Bulletin of the Geological Society of Malaysia, Volume 78, November 2024, pp. 59 - 73
DOI: https://doi.org/10.7186/bgsm78202406

Palynology of Late Oligocene to Pliocene succession in Temana Field of Balingian Province, offshore Sarawak

Ahmad Zamzamie Ishak[1,*], Zainey Konjing[2], Abdul Hadi Abd Rahman[3], Mohd Suhaili Ismail[1], Numair Ahmed Siddiqui[1]

[1] Geosciences Department, Universiti Teknologi PETRONAS, Persiaran UTP, 32610 Seri Iskandar, Perak, Malaysia
[2] Orogenic Geosample Facilities & Laboratories, Lot 6744-3, Jalan Tekali-1, Kawasan Perindustrian Tekali, 1 ½ Miles, Jalan Sungai Tekali, 43100 Hulu Langat, Selangor, Malaysia
[3] Geoscience Consultant, 43, Taman Bertam Perdana, 13200 Kepala Batas, Pulau Pinang, Malaysia
* Corresponding author email address: ahmad_20001019@utp.edu.my

Abstract: Palynological records in Late Cenozoic succession from two Temana wells were reviewed and investigated for palynomorph assemblages, biostratigraphic correlation and age dating, as well as for paleoenvironment and paleoclimate interpretation. The data indicates abundant and diverse pollen and spores deposited in marginal marine with tidal influence setting. Three main palynomorph assemblages were identified from the Temana wells: (1) Zone-1 (dated as Late Oligocene), characterized by abundant *Florschuetzia trilobata* and dominant montane and seasonal elements such as *Picea*, *Tsuga* and *Pinus*, (2) Zone-2 (Early to Middle Miocene), dominated by Kerapah *Casuarina*-type pollen and characterized by increasing abundance of Rhizophoraceae mangrove pollen. Zone-2 can be further differentiated into Subzone-2a and Subzone-2b based on later appearance of *Florschuetzia levipoli*, and (3) Zone-3 (Late Miocene to Pliocene) occurring above a major angular unconformity is marked by a high percentage of the rainforest pollen Rubiaceae and a minor increase in seasonal elements. The interpreted paleoclimate inferred from temporal variations in hinterland-derived pollen shows cyclical pattern from seasonally dry climate in the Oligocene to warm and ever-wet climate, marked by the growth of Kerapah peat swamp during Early to Middle Miocene, and finally a prolong humid climate characterized by rainforest vegetation with minor intermittent seasonality since Late Miocene/Pliocene.

Keywords: Palynology, Sarawak, Late Cenozoic, marginal marine, paleoclimate

INTRODUCTION

The study of fossil records in sedimentary rocks has long been used as stratigraphic tool for correlation, age dating, depositional environment reconstruction and paleoclimate interpretation. The advancement of biostratigraphy has hugely benefited the petroleum industry, whereby various zonation schemes have been developed utilizing the main microfossil groups comprising calcareous nannofossil, planktonic foraminifera and palynomorphs extracted from wells or outcrops (Van Gorsel *et al*., 2014; Lunt, 2022). Palynology is the study of palynomorphs – the acid-resistant organic materials derived from plants and algae. Compared to marine microfossils, palynomorphs especially terrestrially derived pollen and spores are usually marked by restricted geographical distribution, long stratigraphic ranges and strongly controlled by climate and tectonics (Morley, 1991). Nonetheless, they remain as the only microfossil group that can be found in both non-marine and marine rocks and therefore are important as a correlation tool in continental to marginal marine settings that are devoid of planktonic marine fossils.

In NW Borneo, a zonation scheme for Tertiary rocks was first established by Shell Brunei based on the evolutionary changes of *Florschuetzia* lineage (Germeraad *et al*., 1968). Subsequently, Morley (1978) reviewed and adopted the Tertiary palynostratigraphy with additional age-restricted taxa that serve as valuable correlation tool in the region. Sarawak Shell Berhad (SSB) had also introduced their palynological zonation scheme for the Sarawak Cycles calibrated with planktonic foraminifera, as published by Ho (1978) and later revised by Hageman (1987). However, detail criteria of the zone assignment had not been published and thus limited it from being used widely outside SSB and petroleum industry. As biostratigraphic data in Temana were reported using old SSB palynostratigraphy, this poses a problem to establish stratigraphic correlation across Temana Field and regionally. This study attempts to establish alternative biostratigraphy zonation of Temana Field by reviewing the reported palynomorph assemblage changes and age-diagnostic markers using Morley (1978; 1991) as reference. This would assist exploration and development teams in regional correlation and maturing opportunities in the area.

0126-6187; 2637-109X / Published by the Geological Society of Malaysia.

Additionally, the change in vegetation landscape inferred from the palynomorph assemblages would provide better understanding of paleoenvironment and paleoclimate during deposition. Late Cenozoic global climate is dominated by long-term ice-age period following Permian to Eocene greenhouse conditions and the growth of Antarctic ice sheets (Zachos *et al*., 2001). This led to drastic changes in ocean circulation which influenced the regional climate pattern and floral and faunal distribution. The climate pattern in Southeast Asia also shows significant variation of wetter to drier climate throughout the Cenozoic in response to tectonic movement, monsoon activity and glacio-eustatic fluctuation (Morley, 2012). Thus, geological records of pollen and spores with analogue of modern-day plant ecology give valuable insight on the paleovegetation and paleoclimate trend (Morley *et al*., 2019; 2021). The main objectives of this paper are to (1) characterize the palynomorph assemblages, (2) determine the stratigraphic age of the assemblages, and (3) reconstruct the depositional environment and paleoclimate history of the succession.

GEOLOGICAL SETTING

Sarawak is located on the northwestern part of Borneo island and shares borders with Kalimantan of Indonesia to the east and Brunei and Sabah to the north. The continental margin of Sarawak is divided into eight geological provinces – SW Sarawak, West Luconia, Tatau, Balingian, Tinjar, Central Luconia, North Luconia and West Baram Delta (Figure 1). These provinces collectively make up the Sarawak Basin, formed through a complex geological setting related to the subduction beneath NW Borneo margin and opening of South China Sea from Late Cretaceous to Middle Miocene time. The offshore stratigraphy is subdivided into eight sedimentary cycles, each consisting of a regressive sequence bounded by marine transgressive surfaces (Ho, 1978) (Figure 2). The Cycles were interpreted from petroleum exploration well and seismic data, age-calibrated with foraminifera and palynomorphs zonation.

The study area is situated in Balingian Province, a major hydrocarbon producing region in Sarawak Basin with primary reservoir targets in Cycle I and II sediments while Cycle III and V form the secondary targets (Madon & Abolins, 1999). The proven hydrocarbon-bearing Cycle I and II (Oligocene-Early Miocene) were deposited as fluvial to shallow marine deposits following a major collisional orogenic event that formed Rajang Group Fold-Thrust Belt (Figure 2). An overall transgressive deposition from Cycle II to III times (Early to Middle Miocene) culminated in the growth of carbonate build-ups during Cycle IV to V times (Middle-Late Miocene) on the bathymetric highs of the

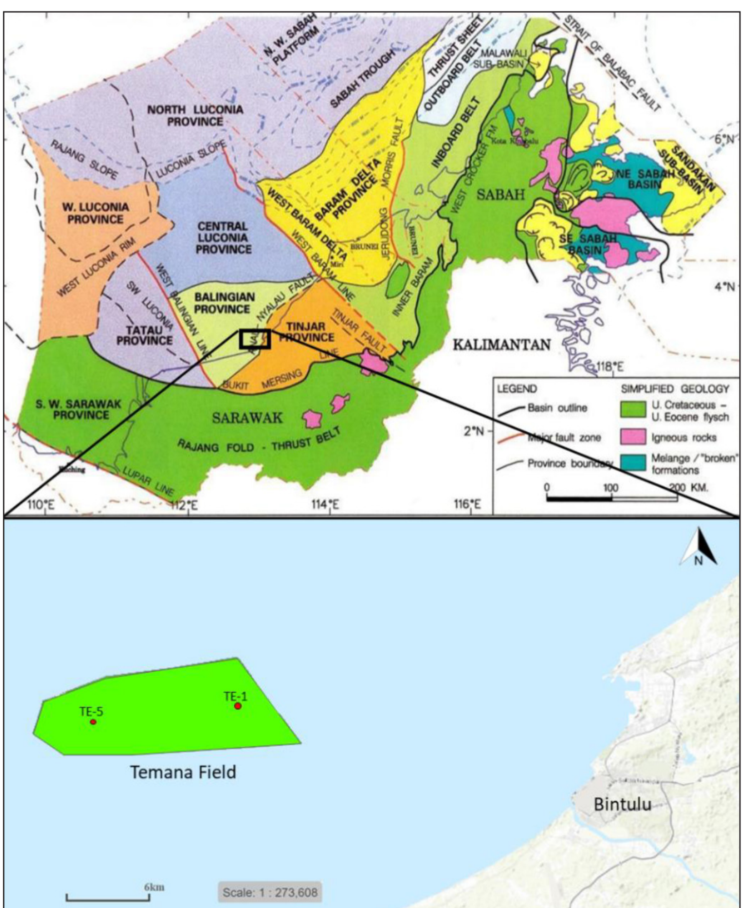

Figure 1: Geological provinces of NW Borneo continental margin (after Madon, 1999). The inset map shows the location of Temana Field and the wells used in this study (TE-1 and TE-5).

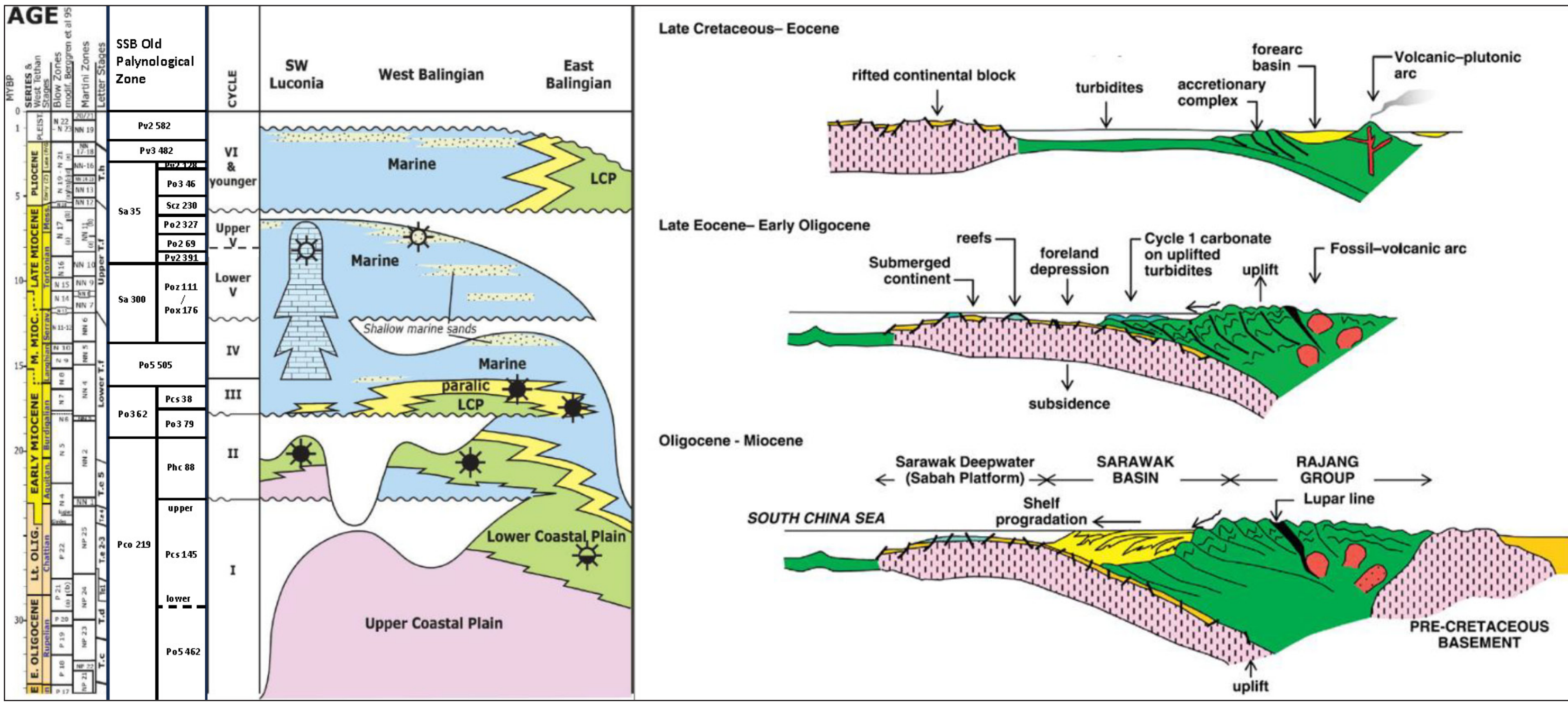

Figure 2: Stratigraphic framework and tectonic setting of Sarawak Basin. Left: Stratigraphic scheme showing the Cycles and sedimentation in Sarawak Basin (after Lunt & Madon, 2017). Right: Schematic diagram showing the subduction of Luconia Block beneath Borneo margin which uplifted Rajang Fold-Thrust Belt and provided sediments to the foreland basin and passive margin of Sarawak Basin (after Madon *et al*., 2013).

Luconia shelf (Lunt & Madon, 2017; Lunt, 2022). Further inboard in the Balingian Province and onshore Sarawak, deposition of deltaic, estuarine and coastal sediments was sourced from multiple provenances (Amir Hassan *et al*., 2013). In East Balingian subprovince, wrench compressional tectonics from Late Miocene to Pliocene had uplifted Cycle I to III strata and formed major angular unconformity over several NE-SW oriented anticlines with hydrocarbon accumulation (Swinburn, 1994; Madon & Abolins, 1999).

The equivalent onshore stratigraphy comprises predominantly of Nyalau Formation, dated as Oligocene to Early Miocene and thought to be contemporaneous to Cycle I and II of offshore Sarawak (Konjing *et al*., 2022; Shoukat *et al*., 2023). Accordingly, outcrops of Nyalau Formation serve as analogue to the prolific hydrocarbon-bearing reservoir in Balingian Province. Recent study has interpreted it to be deposited in fluvio-deltaic marginal marine setting within a broad NW-SE trending embayment affected by mixed tidal and wave energy (Amir Hassan *et al*., 2013; Shoukat *et al*., 2022). Other formations in onshore Balingian Province include the Balingian, Begrih and Liang formations (Middle Miocene to Pliocene), Tatau Formation (Early Oligocene) and Belaga Formation (Late Cretaceous to Late Eocene) (Murtaza *et al*., 2018; Hennig-Breitfeld *et al*., 2019). The sedimentary succession is generally composed of repetitive cycles of interbedded sand and shale with multiple coal layers typical of marginal marine deposits.

Temana Field is located 30 km offshore west of Bintulu town, in a water depth of 29 m (Figure 1). It was discovered by Sarawak Shell Berhad (SSB) in 1962 and has been producing since 1979 from primarily Cycle II to III reservoirs. Cycle I, although hydrocarbon-bearing, is generally considered as tight gas reservoir and not a major producer. The Temana structure is defined as a westward-plunging ENE-WSW anticline bounded by reverse faults on both flanks and crosscut by numerous NE-trending normal and reverse faults (Roy *et al*., 2010). A major angular unconformity clearly visible on seismic, progressively truncates the sediments along the crest of anticline down to Cycle I towards the east (Figure 3).

Temana reservoirs are mainly divided, from top to bottom, into H, I, J and K series. Oil is produced mainly from the H, I and J reservoirs. The original biostratigraphy of Temana Field was based primarily on old SSB palynological zonation for correlation and age dating, as foraminifera and nannofossils are largely absent or not recorded in the well reports. In general, internal well reports indicate the H-series is equivalent to Cycle

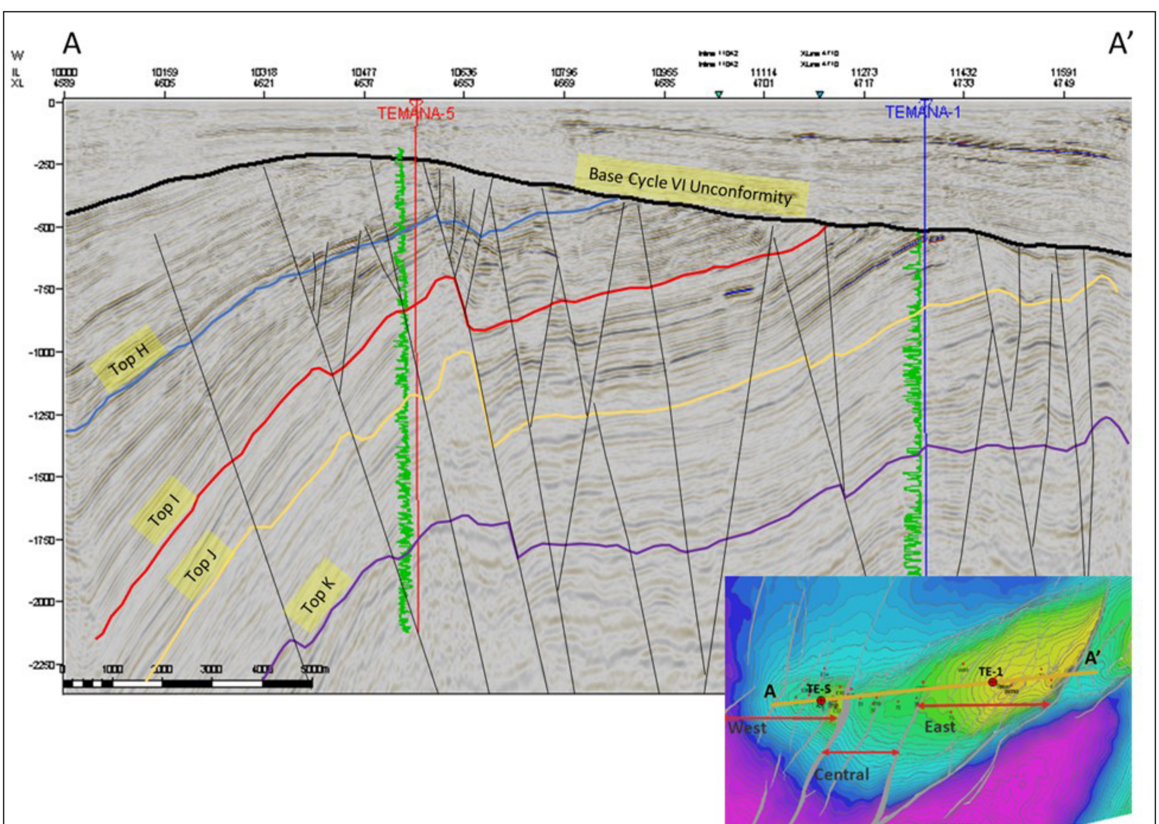

Figure 3: Seismic profile A-A' showing a west-plunging Temana anticline structure with a major angular unconformity (Base Cycle VI Unconformity) eroding Cycle I to III strata. Structure map of Top J-series (bottom right) showing location of A-A' line.

III (Pcs 38 to upper Po3 79 subzones), the I- and J-series are correlatable to Cycle II (lower Po3 79 and Phc 88 subzones), while the K-series is equivalent to Cycle I (Pcs 145 subzone) (Schoonderbeek, 1989, unpublished; Ishak *et al*., 2023). The non-reservoir interval above the major angular unconformity is undifferentiated as Cycle VI and younger succession (Ishak *et al*., 2023).

DATA AND METHODS

Two wells with palynological record were employed in this study, namely Temana-1 (TE-1) and Temana-5 (TE-5), drilled in 1962 and 1971 respectively (location in Figure 1). However, no thin section samples were analyzed due to the old and poor condition of the original samples, hence, no photomicrograph is available for the recorded pollen and spores. Instead, scanned copy of sawtooth diagrams in well reports by SSB showing palynomorph distributions along drilled depth were digitized and re-evaluated using Stratabugs™ software. Several limitations were encountered such as no absolute abundance/percentage value indicated on the original sawtooth diagrams and the abundance peak also appears to be truncated at certain level, hindering full representation of the palynomorph count. Therefore, in this study, the relative position of the curve from zero level is used to indicate its abundance.

Palynological assemblages were then identified and characterized based on the relative abundance trend. The age for each assemblage zone was determined from the presence of age-diagnostic taxa in Sarawak area, as described by Morley (1978; 1991). The palynostratigraphic scheme published by Hageman (1987) lacks details on the definition and marker species used for age dating and thus not used in this study aside from correlation with Sarawak Cycles for regional understanding. Paleoenvironmental and paleoclimatic indicators from the palynomorph distribution were also analyzed based on the modern-day ecology of extant plant species and their probable vegetation type/element. The results were displayed in palynological charts showing variations within different pollen groups: mangrove (which include mangrove and back-mangrove pollens) and hinterland (coastal, *Kerapah*, peat swamp, rainforest, riparian, seasonal, and montane pollens). Depositional environment is inferred from the abundance of local-derived mangrove taxa, commonly associated with coastal plain to marginal marine setting. While hinterland-derived palynomorphs reflect regional vegetation in the catchment area, which is more sensitive to climatic conditions and elevation of the sediment source (Morley *et al*., 2021).

RESULTS

Figures 4-6 show the distribution charts of TE-1 and TE-5 at selected intervals displaying the relative abundance of the palynomorphs – sorted according to their vegetation type/element. Due to strata tilting from east to west, a significant portion of H- and I-series (Cycle II-III) sediment in TE-1 located in eastern part was truncated by a major angular unconformity (Figure 3). TE-5 well in the western area of Temana thus contains a more expanded section covering H- and I-series sediments. Both wells contain a diverse range of pollen and spores from montane to mangrove vegetations, with TE-1 recording 44 taxa and TE-5 contains 41 taxa.

Three main palynomorph assemblage zones, named here as Zone-1, Zone-2 and Zone-3 were described based on distinct characteristics such as appearance and abundance of certain groups of palynomorph. This type of biozone is known as 'Assemblage biozone' whereby three or more taxa are used to define a stratigraphic interval (Nichols, 2009). The different assemblages can be clearly distinguished in Figure 7 that displays the variation of vegetation type/element within local-derived mangrove and hinterland-derived groups.

Zone-1

Zone-1 assemblage is recognized at the deepest stratigraphic level in both wells, TE-1 (1304 m - 2977 m) and TE-5 (1635 m - 2085 m). It is characterized by abundant *F. trilobata* pollen with no other species present from the *Florschuetzia* lineage (i.e., *F. semilobata* and *F. levipoli*). Another important characteristic of Zone-1 is the continuously high occurrence of seasonal and montane elements represented by *Pinus*, *Picea* and *Tsuga*-type pollen (Figure 4). Their abundances, however, rapidly decline across the boundary of overlying Zone-2. Peat swamp pollen such as *Meyeripollis naharkotensis* is also present in the assemblage while Gramineae pollen occurs in small percentage. Rhizophoraceae and *Casuarina*-type pollen are largely absent but show gradual increase in the upper part of Zone-1. Spores are generally rare in this zone.

Zone-2

This zone shows a regular presence of *F. trilobata* associated with *F. semilobata* in the lower part and *F. levipoli* in the upper part. Consistently high percentage of mangrove pollen from Rhizophoraceae and *Brownlowia*-type also characterizes the assemblage. Distinctively, the zone is dominated by the acme of Kerapah peat swamp element represented by *Casuarina*-type in association with *Dacrydium* (Figure 4). Other peat swamp pollen such as *Cephalomappa*, *Dactylocladus*, *Durio*, *Stemonurus* and *Anacolosa*-type appears in low to moderate abundance. Rainforest pollen represented by Rubiaceae-type is also a common feature while montane and seasonal pollen are significantly reduced compared to the Zone-1 below. Spores appear in low percentage throughout the zone, represented by *Lycopodium cernuum*, *Lycopodium phlegmaria* and *Stenochlaena areolaris*. The Zone-2 could be subdivided into a lower part (Subzone-2a) and upper part (Subzone-2b) based on the first appearance of *F. levipoli* pollen in the latter accompanied by a gradual decline in *F. trilobata* (Figure 5). Subzone-2a interval ranges from 561 m to 1304 m in TE-1 and from 620 m to 1635 m in TE-5 well. While

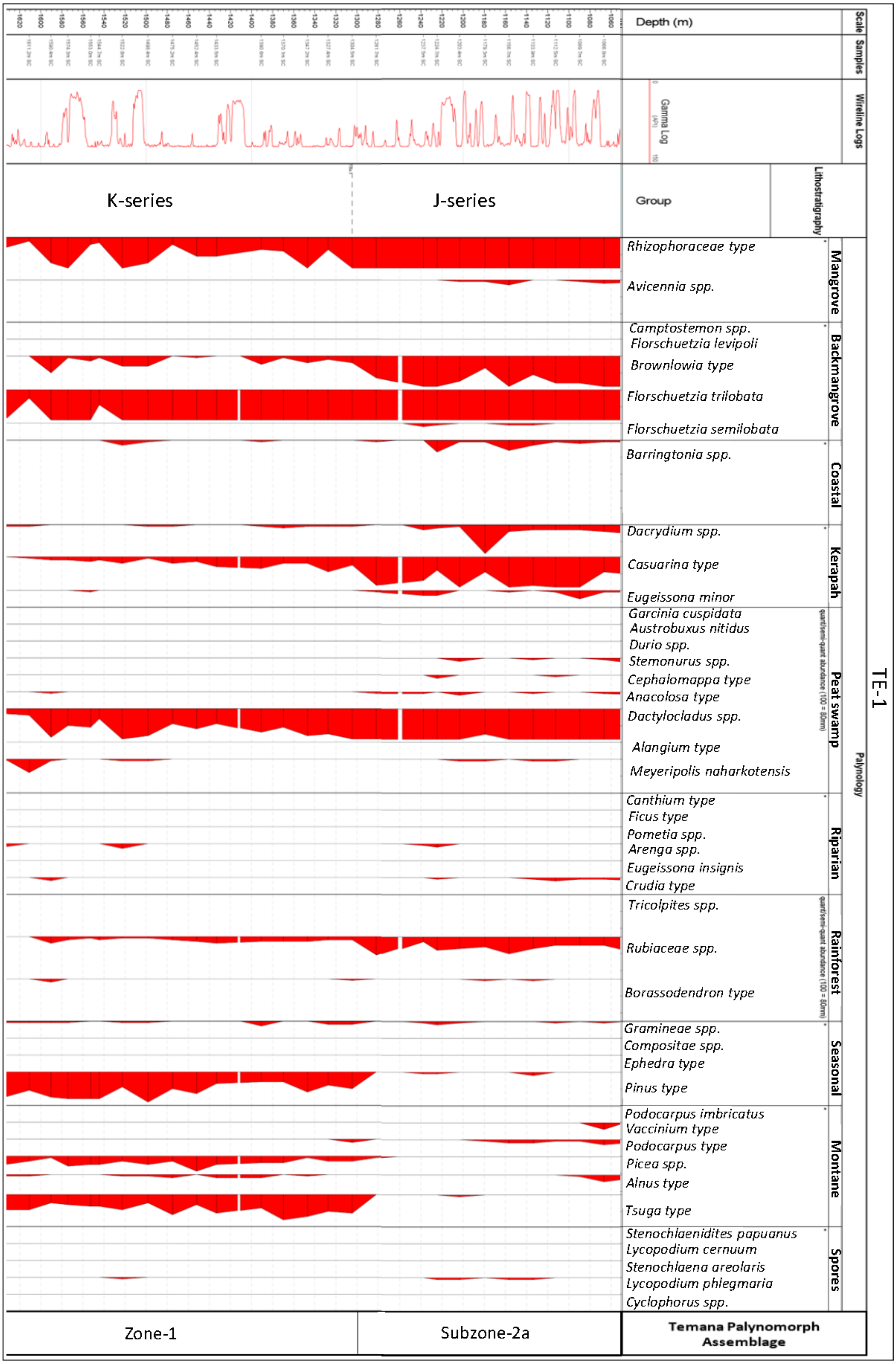

Figure 4: Palynomorph distribution chart of TE-1 showing Zone-2 (Subzone-2a) and Zone-1 assemblages. Zone-1 below is marked by the ubiquitous presence of seasonal and montane pollen such as *Pinus*, *Picea* and *Tsuga* while Subzone-2a is dominated by Kerapah pollen.

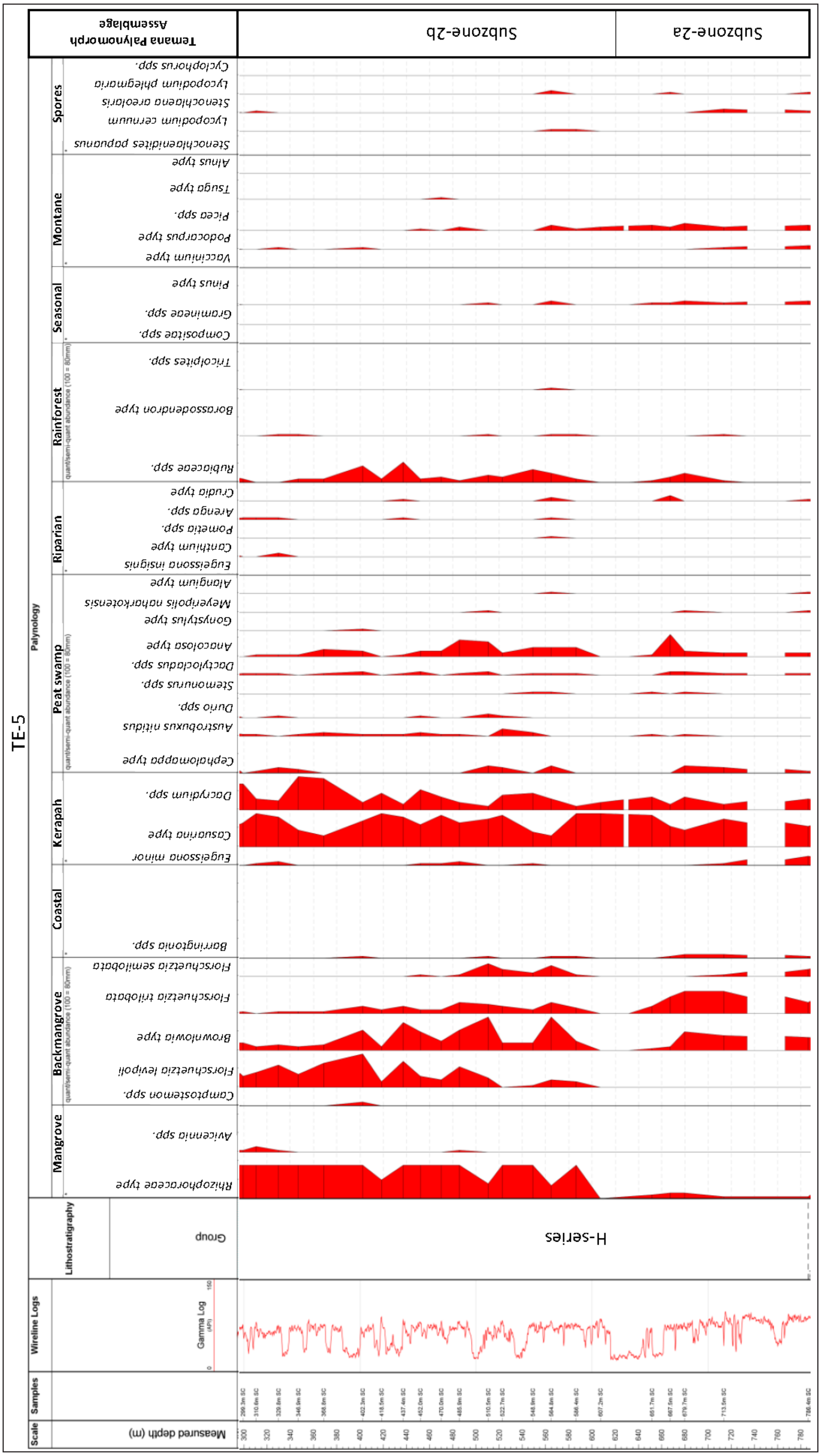

Figure 5: Palynomorph distribution chart of TE-5 well showing Zone-2 assemblages characterized by high abundances of Kerapah pollen. The upper Subzone-2b is separated from Subzone-2a by the first appearance of *F. levipoli* and the decline in the abundance of *F. trilobata*.

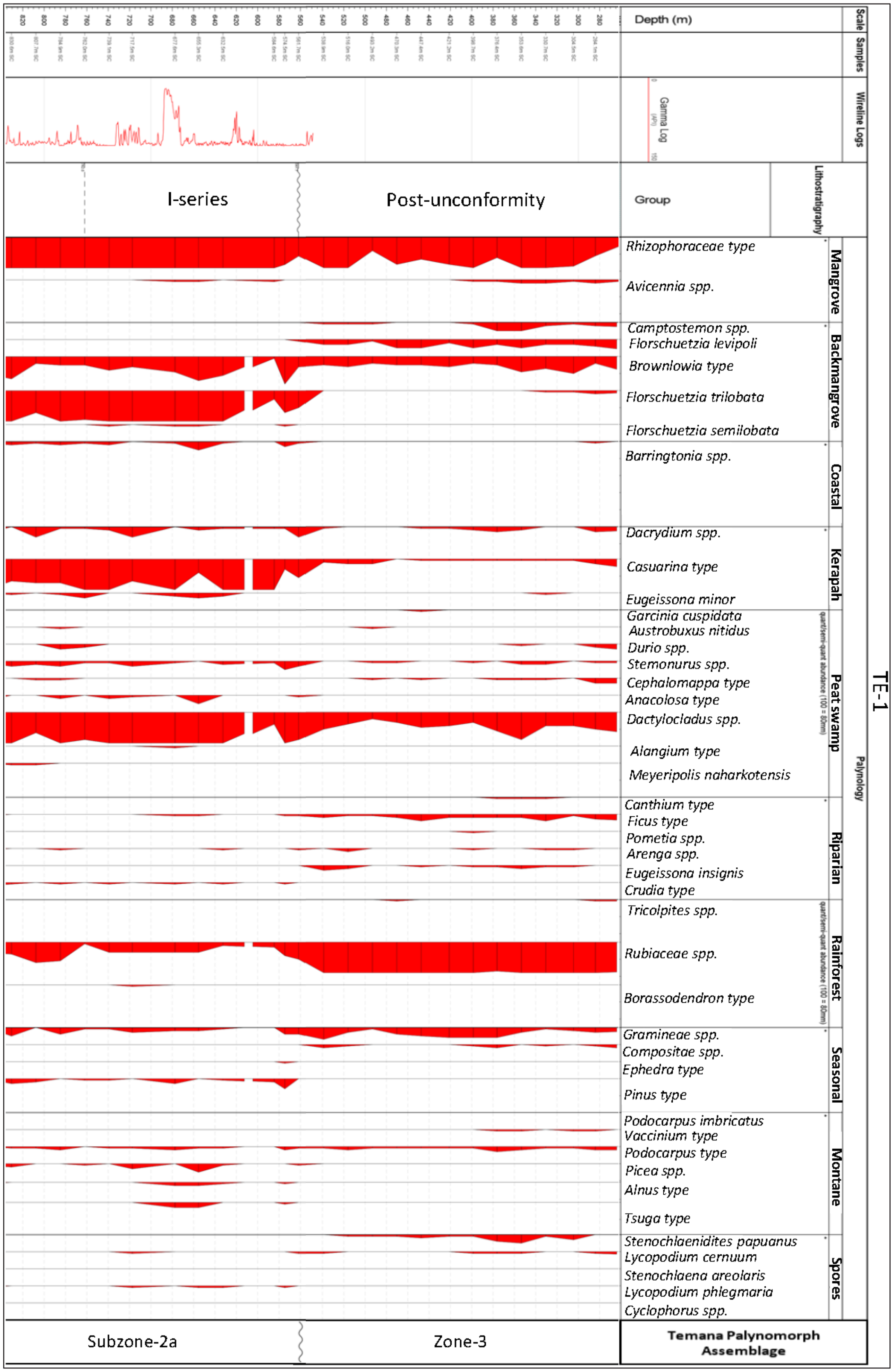

Figure 6: Palynomorph distribution chart of TE-1 showing Zone-3 characterized by acme of rainforest Rubiaceae-type pollen. The Subzone-2a below is dominated by *F. trilobata* and *Casuarina*-type pollen. The boundary between the two zones is the Base Cycle VI Unconformity.

(A)

(B)

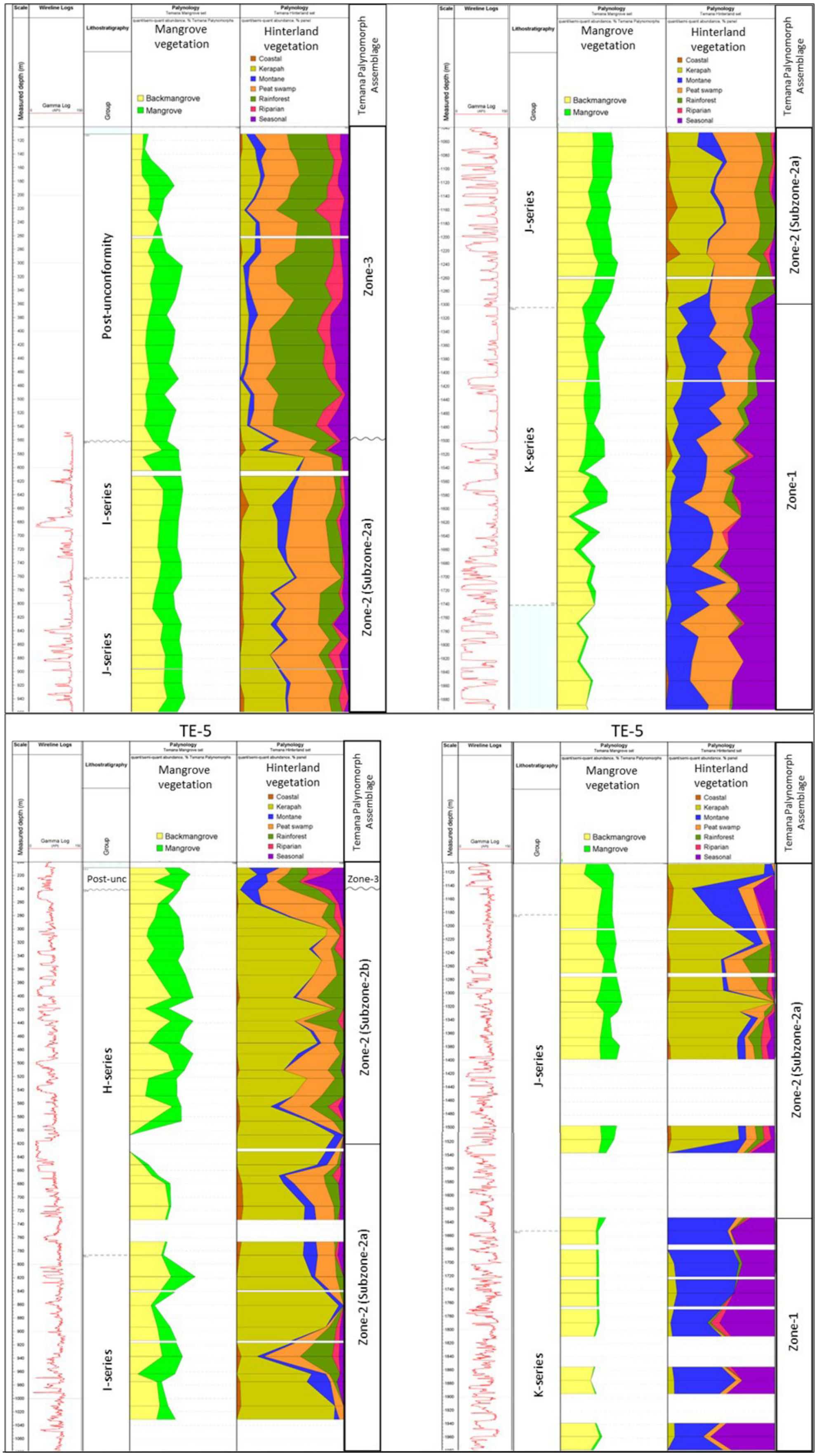

Figure 7: Palynological chart from TE-1 **(A)** and TE-5 **(B)** well showing variation within mangrove and hinterland vegetation group, used for further analysis of paleoenvironmental and paleoclimatic trends. Distinct characteristics are clearly visible for each of the palynomorph assemblage zones suggesting a strong climate-controlled succession.

Subzone-2b is only presence in TE-5 from 241 to 620 m and was eroded at TE-1 well location.

Zone-3

Zone-3 is located in the uppermost interval of TE-1 (111 m - 561 m) and TE-5 (209 m - 241 m), marked by the gradual increase of *F. levipoli* along with presence of back-mangrove *Camptostemon* pollen. A dominant feature of this zone is a significant rise in the abundance of rainforest pollen, which is mainly represented by Rubiaceae-type (Figure 6). The freshwater peat swamp pollen shows a more diverse representation characterized by low-to-moderate percentages of *Garcina cuspidata*, *Austrobuxus nitidus*, *Durio*, *Stemonurus*, *Cephalomappa*, *Dactylocladus* and *Anacolosa*-type. The Kerapah peat swamp pollen, on the other hand, is low in abundance compared to the Zone-2 below. Rhizophoraceae-type mangrove pollen generally shows high percentages with some variability. Seasonal indicators such as Gramineae and *Compositae* pollen are also consistently present throughout while riparian pollen comprising *Canthium*, *Ficus*, *Pometia*, *Arenga* and *Eugeissona insignis* indicate higher diversity and abundance. In addition, spores of *Stenochlaenidites papuanus* start to appear along with minor occurrence of *Lycopodium cernuum* and *Stenochlaena areolaris*.

DISCUSSION

Age and correlation

Palynology is widely used as correlation tool for non-marine rocks as terrestrial-derived palynomorphs are commonly found in both continental to marginal marine deposits (Morley, 1991; Van Gorsel *et al.*, 2014). However, dating rock units by palynology poses a challenge due to its limited regional and stratigraphic distribution patterns which requires calibration with other marine fossils, such as nannofossil and foraminifera. Previous researchers had done extensive studies in Sarawak onshore and offshore sediments to assign age to the palynological record (e.g., Muller, 1966; Ho, 1978; Morley, 1978; Lunt, 2022). This study mainly follows Sarawak palynological zonation by Morley (1978; 1991) as more complete description and definition of the zones were made available as compared to SSB palynological zone and age dating can be clearly determined based on the appearance of certain index taxa such as *Florschuetzia* pollens, *Meyeripollis naharkotensis* and *Stenochlaenidites papuanus*. The estimated age of the palynomorph assemblage zones as well as stratigraphic correlation with Temana reservoirs and offshore Sarawak Cycles are shown in Figure 8 and discussed as follows:

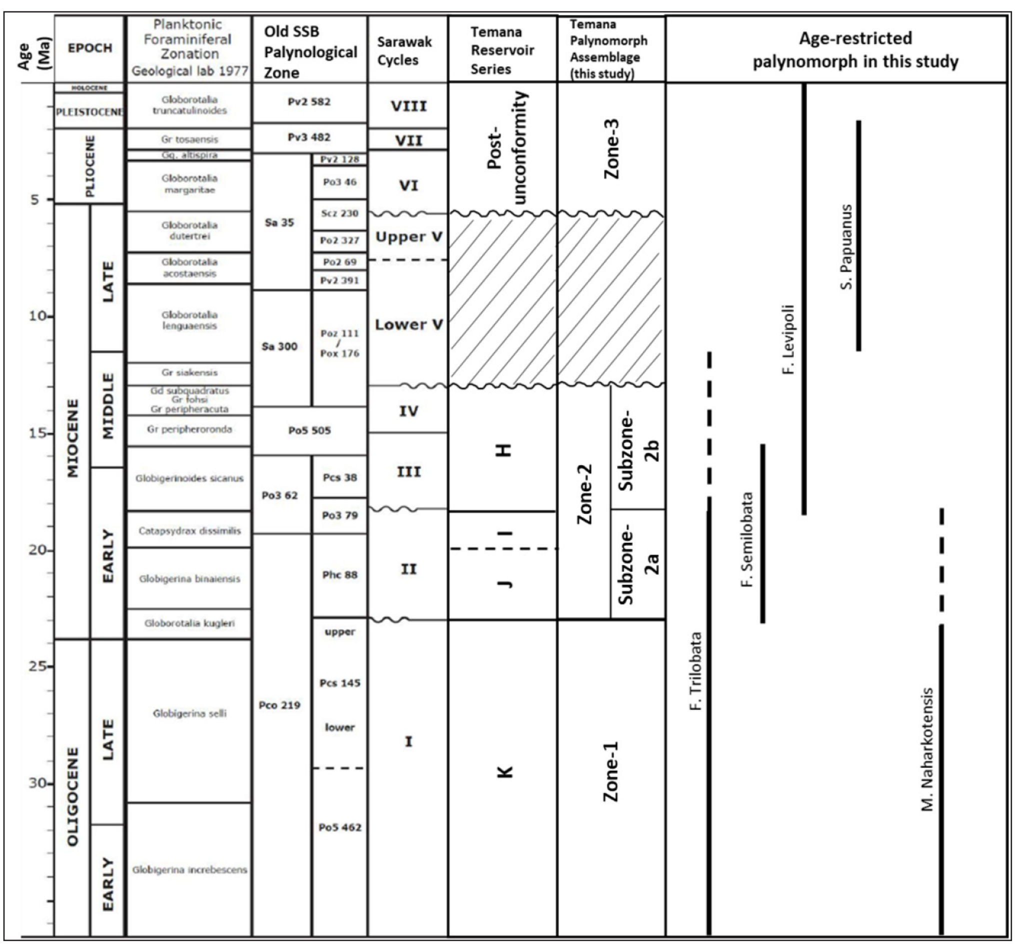

Figure 8: Proposed palynostratigraphy at Temana, with age-restricted taxa (as per Morley, 1978) in comparison to the reservoir groups, Sarawak Cycles and other biostratigraphic schemes such as Old SSB Palynological Zone. Modified from Hageman (1987).

Zone-1

Zone-1 records a high abundance of *F. trilobata*, with notable absence of other *Florschuetzia* species in the assemblage. This suggests a Late Oligocene to Early Miocene age, following the *F. trilobata* zone of Morley (1978, 1991). The common occurrence of *Meyeripollis naharkotensis* pollen further supports Oligocene age where it had been established as a marker in this region (Konjing *et al*., 2022). Acme of montane and seasonal pollens such as *Pinus*, *Picea*, *Alnus* and *Tsuga* also characterizes Oligocene sediments in much of Southeast Asia (Morley, 2012; Konjing *et al*., 2022). The zone can be correlated to Cycle I of offshore Sarawak or the Pcs 145 zone of the old SSB palynological zone (Hageman, 1987). The Temana K-series reservoir belongs to this zone.

Zone-2

The high abundance and continuous occurrence of *F. trilobata* in association with *F. semilobata* and *F. levipoli* indicates an Early to Middle Miocene age corresponding to the *F. levipoli* zone of Morley (1978) (Konjing *et al*., 2022). The zone is further subdivided into two subzones based on the occurrence of *F. levipoli* in the upper part. The older Subzone-2a, consists of both *F. trilobata* and *F. semilobata* is dated as Early Miocene and correlatable to Cycle II or the Phc 88 and Po3 79 zones of the old SSB palynological zonation scheme. Subzone-2b is marked by the first appearance of *F. levipoli* which is equivalent to Cycle III or the Pcs 38 zone of the old SSB palynological scheme and straddles the Early to Middle Miocene (Hageman, 1987). The J and I-series reservoirs reside within Subzone-2a while most of H-series reservoir constitutes Subzone-2b.

Zone-3

Zone-3 occurs above an angular unconformity (at the base of Cycle IV VI, Figure 8) and is marked by the presence of *Stenochlaenidites papuanus*. This pteridophyte spore is an index species of Late Miocene to Pliocene age. The zone also records regular appearance of *Camptostemon*-type mangrove pollen which can be found as early base Middle Miocene but is more common in Late Miocene to Pliocene (Lunt, 2022). *Podocarpus imbricatus* is another marker for the Late Pliocene and is observed in TE-1 well. Thus, Zone-3 is likely to be Late Miocene to Pliocene age and younger, corresponding to Cycle VI or the Sa 35 zone of the old SSB palynostratigraphic scheme (Hageman, 1987). The post-unconformity sediment at Temana is entirely within Zone-3.

Paleoenvironment reconstruction

Knowledge on the distribution of pollen and spores from extant species can be used to facilitate the reconstruction of depositional environment from the geological record (Van Gorsel *et al*., 2014). In coastal plain to marginal marine settings, mangrove and peat swamp plants produce large amounts of pollen that are predominantly preserved in the sediments (Yakzan, 2003). Since the mangrove plant such as Rhizophoraceae is especially sensitive to fluctuations in sea level, a high abundance of the pollen may indicate rising sea level and increasing tidal activity (Morley *et al*., 2021). With exception of a major part of Zone-1, Temana pollen assemblages contain a high abundance of Rhizophoraceae-type mangrove along with the *Florschuetzia* genus which is commonly found along tidal rivers. This can be interpreted to reflect deposition with brackish water condition such as delta plain or intertidal coastal zone (Figure 9).

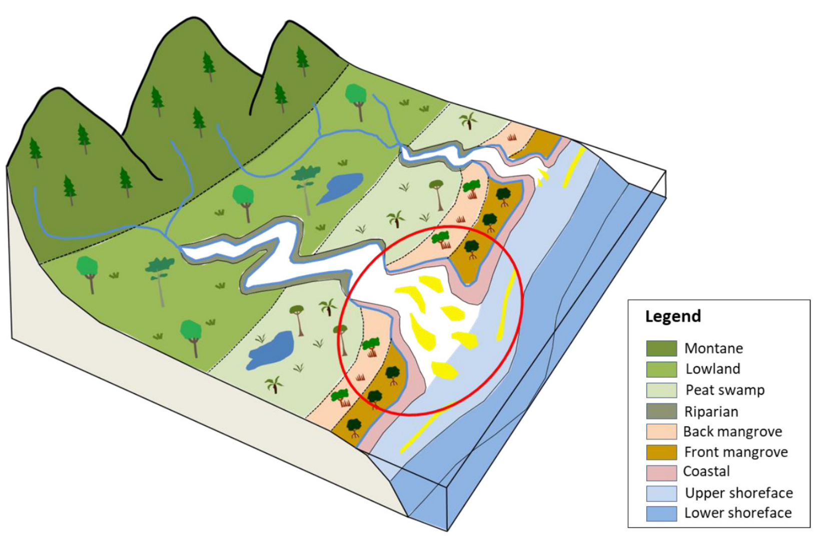

Figure 9: Paleoenvironment model illustrating the varying distribution of vegetation types, from upland to coastal settings. The red outline represents the local depositional environment interpreted at Temana as indicated by the major presence of mangrove pollen. Adapted from Yakzan (2003).

Freshwater peat swamp vegetation typically occupies the coastal plain area behind the mangrove belt/zone and thrives under high rates of precipitation. At Temana, variation in the abundance and diversity of peat swamp pollen was observed in the palynomorph distribution. The Kerapah peat swamp, represented by *Casuarina*-type and *Dacrydium,* is a prominent feature of Zone-2. On the other hand, Zone-1 is characterized by low diversity peat swamp pollen, represented mainly by *Dactylocladus* and *M. naharkotensis* while Zone-3 exhibits a higher diversity of peat swamp taxa. This variation may reflect the changing climatic conditions and migration pattern from tectonic movements.

Paleoclimate interpretation

Hinterland-derived pollen is a valuable indicator of climate trends as they are strongly affected by temperature and moisture conditions. They include montane, Kerapah, peat swamp, riparian, rainforest, coastal and seasonal elements which are transported via water and wind and deposited in the catchment area. Previous studies in Sarawak and the Southeast Asian region indicate climatic cycles from seasonally dry to warm and humid conditions at various timescales driven by global temperature changes, eustasy and plate tectonic movements (Sia *et al*., 2018; Morley *et al*., 2021; Konjing *et al*., 2022). A broadly similar temporal trend was also observed in Temana as shown in Figure 10. The paleoclimatic history is discussed further below:

Oligocene

The Oligocene is represented by Zone-1, which has a distinct hinterland palynofloral characteristics dominated by seasonal and montane elements such as *Pinus*, *Picea* and *Tsuga*. The abundance of these typical conifer pollen of Laurasian affinity suggests proximity to an upland area greater than 1500 m in elevation with a temperate climate (Morley, 2012). Active rifting in the South China Sea region during the Oligocene had led to widespread formation of rifted topography with montane forest on the elevated terrain (Morley & Morley, 2018). A global cooling event marked by Antarctic glacial growth in the Oligocene also had an impact on the background cool and dry climate. The presence of *Pinus* along with Gramineae suggests the development of open woodland and savannah that thrives in seasonal and dry climate which was also recorded in other basins of Southeast Asia (Morley, 2012; Morley *et al*., 2021). The climate became increasingly wet towards the end of the Oligocene, as evidenced by the gradual increase in Rhizophoraceae and *Casuarina*-type pollen, likely to have occurred during a rise in sea level and generally warming period. Palynology study of onshore Nyalau Formation by Konjing *et al*. (2022) also shows similar succession of pollen assemblages.

Early to Middle Miocene

A major change in the palynomorph assemblage was observed in the Early-Middle Miocene, characterized by the dominant Kerapah peat swamp element in Zone-2. The highly abundant *Casuarina* and associated *Dacrydium* pollen in addition to the regular presence of rainforest elements are strong indicators of warm and everwet climate (Lelono & Morley, 2011). This change in pollen assemblages coincided with a rapid decline in seasonal elements, suggesting an overall higher temperature and increased rainfall in the region. The dramatic climate change at the Oligocene-Early Miocene boundary is thought to have been caused by the disruption of the Indonesia Troughflow due to the collision of Australia with the Sunda plate, which brought extra moisture and consequently high precipitation to the Sunda Shelf (Morley, 2012). Initiation of the East Asian monsoon from the Early Miocene onwards could also be related to this event and further induced the change into a humid climate. The rise in global temperatures culminating in Middle Miocene Climatic Optimum has also been recorded from oxygen isotope data (Zachos *et al*., 2001) and contributed to rising sea level and subsequently warm and humid climate.

Late Miocene to Pliocene

The global climate during the Late Miocene to Pliocene period is characterized by cool and dry conditions following the Middle Miocene Climatic Optimum. This had led to widespread expansion of arid conditions and grassland in mid-latitude regions (Chamberlain *et al*., 2014). The palynological record in Borneo, however, indicates a prolonged warm and humid climate such that in Temana it is characterized by substantial increase in the rainforest pollen, especially Rubiaceae. A regular presence of freshwater peat swamp elements with a greater diversity may have resulted from the everwet climate, as was similarly observed in the coal successions of the Mukah-Balingian area (Sia *et al*., 2018; Zainal Abidin *et al*., 2022). However, some seasonality is also indicated by a minor increase in grass (Gramineae) and shrubs (*Compositae)* pollen suggestive of savannah vegetation. Intermittent seasonally dry climate elsewhere in Sunda region has been suggested to occur during lowstand glacial periods while rainforest and peat swamp vegetations thrived during highstand sea level (Morley *et al*., 2021). Therefore, high-frequency sea level fluctuation is thought to have exerted control on the climate since the Late Miocene to Pliocene with an overall warm and humid conditions interrupted by periodically seasonal and dry climate.

CONCLUSION

Three distinct palynological assemblage zones in Temana: Zone-1, Zone-2 and Zone-3, were identified based on the change in relative abundance of palynomorph assemblage from Late Oligocene to Pliocene succession and is generally consistent with the old SSB palynological zonation.

Zone-1 (dated as Late Oligocene) is characterized by abundant *F. trilobata* and dominant montane and seasonal elements such as *Picea*, *Tsuga* and *Pinus*; Zone-2 (Early to

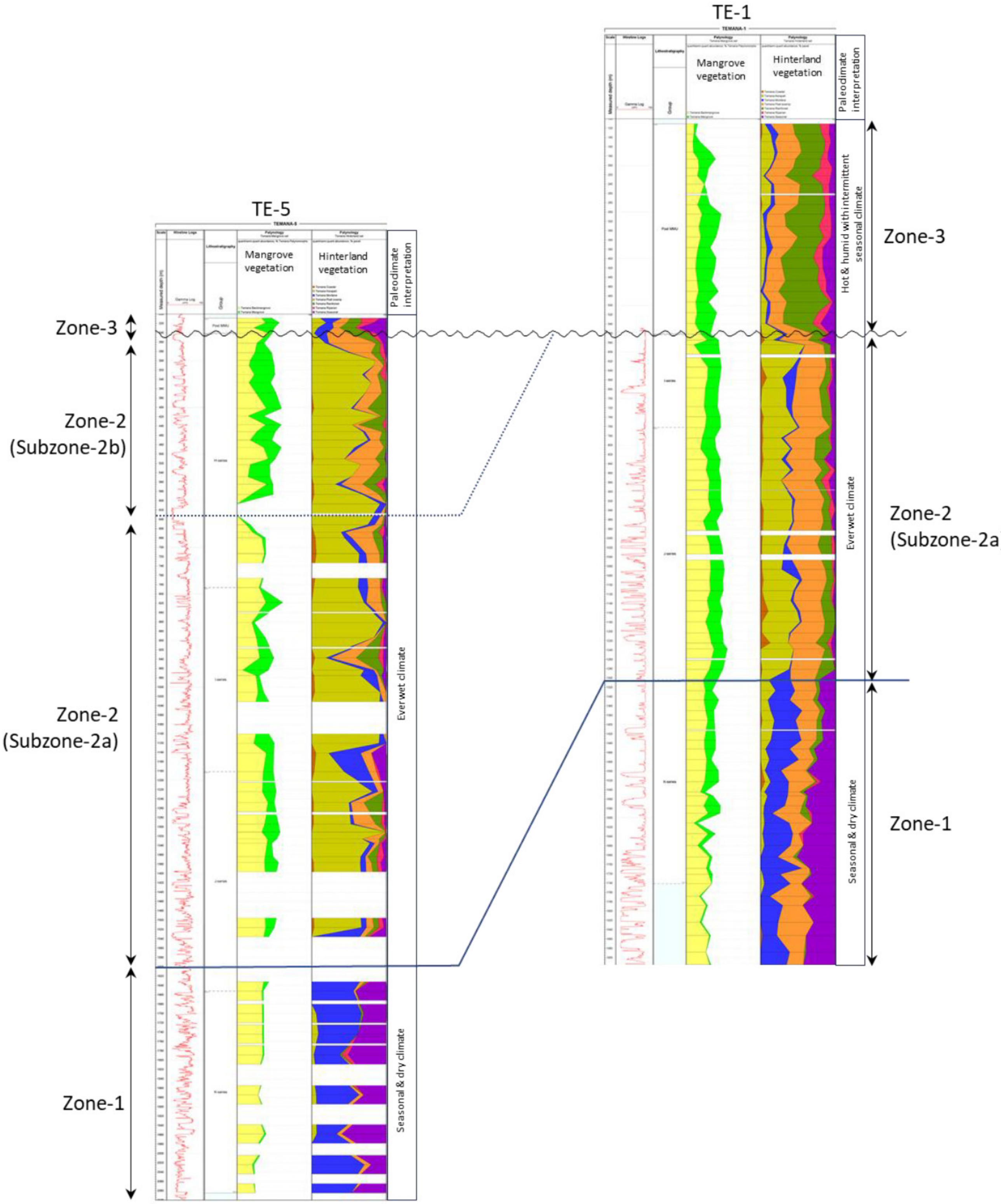

Figure 10: Correlation of the palynomorph assemblage zones between TE-5 and TE-1, and paleoclimate interpretation of the Late Oligocene to Pliocene succession. For legend, refer to Figure 7.

Middle Miocene) is dominated by Kerapah *Casuarina*-type pollen and can be further differentiated into Subzone-2a and Subzone-2b based on later appearance of *F. levipoli*; while Zone-3 (Late Miocene to Pliocene) occurring above a major angular unconformity is marked by a high percentage of the rainforest pollen Rubiaceae and a minor presence of seasonal elements such as the grass pollen Gramineae.

The local depositional environment of Temana is interpreted as marginal marine with brackish water and tidal influence setting, as indicated by the presence of predominantly mangrove pollen such as *Florschuetzia* genus and Rhizophoraceae-type.

The climatic trend at Temana exhibits fluctuation from seasonal and dry climate with montane forest during the Oligocene, to warm and everwet climate during the Early to Middle Miocene characterized by predominantly Kerapah peat swamp vegetation. The humid climate continued until Late Miocene to Pliocene marked by rainforest growth and diverse peat swamp pollen with occurrence of intermittent seasonal climate, possibly corresponding to high-frequency sea level fluctuations.

ACKNOWLEDGEMENTS

This study is self-sponsored as part of MSc thesis at Universiti Teknologi PETRONAS (UTP). The authors would like to thank PETRONAS for granting access to the data and permission to publish this paper. Special gratitude to family, friends, colleagues and various manuscript reviewers from UTP, PETRONAS and GSM who had given valuable guidance and support throughout the research work.

AUTHORS CONTRIBUTION

AZI performed data collection, digitization, palynological analysis and writing the manuscript. ZK helped in designing methodology and interpretation. AHR, NAS and MSI contributed to reviewing and editing of the manuscript.

CONFLICT OF INTEREST

The authors declare there is no conflict of interest in the publication of this article.

REFERENCES

Amir Hassan, M.H., Johnson, H.D., Allison, P.A., & Abdullah, W. H., 2013. Sedimentology and stratigraphic development of the upper Nyalau Formation (Early Miocene), Sarawak, Malaysia: A mixed wave- and tide-influenced coastal system. Journal of Asian Earth Sciences, 76, 301-311.

Chamberlain, C.P., Winnick, M., Mix, H., & Maher, K., 2014. The impact of Neogene grassland expansion and aridification on the isotopic composition of continental precipitation. Glob. Biogeochem. Cycles, 28, 992–1004.

Germeraad, J.H., Hopping, C.A., & Muller, J., 1968. Palynology of Tertiary sediments from tropical areas. Rev. Palaeobot. Palynol., 6, 189–348.

Hageman, H., 1987. Palaeobathymetrical changes in NW Sarawak during the Oligocene to Pliocene. Bulletin of the Geological Society of Malaysia, 21, 91-102.

Hennig-Breitfeld, J., Breitfeld, H.T., Hall, R., Boudagher-Fadel, M., & Thirlwall, M., 2019. A new upper Paleogene to Neogene stratigraphy for Sarawak and Labuan in northwestern Borneo: Paleogeography of the eastern Sundaland margin. Earth-Science Reviews, 190, 1-32.

Ho, K.F., 1978. Stratigraphic framework for oil exploration in Sarawak. Bulletin of the Geological Society of Malaysia, 10, 1-13.

Ishak, A.Z., Siddiqui, N.A., Ismail, M.S., & Abd Rahman, A.H., 2023. Facies Analysis and Stratigraphic Succession of Early Miocene Reservoir in Temana Field, offshore Sarawak. Petroleum and Coal, 65(2), 458-480.

Konjing, Z., Abd Rahman, A.H., Ismail, M.S., & Siddiqui, N.A., 2022. Late Oligocene-Early Miocene palynological succession from marginal marine deposits, Nyalau Formation, Bintulu Sarawak: Palynostratigraphy, paleovegetation and paleoclimate significance. Bulletin of the Geological Society of Malaysia, 74, 17-41.

Lelono, E.B. & Morley, R.J., 2011. Oligocene palynological succession from the East Java Sea. In: R. Hall, M.A. Cottam & M.E.J. Wilson (Eds.), The SE Asian Gateway: History and Tectonics of Australia–Asia Collision. Geological Society of London Special Publication, 355, 333 –45.

Lunt, P., 2022. Field and well evidence for major unconformities in north Sarawak, compared to southwest Sabah, Malaysia. Bulletin of the Geological Society of Malaysia, 74, 69-83.

Lunt, P., & Madon, M., 2017. A review of the Sarawak Cycles: History and modern application. Bulletin of the Geological Society of Malaysia, 63, 77-101.

Madon, M.,1999. Basin Types, Tectono-Stratigraphic Provinces, and Structural Styles. The Petroleum Geology and Resources of Malaysia, PETRONAS, Kuala Lumpur. pp. 79-105.

Madon, M., & Abolins, P., 1999. Balingian Province. The Petroleum Geology and Resources of Malaysia, PETRONAS, Kuala Lumpur. pp. 345-365.

Madon, M., Kim, C.L., & Wong, R., 2013. The structure and stratigraphy of deepwater Sarawak, Malaysia: Implications for tectonic evolution. Journal of Asian Earth Sciences, 76, 312-333.

Morley, R.J., 1978. Palynology of Tertiary and Quaternary sediments in Southeast Asia. Proceedings of the Indonesian Petroleum Association VIth Annual Convention 1977, 255–276.

Morley, R.J., 1991. Tertiary stratigraphic palynology in Southeast Asia: Current status and new directions. Bulletin of the Geological Society of Malaysia, 28, 1–36.

Morley, R.J., 2012. A review of the Cenozoic palaeoclimate history of Southeast Asia. In: Gower, D.J., Johnson, K.G., Richardson, J.E., Rosen, B.R., Ruber, L., & Williams, S.T. (Eds.), Biotic evolution and Environmental change in SE Asia, Systematics Association. Cambridge University Press, Cambridge, pp. 79–114.

Morley, R.J., & Morley, H.P., 2018. Montane pollen indicates character of Mid Cenozoic uplands across Sunda Shelf. In: PESGB SEAPEX Asia Pacific E&P Conference, Olympia Exhibition Centre, London, 27th – 28th June 2018.

Morley, R.J., Dung, B.V., Tung, N.T., Kullman, A.J., Bird, R.T., Van Kieu, N., & Chung, N.H., 2019. High-resolution Palaeogene sequence stratigraphic framework for the Cuu Long Basin, offshore Vietnam, driven by climate change and tectonics, established from sequence biostratigraphy. Palaeogeography,

Palaeoclimatology, Palaeoecology, 530, 113–135.
Morley, R.J., Hasan, S.S., Morley, H.P., M. Jais, J.H., Mansor, A., Aripin, M.R., Nordin, M.H., & Rohaizar, M.H., 2021. Sequence biostratigraphic framework for the Oligocene to Pliocene of Malaysia: High-frequency depositional cycles driven by polar glaciation. Palaeogeography, Palaeoclimatology, Palaeoecology, 561, article 110058.
Murtaza, M., Abd Rahman, A.H., Chow, W.S., & Konjing, Z., 2018. Facies associations, depositional environments and stratigraphic framework of the Early Miocene-Pleistocene successions of the Mukah-Balingian Area, Sarawak, Malaysia. Journal of Asian Earth Sciences, 152, 23-38.
Nichols, G., 2009. Sedimentology and stratigraphy (2nd ed.). Oxford, United Kingdom, Wiley-Blackwell. 432 p.
Roy, A., Abd Mutalib, M.A., & Pathak, R.K., 2010. Delineation of Stratigraphic Prospect from the Integrated Analysis of Geological Model, Well and 3D Seismic Attributes – a Case History from Temana Field, Sarawak, Malaysia. In Petroleum Geology Conference and Exhibition 2010.
Schoonderbeek, A.H.H.G., 1989. Sand Development of the Cycle II/III H and I Reservoirs in the Temana Field. Sarawak Shell Berhad, unpublished report.
Shoukat, N., Siddiqui N.A., Ismail, M.S., & Ali, S.H., 2022. Depositional environment and diagenesis of Early Miocene Nyalau Formation, Sarawak, Malaysia. IOP Conf. Series: Earth and Environmental Science, 1003(1), 012044.
Shoukat, N., Ali, S.H., Siddiqui, N.A., Wahid, Ali., & Bashir, Y., 2023. Diagenesis and sequence stratigraphy of Miocene, Nyalau Formation, Sarawak, Malaysia: A case study for clastic reservoirs. Kuwait Journal of Science, 50(4), 790-802.
Sia, S.G., Abdullah, W.H., Konjing, Z., & John, J., 2018. Floristic and climatic changes at the Balingian Province of the Sarawak Basin, Malaysia, in response to Neogene global cooling, aridification and grassland expansion. CATENA, 173, 445–455.
Swinburn, P., 1994. Structural Styles in The Balingian Province, Offshore Sarawak. Abstract of American Association of Petroleum Geologists International Conference & Exhibition, Kuala Lumpur, Malaysia, 21-24 August 1994. American Association of Petroleum Geologists Bulletin, 78.
Van Gorsel, J.T., Lunt, P. & Morley, R., 2014. Introduction to Cenozoic biostratigraphy of Indonesia - SE Asia. Berita Sedimentologi, 29, 6-40.
Yakzan, A.M., 2003. Distribution of vegetation in present day wetlands: some applications in geoscience. Bulletin of the Geological Society of Malaysia, 46, 271-275.
Zachos, J.C., Pagini, M., Sloan, L., Thomas, E., & Billups, K., 2001. Trends, rhythms and aberrations in global climate 65 Ma to present. Science, 292, 686–693.
Zainal Abidin, N.S., Mustapha, K.A., Abdullah, W.H., & Konjing, Z., 2022. Paleoenvironment reconstruction and peat-forming conditions of Neogene paralic coal sequences from Mukah, Sarawak, Malaysia. Sci. Rep., 12, 8870.

Manuscript received 3 July 2023;
Received in revised form 27 October 2023;
Accepted 2 January 2024
Available online 30 November 2024