Figure 4. MSP Ternary plot of Traverse (1988) showing depositional environment for samples from Kobnaswaso-1 well.

Figura 4. Diagrama ternario MSP de Traverse (1988) que muestra el ambiente de sedimentación de las muestras del pozo Kobnaswaso-1.

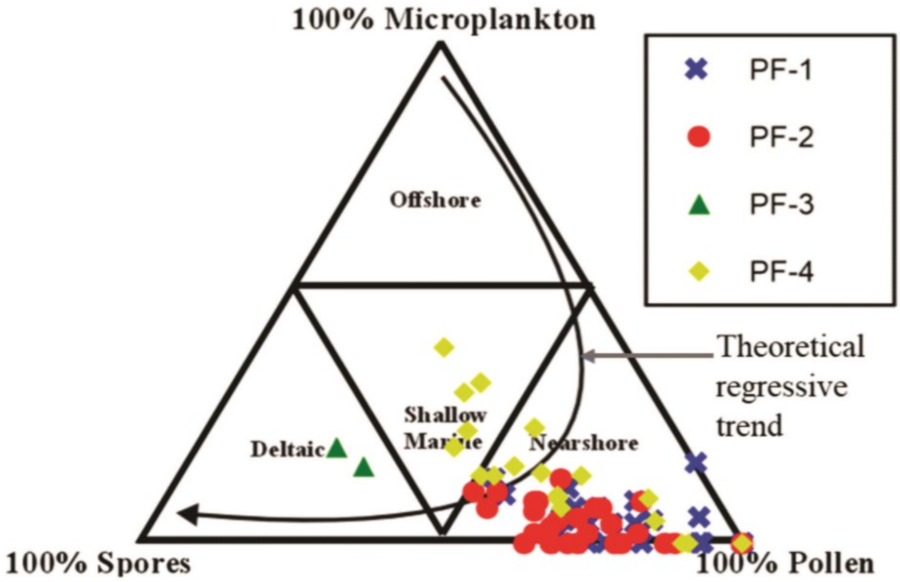


Figure 5. Key to defined palynofacies and kerogen types of samples from Kobnaswaso–1 well using the APP ternary diagram: II—Marginal dysoxic-anoxic basin (Type III kerogen); V—Mud-dominated oxic shelf (Type III > IV kerogen); VI—Proximal suboxic-anoxic shelf (Type II kerogen). (Modified after Tyson, 1993).

Figura 5. Clave para la identificación de palinofacies y tipos de querógeno en muestras del pozo Kobnaswaso-1 mediante el diagrama ternario APP: II—Cuenca marginal disóxica-anóxica (querógeno tipo III); V—Plataforma óxica dominada por lodo (querógeno tipo III > IV); VI—Plataforma proximal subóxica-anóxica (querógeno tipo II). (Modificado de Tyson, 1993).

3.2.1.2. Palynofacies type 2 (PF-2) - Opaque phytoclasts dominant with moderate AOM (Plate 6; Figure C and D).

PF-2 is characterized by the dominance of opaque phytoclasts (53%) with moderate AOM (30%). Palynomorphs and translucent phytoclasts constitute 10% and 7% respectively (Table 2). Sporomorphs recorded from this interval dominate the palynomorph group. Opaque phytoclasts are equant and dark in colour. Amorphous debris is colloidal in state and yellowish brown. Translucent phytoclasts are equant to lath-shaped and internally structured. (See Appendix 4 for samples intervals that fall in PF-2).

3.2.1.3. Palynofacies type 3 (PF-3) - Palynomorphs dominant with AOM (Plate 6; Figure E and F).

PF-3 is composed of well-preserved dominant palynomorphs (50%), and 25% AOM. Opaques and phytoclasts contribute 14% and 12% respectively (Table 2). Terrestrial palynomorphs (mainly miospores) dominate the palynomorph group. Amorphous materials are light brown and appear spongy. Opaque phytoclasts and translucent phytoclasts are equant. (See Appendix 4 for samples intervals that fall in PF-3).

3.2.1.4. Palynofacies type 4 (PF-4) - Translucent phytoclast- ominant with opaques (Plate 6; Figure G and H).

PF-4 is represented by a 51% abundance of translucent phytoclasts diluted with opaques (21%). AOM and palynomorphs contribute 17% and 11% respectively (Table 2). Phytoclasts exist as medium to large yellowish lath-shaped fragments of structured land plant tissues and cuticles. In most forms, the opaques are equant to lath-shaped, with a dark brown to black colour. The palynomorph group is dominated by sporomorphs. Amorphous materials are aggregated, more fibrous, and yellowish-brown in colour. (See Appendix 4 for samples intervals that fall in PF-4).

Plate 6

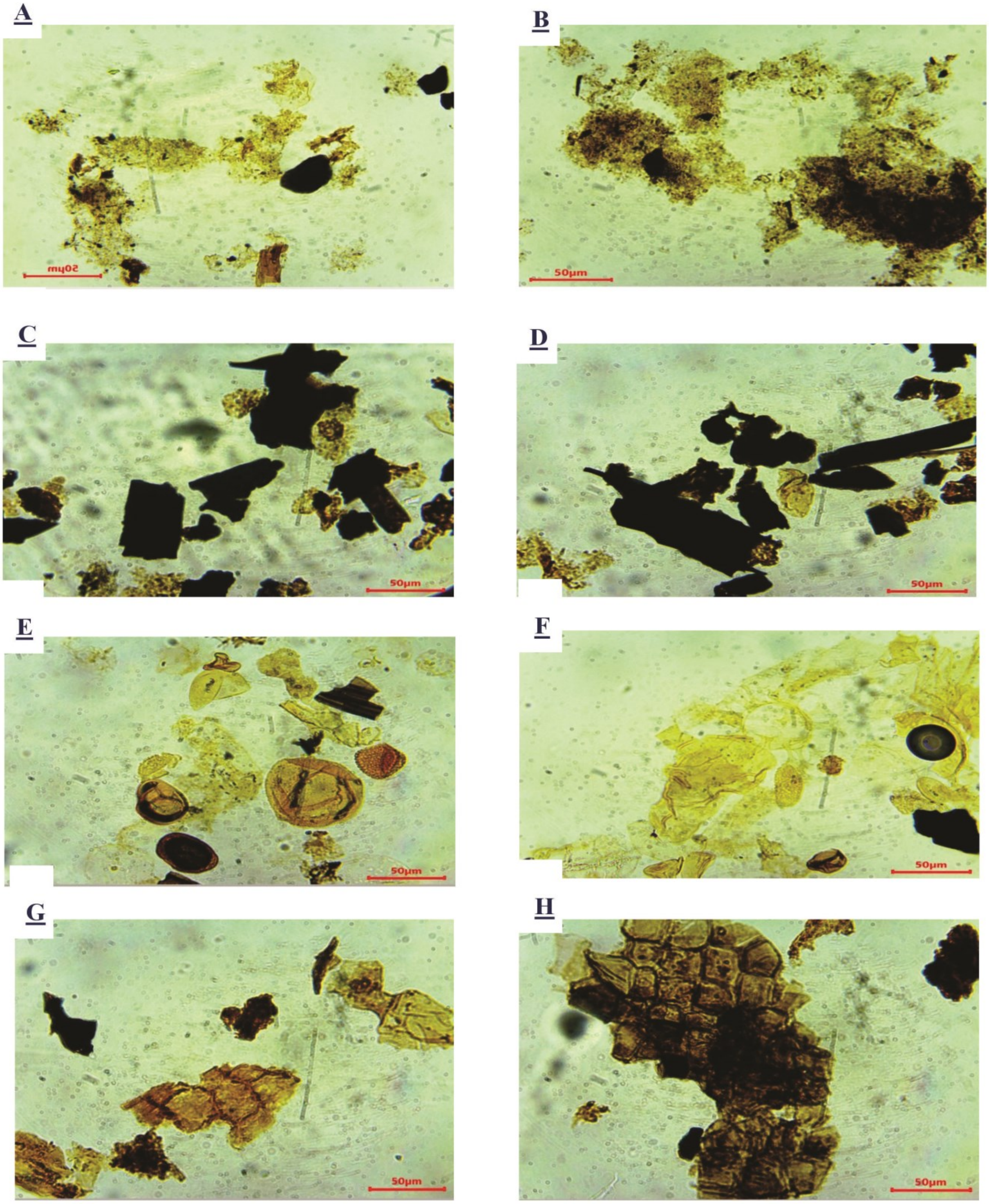


Plate 6. Photomicrograph of palynofacies types in samples from Kobnaswaso-1 well.

Placa 6. Fotomicrografía de los tipos de palinofacies en muestras del pozo Kobnaswaso-1.

3.3. Thermal maturity of the organic matter

Thermal Alteration Index (TAI) values of spore colour compared to Pearson's chart (1990) and the equivalent vitrinite reflectance (Ro %) after referring to correlation chart of Traverse (2007), were evaluated. The results obtained for TAI and its corresponding Ro values are shown in Figure 6.

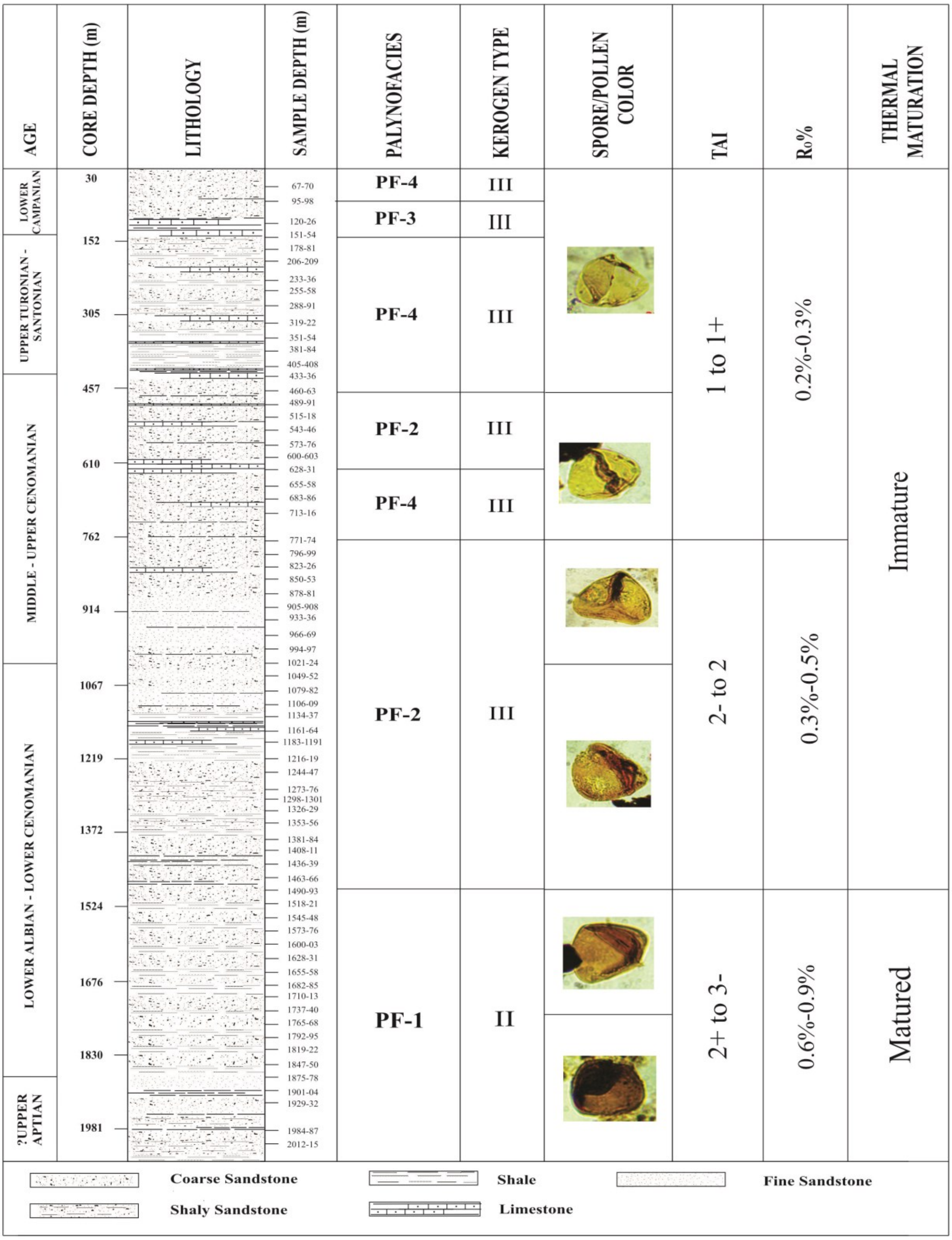


Figure 6. Lithology, sample horizons and thermal maturity data for the Kobnaswaso-1 well.

Figura 6. Litología, horizontes de muestra y datos de madurez térmica del pozo Kobnaswaso-1.

4. Discussion

4.1. Age Assessment

4.1.1. Palynozone I (PZ-I): Afropollis operculatus Total Range Zone

Afropollis operculatus was previously recorded from the Aptian of Egypt (Schrank, 1983; Mahmoud & Moawad, 2002), Mali, & Gabon (Doyle *et al.*, 1982). The LO of *Afropollis operculatus* was used by Schrank & Ibrahim (1995) and Doyle *et al.* (1982) to establish the boundary between the Aptian and Albian stages in Egypt and West Africa (Mali, Ghana, and Senegal).

Based on the presence of *Afropollis operculatus*, and its stratigraphical position regarding to the palynozone II, a ?late Aptian age is assigned to this biozone.

4.1.2. Palynozone II (PZ-II): Elateropollenites jardinei - Sofrepites legouxiae Interval Zone

4.1.2.1 Elateropollenites jardinei - Galeacornea causea Interval Zone (Subzone 1)

Afropollis jardinus within this biozone is acknowledged to have made its appearance in the geological record of North Gondwana during the early Albian times (Brenner, 1963, 1968; Doyle *et al.*, 1977, 1982; Sultan, 1987; Herngreen & Chlonova, 1981; Schrank, 1983; Gubeli *et al.*, 1984; Penny, 1991; Doyle, 1992, 1999; Schrank & Ibrahim, 1995; Ibrahim, 1996; Deaf *et al.*, 2014). In the West African region, *Afropollis jardinus* have been reported from lower Albian rocks in Senegal, (Jardine & Magloire, 1965), in Gabon, Congo, and Senegal from lower Albian strata (Doyle *et al.*, 1982) and in Ghana from the lower Albian sediments (Atta-Peters & Salami, 2006). In northern South America, *Afropollis jardinus* has been identified in lower Albian sediments in Brazil (Herngreen, 1973, 1975; Regali & Viana, 1989), Peru (Brenner, 1968), and in Colombia from late Albian to early Cenomanian age (Herngreen & Dueñas-Jimenez, 1990).

Ephedripites irregularis and Elateropollenites jardinei occurrences within this interval have been reported in the lower to middle Albian strata of Brazil (Herngreen, 1973, 1975; Regali & Viana, 1989; Herngreen *et al.*, 1996; Umeji, 2006), and in Albian sediments of Ghana (Atta-Peters & Salami, 2006). Muller *et al.* (1987) documented the FO and LO of *E. jardinei* from Albian formations in Venezuela.

Reyrea polymorphus has been reported from Aptian - Albian age (Thusu & Van der Eem, 1985; Muller *et al.*, 1987; Herngreen, 1973, 1998). It has also been documented in Egypt, including Albian strata by Mahmoud & Moawad (1999), lower Albian rocks by El - Shamma & Arafa (1988), and Aptian - Albian sediments by Mahmoud & Deaf (2007), late Barremian – Albian age (Zobaa & Oboh-Ikuenobe, 2018).

The age of this subzone is early to middle Albian due to FO of *Elateropollenites jardinei* and the presence of *Afropollis jardinus, Reyrea polymorphus* and *Ephedripites irregularis.*

4.1.2.2. Galeacornea causea, Elateroplicites africaensis and Sofrepites legouxiae Assemblage Zone (Subzone 2)

Elateroplicites africaensis, recovered from this biozone, has been observed in sediments of middle Albian to early Cenomanian age across Africa and South America (Jardine, 1967; Herngreen, 1973; Herngreen & Dueñas-Jimenez, 1990; Schrank, 1990; Dino *et al.*, 1999; Atta-Peters & Salami, 2006). Mackled *et al.* (2013), also reported *Elateroplicites africaensis* from early Cenomanian rocks in Egypt.

Galeacornea causea, initially recorded from lower Cenomanian sediments in Senegal by Jardine (1967), has also been reported in the late Albian in Gabon and northeast Nigeria (Doukaga, 1980; Lawal & Moullade, 1986). *Galeacornea causea* occurrences have also been documented in sediments of mid - Albian to mid - Cenomanian age in Brazil and Colombia (Herngreen, 1973; Herngreen & Jimenez, 1990), middle Albian to Cenomanian rocks in Egypt (Schrank & Ibrahim, 1995; Zobaa *et al.*, 2013; Deaf *et al.*, 2014), and in Ghana (Atta-Peters & Salami, 2006).

Sofrepites legouxiae has been documented from upper Albian to lower Cenomanian sediments of Gabon (Jardiné, 1967), Brazil (Herngreen, 1973, 1975; Herngreen *et al.*, 1996), Egypt (Aboul Ela & Mahrous, 1992; Mahmoud, 1998; Mahmoud & Moawad, 1999), and the late Albian of Senegal (Jardiné, 1967). In regions of the Albian - Cenomanian Elaterate Province, *S. legouxiae* is also confined to the late Albian - early Cenomanian age interval (Herngreen *et al.*, 1996). Makled *et al.*, (2013) reported that *S. legouxiae* is an index fossil in the late Albian to Early Cenomanian strata of Brazil, Senegal and Gabon and north Western Desert (Egypt).

The age of this subzone is late Albian to early Cenomanian due to the LO of *Sofrepites legouxiae* at the top of this interval.

4.1.3. Palynozone III (PZ-III): Triporites sp - Classopollis brasiliensis Interval Zone

4.1.3.1. Triporites sp - Crybelosporites pannuceus Interval Zone (Subzone 1)

The FO of *Triporites* from the sample depth interval of 1021- 24 m indicates a mid - late Cenomanian age. Triporate pollens have been observed in the middle - upper Cenomanian rocks in Senegal (Jardiné & Magloire, 1965), Brazil (Herngreen, 1973), NE Nigeria (Lawal & Moullade, 1986), and Egypt (Ibrahim & Schrank, 1996; Ibrahim, 1996).

The presence of *Elaterosporites klaszii* recovered from this interval has been reported from the middle Albian rocks of Brazil (Herngreen, 1973, 1975), upper Albian - lower Cenomanian strata in Peru and Colombia (Herngreen & Dueñas-Jimenez, 1990) and middle Albian to Cenomanian rocks in both Brazil and Ecuador (Dino *et al.*, 1999). In Africa, *E. klaszii* has been documented from middle to upper Albian rocks in Côte d'Ivoire, Senegal, and Gabon by Jardine (1967) and in the Cote d'ivoire - Ghana (CIG) transform margin (Masure *et al.*, 1998). In the lower Benue Trough of Nigeria, *E. klaszii* has been reported from rocks of the late Albian (Jardiné (1967). *E. klazii* has been also recorded in Albian-Cenomanian rocks of Libya (Batten and Uwins, 1985), rocks of late Albian - early Cenomanian age in northern Sudan (Schrank, 1990), Middle Albian rocks in Egypt (El-Soughier *et al.*, 2013), upper Albian strata in Nigeria (Abubakar *et al.*, 2006), lower Albian - lower Cenomanian rocks in Egypt (Mahmoud & Deaf, 2007), lower Albian - lower Cenomanian rocks of Brazil (Herngreen, 1975), and middle Albian - upper Cenomanian strata in Senegal (Jardine, 1967) and Gabon (Doukaga, 1980). Makled *et al.*, (2013) stated that E. klaszi has a relatively short range and is restricted to middle Albian – Cenomanian strata of Egypt.

In Egypt, *Crybelosporites pannuceus* is a recognized spore from the Albian - Cenomanian age interval (Sultan 1978, 1987; Bassiouni *et al.*, 1992; E1 - Shamma & Baioumi, 1992; Abdel - Kireem *et al.*, 1993; E1-Beialy, 1994a, b; Zobaa & Oboh - Ikuenobe, 2018)). It has also been reported in Tunisia (Reyre, 1966), Peru (Brenner, 1968), and Brazil (Herngreen, 1973).

The occurrence of *Crybelosporites pannuceus*, *Elaterosporites klaszii,* and *Triporites* may suggest a middle to late Cenomanian age for this subzone 1 interval.

4.1.3.1. Classopollis brasiliensis Interval Zone (Subzone 2)

Triorites africaensis is a stratigraphically important taxon in the zone of West Africa and eastern South America (Herngreen, 1975; Lawal, 1991; Ibrahim, 1996). The FO of *Triorites africaensis* is typical of a late Cenomanian age (Jardine and Magloire, 1965; Herngreen, 1973, 1975). In West Africa, *Triorites africaensis* has been documented from upper Cenomanian rocks in Senegal and Ivory Coast (Jardine & Magloire, 1965), Nigeria (Lawal & Moullade, 1986), and Gabon (Boltenhagen, 1980). In easternmost South America, this triporate pollen was also recorded in upper Cenomanian deposits as well (Herngreen, 1973; Regali, 1989). However, *T. africaensis* occur in middle to upper Cenomanian rocks in northern Gondwana rocks (Muller *et al.*, 1987; Ibrahim, 1996).

The LO of *Classopollis brasiliensis* was initially documented from upper Cenomanian rocks in Senegal and Ivory Coast (Jardine' & Magloire, 1965). This taxon was also recorded from strata of the middle - late Cenomanian age in Egypt (Sultan, 1978; Aboul Ela & Mahrous, 1992; El - Shamaa &

Arafa, 1988; Schrank & Ibrahim, 1995; Mahmoud & Moawoad, 1999, 2002; El-Beialy *et al.*, 2010). The well - dated total range (late Cenomanian) of *C. braziliensis* makes this species a significant index fossil in the Albian - Cenomanian Phytogeographic Province (Deaf & Tahoun, 2018).

This biozone shows an abrupt decline in the gymnosperm pollen *Classopollis* spp., which can be compared to the zones of middle - late Cenomanian ages recorded in Senegal and Ivory Coast (Jardine' & Magloire, 1965), and in Egypt (Schrank & Ibrahim, 1995; Ibrahim, 2002; Deaf *et al.*, 2014).

A late Cenomanian age is therefore assigned to this subzone based on the presence of *Triorites africaensis* and *Classopollis brasiliensis*.

4.1.2. Palynozone IV (PZ-IV): Droseridites senonicus Interval Zone

The FO of the *Droseridites senonicus* in this zone is significant. It has been reported from the upper Turonian to Santonian interval (Jardine´ & Magloire, 1965; Lawal & Moullade, 1986; Odebode, 1987; Muller *et al.*, 1987; Salard-Cheboldaeff, 1990; Schrank & Ibrahim, 1995; Ibrahim, 1996; Atta-Peters & Salami, 2006; Apaalse & Atta-Peters, 2013; Deaf *et al.*, 2014). According to El Atfy *et al.* (2023), *Droseridites senonicus* is a marker species in the Coniacian - Santonian of West Africa. *Zlivisporis* has been recorded in this zone and according to Herngreen (1998) it characterizes the Turonian/Coniacian boundary event. It has also been documented from Coniacian rocks in Alabama (Pacltova & Simoncsics, 1970).

A late Turonian to Santonian age is assigned to this biozone based on the presence of the *Zlivisporis* and *Droseridites senonicus* taxa.

4.1.3. Palynozone V (PZ-V) Senegalinium laevigatum - Cordosphaeridium inodes - Andalusiella dubia Assemblage Zone

This zone is characterized by the LO of *Droseridites senonicus* and the FO of *Senegalinium laevigatum, Andalusiella dubia* and *Cordosphaeridium inodes,* which support a Campanian age for the sediments. Several authors have reported these taxa from Campanian - Maastrichtian sediments with only a few ranging into the early Paleocene (Boltenhagen, 1977; Prévôt *et al.*, 1979; Batten & Uwins, 1985; Schrank, 1987, 1990, 1994; Salami, 1982, 1986, 1988; Schrank & Ibrahim, 1995; Schrank & Mahmoud, 1998). The presence of *Dinogymnium acuminatum* and *Spiniferites multibrevis* also provide additional supporting evidence for a Late Cretaceous age.

Other angiosperm taxa (*Mauritidiites crassibaculatus, Proxapertites operculatus, Longapertites marginatus, Proteacidites dahaani, Auriculiidites reticulatus, and Scrabratriporites samoilovitchii)* identified within this biozone have a relatively Late Cretaceous range in the ASA region (Jardine & Magloire, 1965; Salami, 1990; Herngreen & Duenas Jiminez, 1988; Salard–Cheboldaeff, 1990, Schrank, 1992, 1994; Schrank & Ibrahim, 1995; Herngreen, 1998; Atta-Peters & Salami, 2006; El-Soughier *et al.*, 2013).

Because of the limited samples (3) obtained for this zone due to cessation of drilling, an early Campanian age is assigned to this zone based on the FO of the diagnostic species *Senegalinium laevigatum, Dinogymnium acuminatum*, and *Andalusiella dubia.* The miospores, *Mauritiidiites crassibaculatus* together with *Proxapertites operculatus, Longapertites marginatus,* and *Auriculiidites reticulatus* are also noteworthy for a Late Cretaceous age and supports this early Campanian age.

4.2. Paleoenviornmental interpretations

4.2.1. Implications from sporomorphs

Palynofloras within Kobnaswaso-1 well are dominated by sporomorphs with few dinocysts. The abundance of sporomorphs in PZ I, II and III (90%) (Figure 7) indicates deposition within a relatively marginal marine setting, close to land (Mahmoud & Moawad, 2002). This is supported by the presence of numerous tetrads of *Classopollis* which indicates their proximity to the parent flora and are important components of coastal marshes (Hughes and Moody-Stuart, 1967; Goodall *et al.*, 1992; Abdel-Kireem *et al.*, 1993, 1996; Tyson, 1993; Ibrahim, 1996).

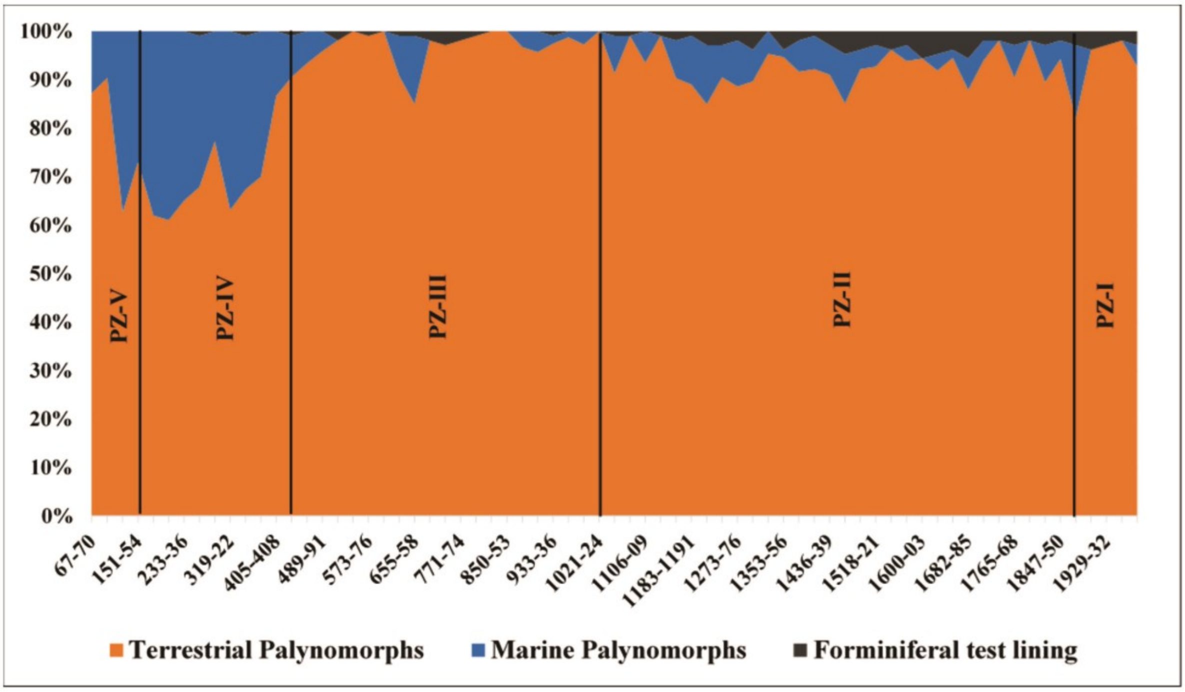


Figure 7. Relative abundance of terrestrial, marine palynomorphs and microforminiferal test lining with increasing depth from Kobnaswaso-1 well within the depth interval of (67 - 70 m to 2012 - 2014 m).

Figura 7. Abundancia relativa de palinomorfos terrestres y marinos y revestimiento de conchas microforminíferas con el aumento de la profundidad desde el pozo Kobnaswaso-1 dentro del intervalo de profundidad de (67 - 70 m a 2012 - 2014 m).

The dominance of diverse xerophytes *(Classopollis* and ephedroids) (Figure 2) in Palynozones I, II, and III indicates a tropical arid or semi - arid climatic conditions. (Srivastava, 1976; Schrank & Nesterova, 1993; Schrank & Ibrahim, 1995; Mahmoud & Moawad, 2002; Atta-Peters & Salami, 2006; El-Soughier *et al.*, 2013). Compared to Palynozone III, taxa within Palynozone II are more fairly diversified, with *Classopollis* and *Araucariacites*. This indicates the seasonal prevalence of conifer araucariacean forests in relatively dry hinterlands during deposition (Mahmoud & Moawad, 2002; El-Beialy *et al.*, 2011). The occurrence of the spore *Crybelosporites* at some depths within Palynozone IV indicates that freshwater habitats (lakes and ponds) existed at the time of deposition (Schrank & Mahmoud, 1998; El-Beialy, 1995; Mahmoud & Moawad, 2002; El-Beialy *et al.*, 2010; El-Soughier *et al.*, 2013). The presence of elaterate pollen, which was presumably generated by gnetalean plants (Dino *et al.*, 1999) and *Afropollis jardinus* in the Albian sediments, indicates some level of humid conditions for these gnetalean and *Afropollis* parent plants to grow in coastal plains (Schrank, 2001; Deaf *et al.*, 2014; Atta-Peters & Salami, 2006). The occurrence of trilete fern spores (*Cyathidites, Cicatricosisporites*, and *Deltoidspora*) in the studied interval is most likely due to the local pteridophyte vegetation that grows on wetlands during humid conditions (Playford, 1971; Schrank & Mahmoud, 1998; Mahmoud & Moawad, 2002; Mahmoud, 2003; Atta-Peters & Salami, 2006; El-Beialy *et al.*, 2010; El-Beialy *et al.*, 2011).

The presence of the triporate Proteaceae (*Proteacidites dahaani*) in the upper Turonian-Santonian (Palynozone IV) sediments suggest the occurrence of rainforest under humid tropical climatic conditions. (Schrank 1987; Herngreen *et al.*, 1996; El-Beialy *et al.*, 2010).

Sporomorphs from the Campanian (Palynozone V) are related to those from the Senonian Palmae Province in the ASA region, which are indicative of a warm tropical to subtropical climate (Smith *et al.*, 1982; Herngreen *et al.*, 1996; Herngreen, 1998). *Proxapertites, Longapertites*, and *Mauritiidites* are monocolpate pollens related to the extant Nypa Palmae plants, which thrive nowadays in mangrove ecosystems (Schrank, 1987, 1994; Herngreen, 1998). Therefore, the presence of these monocolpates in Palynozone V suggest the existence of a mangrove setting of a warm humid tropics. In addition, the dominance of pteridophytes fern spores (*Cyathidites, Cicatricosisporites*, and *Deltoidspora*) over spheroidal pollen grains compliments the deposition in a marginal marine depositional environment (Tyson, 1995, Tahoun & Deaf, 2016; Deaf & Tahoun, 2018).

4.2.2. Implications from Dinoflagellates

In Palynozones I, II, and III (489 - 91 m to 2012 - 15 m) sporomorphs are dominant (Figure 8) with the occurrence of few to rare of *Spiniferites, Oligosphaeridium, Cyclonephelium* (Figure 2) and foraminiferal test linings (Figure 7), which affirms the existence of relatively nearshore/shallow marine setting of normal salinity. (Davey, 1970; Downie *et al.*, 1971; Harding, 1986; Uwins & Batten, 1988; Quattrochio *et al.*, 2006; Mahmoud *et al.*, 2007; El-Soughier *et al.*, 2013).

In Palynozones IV and V, there is an increase in the proportion of dinocysts in comparison to the other biozones (Figure 7). Dinocyst in Palynozone V are particularly dominated by the peridinoids (*Andalusiella and Senegalinium*) which are typical of the *Wetzeliella* Association of Downie *et al.* (1971). According to Downie *et al.* (op. cit) these taxa are typical of a brackish or lagoonal/estuarine environment.

4.2.3. Implications from palynofacies analysis

4.2.3.1. Palynofacies type 1 (PF-1) AOM dominant with opaques

Samples that reflect PF-1 plot within field VI of the APP ternary diagram of Tyson (1995) (Figure 4) indicating proximal suboxic-anoxic shelf redox condition. This field implies kerogen type II, (oil-prone) facies due to the prevalence of AOM.

The dominance of well-preserved AOM (53%) (Figure 8) elements suggests somewhat reducing conditions with low energy and high water depth periods, indicating a slightly deeper marine setting, which is far away from active fluvio-deltaic systems (Tyson, 1993; Gentzis *et al.*, 2019). The high record of opaque phytoclasts (30%) indicates a deeper shallow marine environment (Tyson, 1993; Aboul Ela *et al.*, 2019). The Microplankton-Spore-Pollen (MSP) ternary diagram of Traverse (1988) supports a nearshore environment (Figure 5). Within the sporomorph group, *Classopollis* and other sphaeroidal pollen grains (*Araucariacites* and *Inaperturopollenites*) outnumber the pteridophyte spores, reflecting a slightly distal depositional setting within a nearshore environment (Batten 1999; Gentzis *et al.*, 2019). In addition, the presence of *Oligosphaeridium* and *Cyclonephelium* points to an inner-shelf setting under suboxic-anoxic conditions (Figure 8) (Mahmoud & Moawad, 2002; Deaf & Tahoun, 2018).

4.2.3.2. Palynofacies type 2 (PF-2) - (Opaque phytoclasts) dominant with moderate AOM

PF-2 plots within field II of Tyson's (1995) APP ternary diagram (Figure 4), reflecting a marginal dysoxic-anoxic basin redox condition. This facies is indicative of kerogen type III, (gas-prone) due to the prevalence of opaque phytoclast.

High values of opaque phytoclasts typically denote proximity to terrestrial sources or the repositioning of terrestrial materials from fluvio-deltaic origins (Carvalho *et al.*, 2013). However, a high record of opaque phytoclasts can also be ascribed to transportation over a prolonged period in oxidized proximal offshore settings (Tyson, 1993; Aboul Ela *et al.*, 2019; Achaegakwo and Atta-Peters). The presence of colloidal AOM indicates coastal oscillation (Batten, 1983; Zavattieri *et al.*, 2008).

PF-2 shows higher concentrations of pteridophyte spores than PF-1, suggesting a slightly shallower depositional setting (Mahmoud and Deaf, 2007; Tahoun & Deaf, 2016; Deaf & Tahoun, 2018; Gentzis *et al.*, 2019). The presence of some *Classopollis* tetrads also indicates a brief period of transport and consequently deposition in nearshore environments since prolonged transport would cause the splitting of the tetrads (Carvalho *et al.*, 2006). Traverse's (1988) MSP ternary diagram (Figure 5) also supports a nearshore environment. The rare occurrences of typical marine dinocysts support a strong terrestrial input in a marginal marine setting for PF-2.

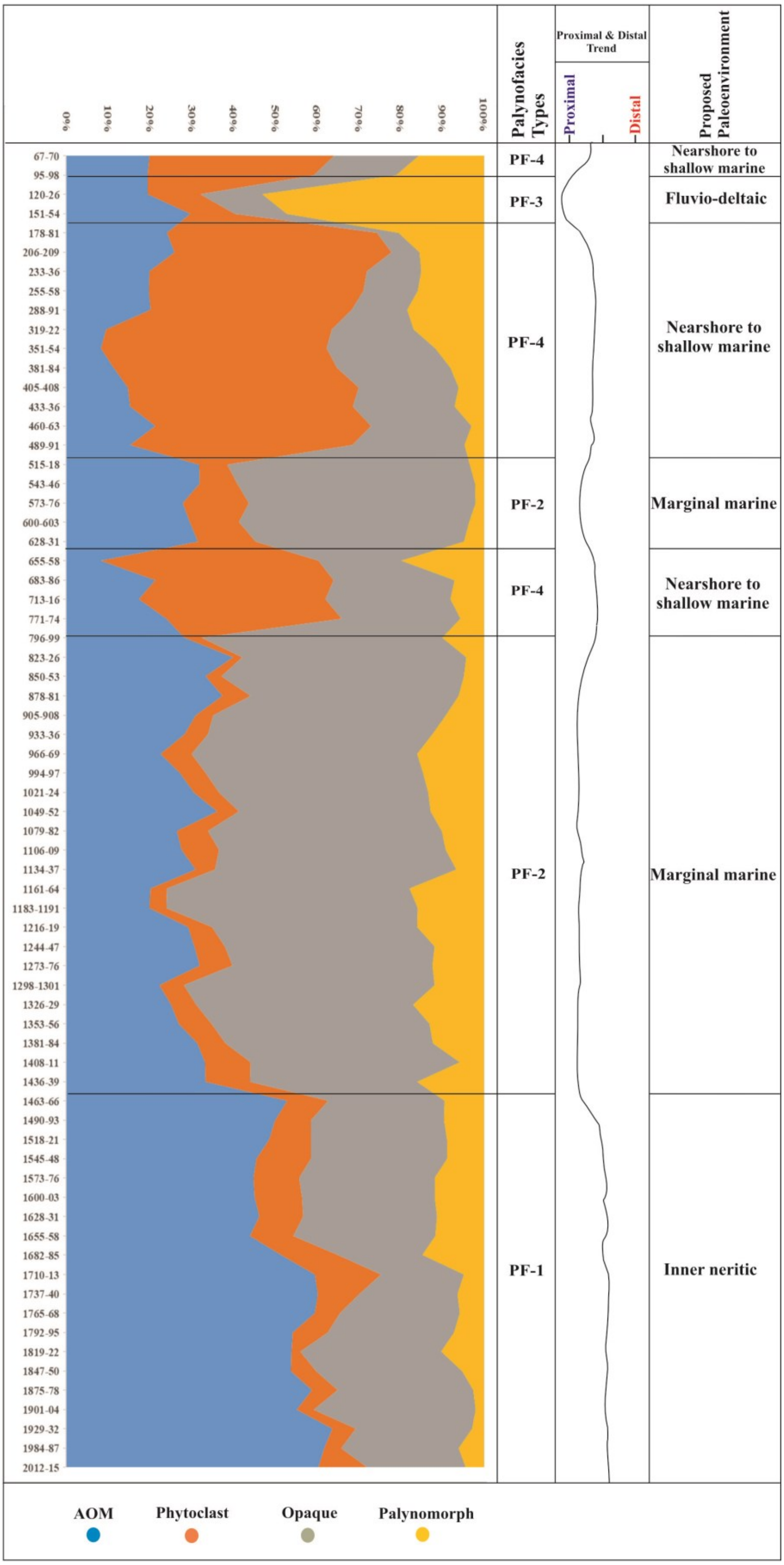


Figure 8. Distribution of palynofacies types, proposed paleoenvironments and proximal-distal trend in the Kobnaswaso-1 well.

Figura 8. Distribución de tipos de palinofacies, paleoambientes propuestos y tendencia proximal-distal en el pozo Kobnaswaso-1.

4.2.3.3. Palynofacies type 3 (PF-3) - Palynomorphs dominant with AOM

Samples of PF-3 are confined within field V of Tyson's (1993) APP ternary diagram (Figure 4). This depicts deposition in a mud-dominated oxic shelf (distal shelf) and is characterized as a kerogen type III, (gas-prone) due to abundance of terrestrial palynomorphs.

The fact that sporomorphs account for about 82% (See Appendix 3) of the palynomorph assemblage reflects proximity to the source area (Zobaa *et al.*, 2013; Martinez *et al.*, 2008). According to Zavattieri *et al.* (2008), a high percentage of sporomorphs in comparison to other microplanktons indicates a delta top facies. The predominance of pteridophyte spores in PF-3 reflects a very shallower depositional setting in a nearshore zone as compared to PF-1 and PF-2 (Tyson, 1995; Tahoun & Deaf, 2016; Gentzis *et al.*, 2019). The presence of Palmae pollen types (*Proxapertites, Longapertites,* and *Mauritiidites*) within this palynofacies further suggests a mangrove setting of a nearshore environment (Schrank, 1987; Herngreen, 1998; El Diasty *et al.*, 2019). Traverse's (1988) MSP ternary diagram (Figure 5) also supports a deltaic depositional environment. Among the few dinocysts recovered from PF-3, peridinoids of the *Wetzeliella* Association (*Andalusiella* and *Senegalinium*) are dominant suggesting a nearshore (estuarine/brackish) environment (Downie *et al.*, 1971). Therefore, PF-3 must have deposited in fluvio-deltaic environment under a mud-dominated oxic conditions (Figure 8).

4.2.3.4. Palynofacies type 4 (PF-4) - Phytoclast (translucent) dominant with opaques

The samples that constitute PF-4 are located in field II of Tyson's (1995) APP ternary diagram (Figure 4). This is indicative of a marginal dysoxic-anoxic basin redox condition, and implies kerogen III (gas-prone) due to the high concentration of phytoclasts and opaques which dilutes the AOM.

The prevalence of translucent phytoclasts over opaques suggests proximity to the terrestrial source area or rapid transportation (Tyson, 1995; Zobaa *et al.*, 2013). Although turbidity currents in deeper waters can also lead to deposition, elevated concentrations of phytoclasts often suggest river deposition in estuarine and deltaic settings (Tyson, 1995; Batten, 1996; Al-Ameri *et al.*, 2001; Carvalho *et al.*, 2013). The elevated occurrence of terrestrial palynomorphs relative to marine palynomorphs and the modest input of AOM (17%) indicate deposition in shallower marine conditions close to land vegetation under dysoxic-suboxic conditions (Alaug *et al.*, 2014). Deeper depths (655 - 658 m, 683 - 685 m, 713 - 716 m, and 771 - 774 m) of PF-4 exhibit a higher prevalence of *Classopollis* and sphaeroidal pollen grains pointing to a distal nearshore setting, while the upper part of this palynofacies show a higher presence of pteridophyte spores indicating a relatively shallower nearshore environment. Additionally, Traverse's (1988) MSP diagram (Figure 5) reinforces a trend of shallow marine to nearshore conditions.

4.2.4. Source rock potential and maturity of organic matter type

El Atfy (2021) points that optical investigations of organic matter in sediments has revealed that palynofacies analysis provides direct information on biological sources and constituents of particulate organic matter assemblage which permits the use of palynofacies analysis as an aid in petroleum source potential interpretation. Aggarwal (2021) stated that the concurrence of TAI (Thermal Alteration Index) with palynofacies is an excellent parameter for source rock evaluation and has been used widely by various researchers.

The investigation of visual kerogen analysis using observed spore colouration in the samples resulted in two major thermal maturation levels for the succession in the Kobnaswaso-1 well. For PF-1 (1490 - 1494 m to 2012 - 2015 m) (Figure 7), the observed spore colour ranged from bright orange to tan which correspond to TAI values of 2+ to 3-, and Ro values of 0.6 - 0.9%. This is dominated by mainly AOM indicative of kerogen type II and shows a matured, oil-prone source rock.

For the lower sample depths of PF-2 (771 - 774 m to 1490 - 1494 m) (Figure 6), spore colour ranged between sunny yellow to yellow orange correlating to TAI values of 2- to 2 and Ro values of 0.3 - 0.5%, which is characteristic of kerogen type III (phytoclast dominant), indicating an immature, gas-prone source rock. Upper sample depths of PF-2 (460 - 463 m to 628 – 631 m), PF-3 and PF-4 show spore colour of between pale yellow to yellow corresponding to TAI values of 1 to 1+, and Ro values of 0.2 - 0.3% which implied kerogen type III (phytoclast dominant), suggestive of an immature, gas-prone source rock.

4.2.5. Cretaceous Provincialism

The microfloral complex of the succession from the Kobnaswaso-1well is indicative of the Pre-Albian Early Cretaceous *Dicheiropollis etruscus/Afropollis* Province, Albian-Cenomanian Elaterate Province and the Senonian Palmae Province (Herngreen, 1980).

The presence of the diagnostic microflora *Afropollis operculatus* and other associated taxa such as *Araucariacites* and *Classopollis* situates the PZ I within Pre-Albian Early Cretaceous *Dicheiropollis etruscus/Afropollis* Province.

Sporomorph taxa (*Elateroplicites, Elateropollenites, Elaterosporites, Galeacornea, Sofrepites, Ephedripites, Equisetosporites, Gnetaceaepollenites,* and *Classopollis*) recorded within PZ II, and III justifies the assignment of these zones to the Albian-Cenomanian Elaterate Province.

Palmae palynoflora (*Retimonocolpites* plexus, *Longapertites, Proxapertites, Mauritiidites*), and associated types (*Proteacidites and Zlivisporis)* recorded within PZ IV and PZ V provide evidence for the Senonian Palmae Province and implies a warm humid climate for the sediments (Herngreen, 1996). Dinoflagellate cyst, *Andalusiella* and *Senegalinium* of the PZ-V compliments the above observation. These elements are typical of the Malloy Suite of Lentin & Williams (1980), which typify the tropical to subtropical warmer climate in the equatorial region.

5. Conclusions

This study on palynostratigraphy, palynofacies, and thermal maturation of 69 cutting samples from the Kobnaswaso-1 well, onshore Tano Basin, made the following observations of special significance:

The qualitative and quantitative distributions of index palynomorph taxa within the Kobnaswaso-1 well establishes five palynozones. These are *Afropollis operculatus* Total Range Zone (PZ-I) (? late Aptian), *Elateropollenites jardinei - Sofrepites legouxiae* Interval Zone (PZ-II) (early Albian to early Cenomanian), *Triporites* sp - *Classopollis brasiliensis* Interval Zone (PZ-III) (mid-late Cenomanian), *Droseridites senonicus* Interval Zone (PZ-IV) (late Turonian-Santonian), and *Senegalinium laevigatum - Cordosphaeridium inodes - Andalusiella dubia* Assemblage Zone (PZ-V) (early Campanian). PZ-I, PZ-II, and PZ-III indicates sediment deposition in relatively shallow marine habitats with vegetation growing in coastal local wetlands under semi-arid/arid climatic conditions. PZ-IV indicates the presence of rainforest trees under humid climatic conditions. PZ-V reflects sedimentation in mangrove environment under a warm humid tropical to subtropical climate.

Palynofacies analysis revealed four palynofacies types: PF-1 (inner neritic zone with proximal suboxic-anoxic shelf condition), PF-2 (marginal marine setting with marginal dysoxic-anoxic basin redox condition), PF-3 (fluvio-deltaic and mud-dominated oxic shelf), and PF-4 (nearshore to shallow marine environment with dysoxic-anoxic redox condition). PF-1 is dominated by oil-prone materials (kerogen type II), while PF-2, PF-3, and PF-4 are dominated by gas-prone materials (kerogen type III). Observed Thermal Alteration Index (TAI) and Vitrinite Reflectance (Ro) indicate that, samples for PF-1are thermally mature source rock, whereas those of PF-2, PF-3, and PF-4 are considered thermally immature source rocks.

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Authorship contribution statement

Benjamin Fameyeh: Conceptualization, Formal analysis, Investigation, Methodology, Writing (Original draft).
David Atta-Peters: Conceptualization, Formal analysis, Investigation, Methodology, Writing (Review, editing and proof reading).
Chris Achaegakwo: Formal analysis, Investigation, Methodology.
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APPENDICES

Appendix 1. Showing the optical results obtained from the microscopic work

DEPTHS	AOM	OPAQUE	PHYTOCLAST	PALYNOMORPH				
				SPORE	*POLLEN*	*GONYAULAX*	*PERIDINACEAN*	Foram
67-70	232	120	70	27	41	15	11	1
95-98	228	104	64	36	58	18	13	1
120-26	98	74	63	89	102	30	35	0
151-54	149	62	53	78	108	20	30	0
178-81	121	26	251	19	53	10	20	1
206-209	130	34	259	23	24	10	20	4
233-36	212	99	166	6	2	3	12	0
255-58	232	65	130	20	30	13	10	1
288-91	222	97	137	10	24	3	7	2
319-22	28	98	290	11	42	12	19	0
351-54	42	130	270	13	20	21	4	1
381-84	57	136	267	6	22	10	2	0
405-408	74	120	276	6	20	4	0	1
433-36	77	122	266	4	28	3	0	1
460-63	107	120	258	4	10	1	0	1
489-91	80	140	276	3	20	1	0	1
515-18	159	290	34	0	17	0	0	2
543-46	160	284	45	3	8	0	0	0
573-76	140	271	79	2	8	0	0	1
600-603	148	275	59	2	16	0	0	0
628-31	158	249	69	3	19	1	1	1
655-58	42	99	260	26	59	9	5	1
683-86	107	145	213	3	32	0	0	4
713-16	87	150	223	4	36	0	0	2
771-74	120	142	210	0	28	0	0	1
796-99	142	288	20	0	50	0	0	0
823-26	200	268	11	6	15	0	0	0
850-53	167	290	19	3	21	0	0	0
878-81	187	249	34	6	23	1	0	0
905-908	155	278	21	13	31	2	0	1
933-36	142	268	28	10	51	0	1	0
966-69	113	270	37	27	52	0	1	0
994-97	136	260	31	22	49	2	0	0
1021-24	153	250	30	24	43	0	0	1
1049-52	181	229	26	19	40	5	0	1

1079-82	133	280	37	16	35	0	0	0
1106-09	138	271	45	18	25	3	0	1
1134-37	155	289	23	7	26	0	0	2
1161-64	101	290	20	27	55	6	1	1
1183-1191	100	301	20	31	40	5	3	3
1216-19	146	245	29	19	51	9	1	3
1244-47	154	251	36	12	43	4	0	3
1273-76	160	239	39	22	34	5	1	2
1298-1301	112	300	29	12	43	4	0	3
1326-29	126	259	30	21	60	4	0	8
1353-56	135	261	39	16	48	0	1	3
1381-84	157	248	34	12	45	3	1	2
1408-11	166	250	55	6	21	1	1	1
1436-39	167	200	53	25	50	4	1	3
1463-66	265	139	49	11	31	5	0	5
1490-93	250	159	43	13	33	2	0	3
1518-21	243	163	50	12	30	2	0	3
1545-48	228	163	65	10	34	0	0	2
1573-76	224	162	54	14	43	2	0	3
1600-03	226	159	56	15	44	0	0	2
1628-31	231	160	53	11	43	2	0	3
1655-58	220	170	52	17	40	1	0	4
1682-85	254	100	67	15	53	4	1	6
1710-13	298	99	79	3	20	0	1	2
1737-40	301	117	50	2	30	0	0	0
1765-68	298	143	30	7	20	1	1	1
1792-95	271	151	42	6	30	0	0	0
1819-22	270	169	10	7	40	3	1	1
1847-50	269	175	30	4	21	1	0	0
1875-78	294	162	31	0	11	2	0	0
1901-04	276	194	20	3	7	0	0	0
1929-32	319	139	28	1	13	0	0	0
1984-87	309	141	20	0	30	0	0	0
2012-15	302	118	58	1	20	1	0	0

Appendix 2. Relative Percentage Abundance of SOM and Palynomorphs.

DEPTHS (ft)	AOM	PHYTOCLAST	OPAQUE	PALYNOMORPH
67-70	46	14	24	16
95-98	46	13	21	21
120-26	20	13	15	53
151-54	30	11	12	47
178-81	24	50	5	20
206-209	26	52	7	15
233-36	42	33	20	5
255-58	46	26	13	15
288-91	44	27	19	9
319-22	6	58	20	17
351-54	8	54	26	12
381-84	11	53	27	8
405-408	15	55	24	6
433-36	15	53	24	7
460-63	21	52	24	3
489-91	16	55	28	5
515-18	32	7	58	3
543-46	32	9	57	2
573-76	28	16	54	2
600-603	30	12	55	4
628-31	32	14	50	5
655-58	8	52	20	20
683-86	21	43	29	7
713-16	17	45	30	8
771-74	24	42	28	6
796-99	28	4	58	10
823-26	40	2	54	4
850-53	33	4	58	5
878-81	37	7	50	6
905-908	31	4	56	9
933-36	28	6	54	12
966-69	23	7	54	16
994-97	27	6	52	15
1021-24	31	6	50	13

1049-52	36	5	46	13
1079-82	27	7	56	10
1106-09	28	9	54	9
1134-37	31	5	58	7
1161-64	20	4	58	18
1183-1191	20	4	60	16
1216-19	29	6	49	16
1244-47	31	7	50	12
1273-76	32	8	48	12
1298-1301	22	6	60	12
1326-29	25	6	52	17
1353-56	27	8	52	13
1381-84	31	7	50	12
1408-11	33	11	50	6
1436-39	33	11	40	16
1463-66	53	10	28	9
1490-93	50	9	32	10
1518-21	49	10	33	9
1545-48	46	13	33	9
1573-76	45	11	32	12
1600-03	45	11	32	12
1628-31	46	11	32	11
1655-58	44	10	34	12
1682-85	51	13	20	15
1710-13	60	16	20	5
1737-40	60	10	23	6
1765-68	60	6	29	6
1792-95	54	8	30	7
1819-22	54	2	34	10
1847-50	54	6	35	5
1875-78	59	6	32	3
1901-04	55	4	39	2
1929-32	64	6	28	3
1984-87	62	4	28	6
2012-15	60	12	24	4

Appendix 3. Relative Percentage Abundance of Palynomorphs.

Depth (ft)	Terrestrial		Marine	
	Spore	Pollen	Gonyaulax	Peridinacean
67-70	32	48	12	8
95-98	26	45	19	10
120-26	38	29	19	14
151-54	27	41	18	14
178-81	38	22	15	23
206-209	32	29	14	25
233-36	39	26	8	27
255-58	27	41	18	14
288-91	23	55	7	16
319-22	13	53	17	23
351-54	23	46	26	7
381-84	15	55	25	5
405-408	20	67	13	0
433-36	11	80	9	0
460-63	28	67	6	0
489-91	14	83	3	0
515-18	0	100	0	0
543-46	27	73	0	0
573-76	20	80	0	0
600-603	11	89	0	0
628-31	13	79	4	4
655-58	26	60	9	5
683-86	9	91	0	0
713-16	10	90	0	0
771-74	0	100	0	0
796-99	0	100	0	0
823-26	29	71	0	0
850-53	13	88	0	0
878-81	20	77	3	0
905-908	28	67	4	0
933-36	16	82	0	2
966-69	34	65	0	1
994-97	30	67	3	0
1021-24	36	64	0	0
1049-52	30	63	8	0
1079-82	31	69	0	0

1106-09	39	54	7	0
1134-37	21	79	0	0
1161-64	30	62	7	1
1183-1191	39	51	6	4
1216-19	24	64	11	1
1244-47	20	73	7	0
1273-76	35	55	8	2
1298-1301	20	73	7	0
1326-29	25	71	5	0
1353-56	25	74	0	2
1381-84	20	74	5	2
1408-11	21	72	3	3
1436-39	31	63	5	1
1463-66	23	66	11	0
1490-93	27	69	4	0
1518-21	27	68	5	0
1545-48	23	77	0	0
1573-76	24	73	3	0
1600-03	25	75	0	0
1628-31	20	77	4	0
1655-58	29	69	2	0
1682-85	21	73	5	1
1710-13	13	83	0	4
1737-40	6	94	0	0
1765-68	24	69	3	3
1792-95	17	83	0	0
1819-22	14	78	6	2
1847-50	15	81	4	0
1875-78	0	85	15	0
1901-04	30	70	0	0
1929-32	7	93	0	0
1984-87	0	100	0	0
2014-15	5	91	5	0

Appendix 4. Sample intervals of Palynofacies types.

Palynofacies type 1	1463-66m, 1490-93m, 1518-21m, 1545-48m, 1573-75m, 1600-4m, 1628-31m, 1655-59m, 1682-84m, 1710-13m, 1737-40m, 1765-68m, 1792-95m, 1820-24m, 1847-50m, 1875-78m, 1902-5m, 1929-32m, 1984-87m, 2012-14m
Palynofacies type 2	515-17m, 543-45m, 573-75m, 600-603m, 628-30m, 796-98m, 823-25m, 850-53m, 878-80m, 905-907m, 933-35m, 966-968m, 994-97m, 1021-24m, 1049-52m, 1079-81m, 1106-8m, 1134-37m, 1161-64m, 1185- 87m, 1216-18m, 1244-46m, 1273-75m, 1298-301m, 1326-28m, 1353-56m, 1381-84m, 1408-10m
Palynofacies type 3	120-26m, 151-154m
Palynofacies type 4	67-69m, 95-99m, 178-80m, 206-8m, 233-35m, 255-57m, 288-290m, 319-22m, 351-54m, 381-84m, 405- 8m, 433-35m, 460-63m, 489-91m, 655-57m, 683-85m, 713-15m, 771-75m