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Late Oligocene-Early Miocene palynological succession from marginal marine deposits, Nyalau Formation, Bintulu Sarawak: Palynostratigraphy, paleovegetation and paleoclimate significance

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Abstract: Palynological analysis was conducted on one hundred and twenty-four samples collected from ten sedimentary outcrops in Sangan, Tatau, Bintulu and Similajau areas of central Sarawak. These outcrops form part of the Oligocene-Miocene marginal marine successions of the Nyalau Formation. Rich palynomorph assemblages were recovered from the samples and they provide well-preserved palynological record for the Oligocene-Miocene boundary in the onshore of northwest Borneo. Three distinct palynological zones were identified based on changes in pollen assemblages. The three zones are informally named FT-I, FT-II and FT-III. The FT-I zone is characterized by high frequency of *Florschuetzia trilobata* with common *Florschuetzia semilobata* including sporadic *Meyeripollis naharkotensis.* High percentage of *F. trilobata* and sporadic occurrence of *F. semilobata* are typical of the FT-II zone. Another important characteristic for this zone is characterized by common to abundant *Casuarina* type pollen while *M. naharkotensis* is virtually absent. The FT-III zone is marked by the presence of *Florschuetzia levipoli.* The zone is also characterized by abundant *F. trilobata* including regular occurrence of *F. semilobata* with common montane elements represented by *Pinus, Picea, Alnus, Ephedra* and *Tsuga.* All the identified zones record regular occurrence of Gramineae throughout with strong variation in diversity and frequency of peat swamp taxa represented by *Blumeodendron* type, *Calophyllum* type, *Stemonurus* type *Calamus* type and *Dactylocladus* type. The mangrove element such as *Rhizophora* type exhibits gradual increased in number throughout the FT-I and FT-II zone and showing reduced abundance in FT-III zone. These three zones are correlatable to the Late Oligocene to Early Miocene palynostratigraphy of the Cycle I and Cycle II in the Sarawak Basin. The palynological successions from these areas suggest a typical wet climate with intermittent seasonally dry conditions throughout the Late Oligocene - Early Miocene. This is evident from the regular occurrence of grass pollen i.e., Gramineae/Poaceae with common rain forest and peatswamp elements. This is supported by the common to high frequency of mangrove pollen notably *Rhizophora* type (*Zonocostites ramonae*). The Early Miocene may have experienced occasional super wet climatic conditions where rain forest pollen assemblages were prevalent including intermittent acme of *Casuarina* type pollen.

Keywords: Palynostratigraphy, paleoclimate, paleovegetation, Nyalau Formation

INTRODUCTION

Marginal marine deposits are widespread along the onshore area of Sarawak. These Late Oligocene to Early Miocene rock successions are correlatable to the Cycle I/ II of Sarawak Cycle (Ho, 1978) which represents a period when terrestrial to marginal marine depositional systems were prevalent (e.g., Amir Hasan *et al.,* 2013). The basal Miocene in the Sarawak Basin is characterized by regional transgression (e.g., Hageman *et al.*, 1987) which marks the progressive changes in paleovegetation and paleoclimate from a relatively cool and temperate to hot and humid climate (Lunt & Madon, 2017). According to Zachos *et al.* (2001), the Late Oligocene (Chattian, 28.4-23.03 Ma; Gradstein *et al.*, 2005) had experienced a global warmth 'greenhouse' with ice-free poles right after the early Eocene Climatic Optimum based on deep sea oxygen isotopes. This was followed by a progressive 17-million-year long term trend of cooler conditions in the Neogene. In contrast, seasonal climates were pronounced across for much of Southeast Asia during the Late Eocene and Oligocene as suggested by the reduction of perhumid elements in the pollen assemblages (Morley & Morley, 2013; Morley, 2018). The Oligocene-Early Miocene palynological succession from the onshore Sarawak region have not been well-documented. Muller (1968) was the first to conduct a detailed palynological studies on the Cretaceous-Eocene strata of the Pedawan

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and Plateau Sandstone formations within the Kuching area. Apart from Muller (1968) study, Germeraad *et al.* (1968) palynological studies of the northwest Borneo region provided crucial information on palynostratigraphy even though the Eocene and Oligocene palynological data are very limited. In addition, several studies on the Miocene deposits were conducted within the central Sarawak such as Mukah and Balingian areas which provide crucial palynological information within this region (e.g., Sia *et al.*, 2014; Sia *et al.*, 2019; Zainal Abidin *et al.*, 2022).

The present study is the first detailed palynological analysis of the Late Oligocene-Early Miocene sedimentary successions in Bintulu area, onshore Sarawak. This study examines miospores from three sectors covering ten sedimentary successions from the Nyalau Formation in central Sarawak (Figure 1). The objective of this study is to evaluate the significance of the palynological assemblages of the successions in terms of palynostratigraphy, paleovegetation and paleoclimate.

GEOLOGICAL SETTING

The Sarawak Basin

The Sarawak Basin (Upper Eocene-Recent) sedimentary succession unconformably overlies the folded and thrusted Rajang Group. The basin is widely regarded as the rifted southern margin of the Oligocene-Recent South China Sea. The development of the basin resulted from the closure, deformation and uplift of a Late Cretaceous-Eocene proto-

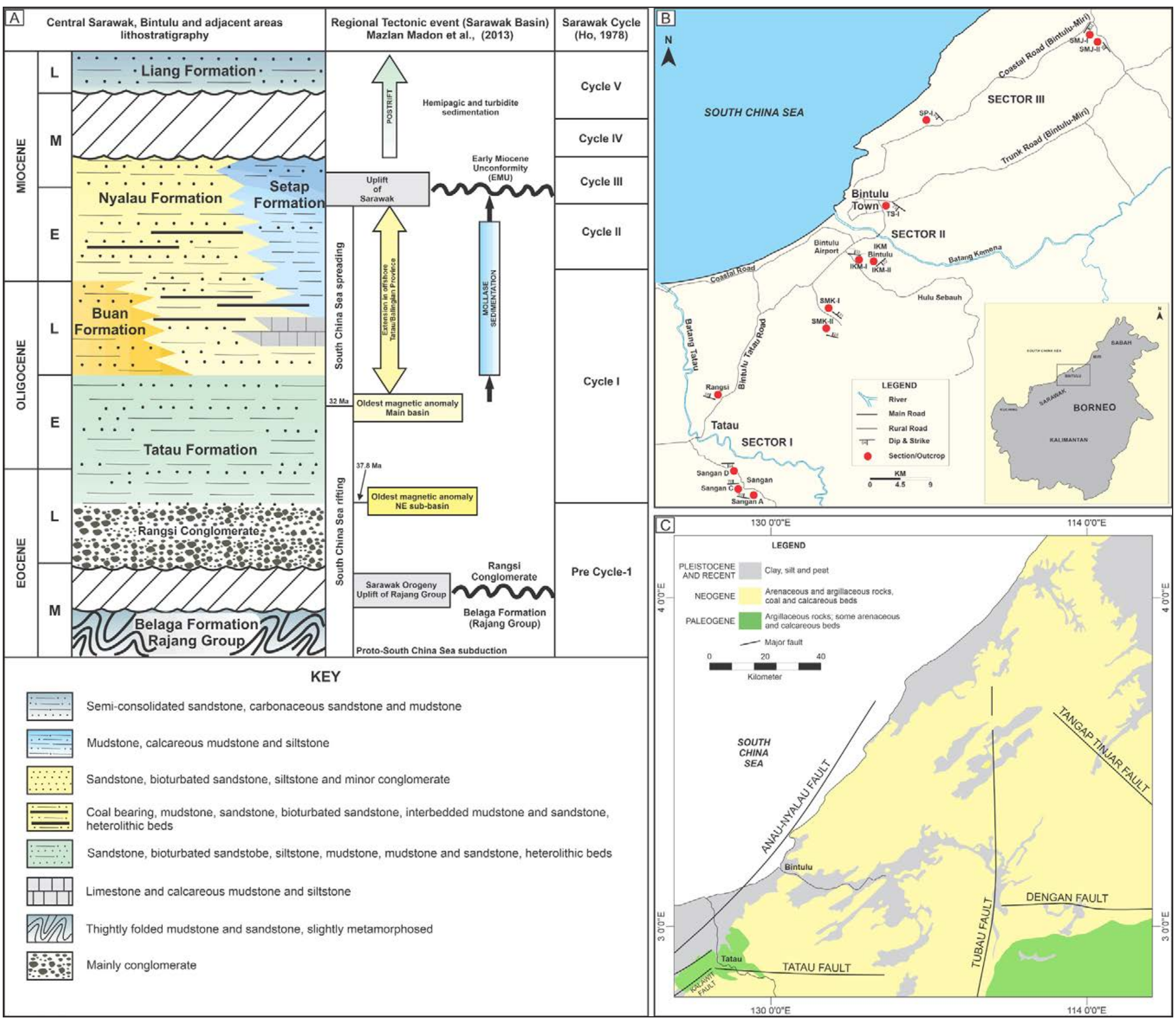

Figure 1: A. Lithostratigraphic scheme of central Sarawak, modified from various sources (e.g., Madon, 1999; Hutchison, 2005) and offshore Sarawak Cycle (Ho, 1978) with regional tectonic event (Mazlan Madon *et al.*, 2013). B. Location map of the study area. C. Area extent of the Nyalau Formation and its adjacent equivalent Neogene rocks bounded in the southeast by the older Paleogene rocks of Belaga Formation. Redrawn from Bintulu Geological map, Jabatan Mineral dan Geosains Malaysia (2017).

South China Sea or “Rajang Sea”. The deformed deep marine sedimentary rocks of the Rajang Sea, commonly referred to as the Rajang Fold-and-Thrust Belt, now forms the basement of the Sarawak Basin. The weathering and erosion of parts of the Rajang Fold-and-Thrust Belt provided the sedimentary fill for the younger basin. The lower and older sections of the Sarawak Basin is well exposed in the coastal areas of central Sarawak, around the Mukah, Bintulu and Niah towns (Madon, 1999; Madon *et al.*, 2013).

The stratigraphy of onshore Sarawak was first reviewed by Lietchti *et al.* (1960) based on lithostratigraphy and time stratigraphy using the foraminifera. In the offshore part of Sarawak, the stratigraphic nomenclature was developed by Sarawak Shell Berhad (Ho, 1978) based on regressive and transgressive cycles and aided by regional high resolution palynological zones, foraminifera and nannofossil zones derived from numerous well data (Figure 2). In central Sarawak particularly within Bintulu and neighboring areas, folded-and-thrusted pre-cycle I and/or pre-Oligocene sedimentary rocks belonging to the Belaga Formation (Late Eocene) of the Rajang Group is well exposed. This is unconformably overlain by the Upper Eocene to Oligocene, coastal to neritic Tatau Formation. This formation passes up gradually into marine shale of the Oligocene age, Buan Formation. Around the Bintulu area, sedimentary rocks belonging to the Upper Oligocene-Middle Miocene Nyalau Formation (Cycle I/II) is well exposed. The Nyalau Formation, characterized by successions of trough cross-bedded, herringbone cross-bedded and hummocky cross-bedded sandstones, in places coal-bearing, has been interpreted as deposits of mixed tide-and-wave influenced depositional environments. This formation is unconformably

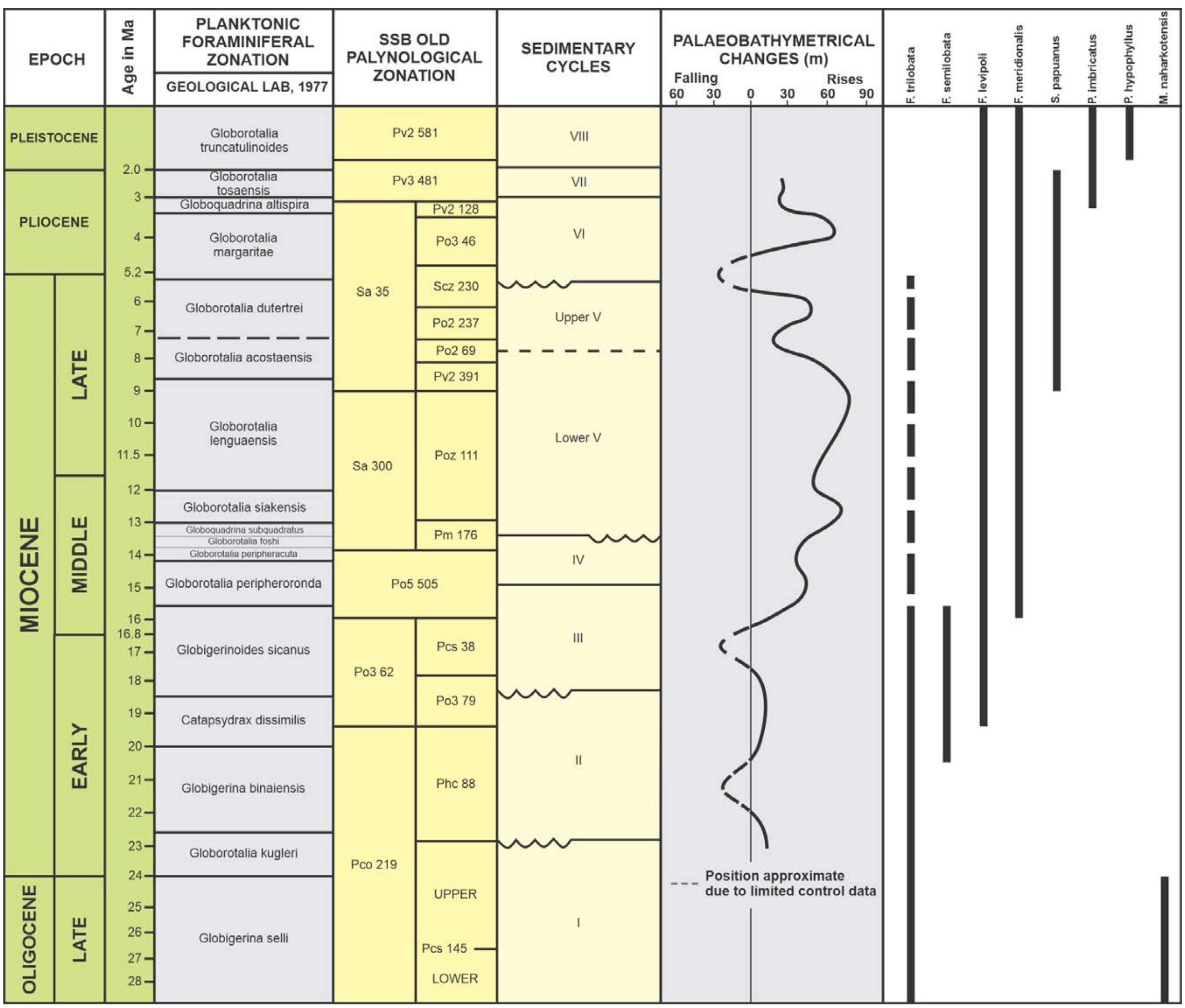

Figure 2: Sarawak basin old palynological and foraminifera zone and Sarawak cycle summary published by Hageman (1987). Small portion of Cycle I is within Early Miocene where top boundary of Cycle I is defined based Pcs 145 (*Meyeripollis naharkotensis* zone). While Cycle II is correlatable to the Phc 88 (*Dactylocladus* zone) and Po3 79 (*Casuarina* zone).

overlain by the younger Liang Formation of Pliocene age. The Setap Shale Formation covers the area towards the northern part of Bintulu. This formation usually characterized by thick pale gray mudstone, calcareous, with thin sandstone layers including calcareous nodules. The contact between Setap Shale Formation and Nyalau Formation is not clear as some authors have reported that it has conformable and interfingering contact with the Nyalau Formation.

Nyalau Formation

The Nyalau Formation was previously described by Liechti *et al.* (1960) and Kho (1968) and interpreted to have been deposited during Oligocene-Early Miocene (Wolfenden, 1960). The formation has been correlated to the hydrocarbon-bearing Cycles I and II of the Balingian Province offshore Sarawak (Du Bois, 1985). Amir Hasan *et al*. (2013) have conducted extensive research on the Nyalau Formation especially on facies analysis. In addition, a palynological study was also conducted by Amir Hasan *et al.* (2013) and used the genus *Florschuetzia trilobata* to determine the possible age of the formation. However, independent dating by using this species alone is inaccurate as this species has long stratigraphic range in Sarawak (Oligocene-Late Miocene) and usually occurs in abundance during Oligocene and becomes reduced towards Late Miocene. Most of the outcrops belonging to this formation are well-exposed and scattered along the road connecting Tatau-Bintulu, Bintulu-Miri coastal road and rural road to Ulu Sebauh and Samarakan. The Nyalau Formation comprises sedimentary facies interpreted to have been deposited within mixed tidal-and-wave sedimentary environments. The lower part of the formation which occupies some parts of Ulu Sebauh area is referred to as Biban Sandstone Member, consists of mixed tidal and wave sandstones, with bioturbated mudstones interbeds and common siderite nodules. The Nyalau Formation conformably overlies the Buan Formation and apparently shows interfingering contact with Setap Shale Formation (e.g., Madon, 1999; Hutchison, 2005) (Figure 1).

MATERIAL AND METHODS

Extensive field investigations were carried out along the Tatau-Bintulu Road in Bintulu area. Ten (10) stratigraphic sections totalling up to 375 m in thickness were evaluated and documented (Table 1). Detailed and close sampling programme were implemented for palynological analysis; a total of one hundred twenty-four (124) samples were collected and subjected to palynological analysis. Most of the samples were selected from mudstone facies such as carbonaceous mudstone, dark grey mudstone, laminated mudstone, paleosol including coal. Several samples of coarser lithology such as siltstone and very fine-grained sandstone were also sampled as control samples. Samples for palynology were subjected to standard palynological preparation (e.g., Wood *et al.*, 1996; Halbritter *et al.*, 2018). Prior to hydrochloric acid and hydrofluoric acid treatment,

Table 1: Table showing brief outcrop descriptions and peculiar outcrop markers including approximate thickness and number of samples involved for palynological analysis.

NO	OUTCROP NAME/ PECULIAR OUTCROP FEATURES	NUMBER OF SAMPLES	SECTOR/AREA	APPROXIMATE THICKNESS (m)
1	Sangan-A / Sand dominated with heterolithic and bioturbated mudstone	3	SECTOR I / Sangan, Tatau	30
2	Sangan-C / Sand dominated, heterolithic mudstone and sparsely bioturbated	4	SECTOR I / Sangan, Tatau	20
3	Sangan-D / Fining upward trough cross bedded sandstone overlain by dark grey mudstone	5	SECTOR I / Sangan, Tatau	25
4	Rangsi / Thick conglomerate beds and sandstone succession with thin dark grey mudstone intercalated	6	SECTOR I / Tatau	30
5	SMK1 / Coal bearing succession with thick carbonaceous mudstone and paleosol	40	SECTOR II / Samarakan	40
6	IKM-I / Coal bearing succession, carbonaceous mudstone and paleosol	23	SECTOR II / Bintulu Town	25
7	TS-I / Thick dark grey mudstone with sandstone interbeds	20	SECTOR II / IKM Bintulu	65
8	SP-I / Sand dominated, heterolithic bioturbated mudstone with thin paleosol and carbonaceous mudstone	10	SECTOR III / Sungai Plan	65
9	SMJ-I / Sand dominated with intervals of heterolithic and bioturbated mudstone	3	SECTOR III /Similajau	55
10	SMJ-II / Thick dark grey mudstone overlying thick sandstone	10	SECTOR III /Similajau	20

samples were crushed into moderate-to- fine powder form by avoiding total grinding. Residue obtained after acid digestion were neutralized using mineral-free water. After that, heavy liquid of zinc bromide with 2.2 specific gravity was applied on remaining residue for organic matter separation. The extracted residue was then subjected for oxidation via 10% nitric acid and 10% KOH treatment. The oxidized residues were smeared on glass slide and mixed with alcohol solution and left until dry. A drop of Norland 61 optical adhesive glue was used as mounting medium to mount cover slip onto the ready slide. The quantitative studies or so-called Quaternary methods (Poumot, 1989) were applied in this study with some modification, entailing an attempt to identify and count a standard of at least 100 palynomorphs for each sample analysed. Identification of palynomorphs was based on published works by Germeraad *et al.* (1968), Anderson & Muller (1975), Morley (1976), Ahmad Munif Koraini *et al.* (2012), Mao *et al.* (2012), Poliakova & Behling (2016) and Tang *et al.* (2020) which focus more on Southeast Asia taxa.

Palynological analysis of the Nyalau Formation

The palynomorph recovery and extraction from the samples were relatively good and preservation at some sections was excellent. Selected palynomorphs recovered from the samples are presented in Figures 10, 11, 12, 13 and 14. Carbonaceous mudstone usually contained abundant miospores and counting normally exceed one hundred counts per sample. The analysed samples also contained terrestrial palynodebris such as algal, fungal including cuticles and various types of woody materials. Algal types from the family of Hydrodicteaceae (*Pediastrum* sp.), Botryococcaceae (*Botryococcus* sp.) and Prasinophyceae (*Pterospermella* sp.) including microforaminiferal test linings were also identified in several samples. Unlike pollen and spores, their occurrence was sporadic and not abundant. In addition, dinoflagellate cysts were also observed in several samples especially from marine lithofacies. However, the main emphasis was placed on the pollen and spores which served as the primary aim of the current study. As expected, the coarser-grained lithology such as siltstone and very fine-grained sandstone are barren of miospores.

In this study, the palynological analysis on coarser lithologies were considered crucial control samples. The purpose was to identify a clear trend of the palynomorphs when dealing with close sampling programme. This allows the direct identification of any changes in the pattern of the palynomorphs, whether it is abrupt or gradual. Moreover, the problem can be addressed if the sudden or abrupt changes are caused by lithologic types, preservation or truly shift in environment. The scarcity of palynomorphs in much coarser lithology normally related to winnowing effect (e.g., Muller, 1959; Richardson & Rasul, 1990). The palynomorphs are likely to behave like silt-sized particles during deposition. Thus, during or right after deposition the palynomorph may experience mechanical degradation resulted from continuous clastic particle abrasion which in turn lead to significant loss of the palynomorphs especially in much coarser lithology (i.e., siltstone, sandstone). In addition, biodegradation by bacteria and fungi may have contributed to the paucity of palynomorph especially when the water column are well oxygenated.

Chemical digestion during preparation of studied palynological samples may not contribute to the loss of palynomorphs in this study. Thus, it can be neglected. The outer layer/exine of palynomorphs contain chemical resistant namely sporopollenin. This layer is resistant to oxidation and acetolysis treatment. However, long exposure to strong oxidation agent such as potassium hydroxide may damage the sporopollenin of palynomorphs. In general, the palynological data discussed in this paper was carefully evaluated to meet the standard of palynological and botanical naming protocol (e.g., Muller, 1981; Morley, 1998; Moar *et al.*, 2011).

Evidence of reworking and challenges

Evidence of reworking are relatively uncommon in the Nyalau Formation samples; only few older species were identified. Reworking is indicated by the presence of Upper Cretaceous-Eocene species such as *Apiculatisporites* sp., *Classopollis* sp., *Cicatricosisporites dorogensis*, *Matonisporites* sp. These species are typical of the Late Cretaceous forms which have previously been recorded in the Late Cretaceous and Eocene sediments elsewhere (e.g., Muller, 1968; Uyop Said & Ahmad Jantan, 1994a; Uyop Said & Ahmad Jantan, 1994; Uyop Said *et al.*, 2003). For each outcrop, the palynostratigraphic discussion and all the data presented herein were emphasized on certain taxon and suprageneric group that were considered significant in terms of palynostratigraphy. In Southeast Asia, marker taxa are relatively a few especially in the Tertiary deposits. Hence, palynological dating is extremely difficult particularly in non-marine to marginal marine strata.

RESULTS

Local palynomorph assemblage zones

The descriptions and definitions of palynomorph assemblage proposed herein are based on changes in assemblage. These palynomorphs assemblage zones might be useful at least for local correlation and serve as reference and comparison for Oligocene-Miocene boundary of the Northwest Borneo region. Changes in the pollen and spores' assemblages within the studied sections have allowed the recognition of three local palynomorph assemblage zones and these are FT-I - *Meyeripollis naharkotensis-Florschuetzia trilobata* Assemblage Zone, FT-II - *Florschuetzia trilobata-Florschuetzia. semilobata* Assemblage Zone and FT-III - *Florschuetzia trilobata - Florschuetzia levipoli* Assemblage Zone. Each local zone is informally named using the short form of 'FT' which represents the name of the species of *Florschuetzia trilobata.* The species of *F. trilobata* forms a basis for each zonation since it records high abundance in each zone. Where possible, these local palynomorph assemblage zones have been compared and calibrated with high level pollen zone of the Northwest Borneo (e.g., Ho, 1978; Hageman, 1987). In the following paragraphs the zones are discussed according to the distribution and range charts on selected studied sections (Figure 3 to Figure 6).

I. Zone FT-I (*Meyeripollis naharkotensis-Florschuetzia trilobata* Assemblage Zone)

Definition: The FT-I zone is characterized by the high frequency of *F. trilobata* with common *F. semilobata*. The common to abundant *Verrucatosporites usmensis* spore also typifies the zone. Gramineae/Poaceae is regularly found in moderate frequency and shows a distinct abundance in certain studied sections. Angiosperm pollen represented by peatswamp -elements exhibits strong variation and normally characterized by regular to common representation of taxa such as *Blumeodendron* type, *Calophyllum* type, *Stemonurus* type, *Calamus* type and *Dactylocladus* type. The peat swamp elements that represented by the above-mentioned taxa usually made up of more than 20% from the total peat swamp pollen. In addition, the zone as a whole is marked by gradual increases of *Rhizophora* type which shows good representation that usually typifies the zone in general. In addition, riparian elements such as *Ilex*, *Pandanus*, and Myrtaceae also occur but never dominant. Another important characteristic for this zone is shown by the low frequency of *Brownlowia* type and the absence of much younger marker such as *F. levipoli*. The presence of single grain of *Meyeripollis naharkotensis* i.e., SMK-I section, IKM-I section and SMJ2 section, may also characterizes the zone. However more samples need to analyse to confirm whether the species is in-situ or reworked.

Age/Stratigraphy: The presence of *Meyeripollis naharkotensis* indicates a pre-Tertiary age. According to Baksi & Venkatachala (1971) this species ranges from Upper Eocene-Lower Miocene based on samples from Assam sediments. The type species of *M. naharkotensis* also occurs in Borneo sediment and comparable to that of species found in Assam, India (Kemp, 1974, Muller pers. comm). In Sunda region the extinction level of *F. trilobata* is believed near the boundary of Middle-Late Miocene (Morley, 1991) although slightly earlier in Thailand which is Middle Miocene (Watanasuk, 1990). The species records different level of its first appearance in Sunda region (e.g., Morley, 1991). In addition, Oligocene time records a consistent seasonal climate characterized by the common occurrence of grass pollen, reduction of pre-humid elements in pollen record and rarity of coals (Morley, 2018). This is consistent with the present study where Gramineae/Poaceae is considerably common throughout this zone. Thus, the Late Oligocene to earliest Miocene is suggested for this zone.

II. Zone FT-II (*Florschuetzia trilobata-Florschuetzia semilobata* Assemblage Zone)

Definition: High percentage of *F. trilobata* and sporadic occurrence of *F. semilobata* are typical of the FT-II zone. Like FT-I zone, *V. usmensis* and Gramineae/Poaceae are regular to common. In addition, *Rhizophora* type is rather well-represented and shows considerably increased in abundance compared to the previous zone. Mangrove and back mangrove elements are relatively frequent to regular in this zone which is characterized by *Brownlowia* type and *Avicennia* type. Angiosperm pollen especially those peat swamp taxa show strong variation in diversity where taxa like *Blumeodendron* type, *Calophyllum* type, *Stemonurus* type *Calamus* type and *Dactylocladus* type are regular and common throughout the zone. Montane elements in which represented by taxa such as *Picea*, *Pinus*, *Tsuga* and *Alnus* are common to low and forms as background elements in this zone. Another important characteristic for this zone is characterized by common to abundant *Casuarina* type pollen. *M. naharkotensis* is virtually absent in this zone.

Age/Stratigraphy: Sporadic occurrence of *F. semilobata* and abundant *F. trilobata* suggesting at least an Early Miocene for this zone. This is further supported by the absence of any younger marker such as *F. levipoli*. In addition, this is in accordance with the assemblage of the miospores in which angiosperm shows strong variation in terms of diversity and frequency. The strong variation of angiosperm pollen represented by peat swamp elements may coincide with the major climatic change occurred in Early Miocene where coals were formed in many areas of Sunda region in which peat swamps taxa became widespread (Morley & Flenley, 1987; Morley, 1998). Moreover, the representation of montane elements (e.g., *Pinus*, *Picea*, *Alnus*) supports the interpretation since these taxa are abundant in the Oligocene and earliest Miocene (Morley, 1998). In general, these taxa are Laurasian montane elements that dispersed into the Sunda region during the Laurasia connection with East Asia (Morley, 1998). Muller (1966) addressed that montane pollen such as *Picea*, *Pinus*, *Ephedra*, *Tsuga* and *Alnus* are common in Oligocene and Early Miocene deposits of northwest Borneo.

III. Zone FT-III (*Florschuetzia trilobata - Florschuetzia levipoli* Assemblage Zone)

Definition: This zone is marked by the presence of *Florschuetzia levipoli.* The zone is also characterized by abundant *F. trilobata* including regular occurrence of *F. semilobata.* Montane elements represented by *Pinus*, *Picea*, *Alnus*, *Ephedra* and *Tsuga* are common throughout the zone and exhibits distinct increased in abundance. *Rhizophora* type shows abrupt decreasing in number, while back mangrove elements also showing slight decreasing trend. The peat swamp elements in this zone also showing strong variation in terms of frequency and diversity. The increasing number of peat swamp pollen and relatively rich in diversity typify this zone as a whole.

Age/Stratigraphy: Based on restricted marker taxa and pollen assemblage, an Early Miocene to probably basal Middle Miocene age would be suggested for this zone. This is based on the presence of *F. levipoli* in which supported by common of *F. semilobata* and abundant *F. trilobata*. High frequency of montane pollen including high diversity peat swamp pollen supports the interpretation.

Field occurrences and interpretation of palynological successions

a. Sector I – Sangan-Tatau area

Eighteen samples were selected from four outcrops within this sector and were analysed for their palynomorphs content. The occurrence and distribution of palynomorphs data are given in full in Table 2. These data provide the basis for which the palynomorph assemblage zone within the sections have been recognised. Description for each of these outcrops is presented in the following subsection below.

Sangan A section

Description

The palynological composition recorded from this section is characterized by abundant *F. trilobata* and common to regular occurrence of *Rhizophora* type throughout (Table 2). All samples also contain common Gramineae/Poaceae. Peat swamp and back mangrove elements are also present but never dominant. The taxa of *Dactylocladus* type, *Blumeodendron* type, *Calamus* type and *Callophylum* type are the dominant peat swamp taxa in which forms about 30% from the total peat swamp pollen. While back mangrove pollen is dominated by low frequency of *Avicennia* type and *Brownlowia* type. Very low marine signature was recovered which is represented by dinoflagellates cyst and microforaminiferal test lining. Both were identified only in sample Sangan A-S1. In addition, sporadic occurrence of montane and temperate angiosperm such as *Picea* and *Celtis* also typify the palynological composition of this section. Marker such as *F. semilobata* and *F. levipoli* were virtually absent from the studied samples.

Interpretation and correlation

Late Oligocene or an earliest Miocene age based on palynomorph assemblage and restricted marker species are consistent and therefore have allowed this section to be assigned to the FT-I zone. The consistence occurrence of *F. trilobata* in which occurs in great number throughout and supported by regular to common Gramineae/Poaceae including common peat swamp elements shows that the section is a typical characteristic of FT-I zone. The zone FT-I is recognized throughout the sector I of the study area and probably extend laterally above and below the examined section. The FT-1 zone of this section may correlatable with the *Brownlowia* pollen zone *sensu* Ho (1978) and old Sarawak Shell Berhad (SSB) palynological zone of Pcs 145 - Phc 88 *sensu* Hageman (1987). This signifies the Late Oligocene to Early Miocene within Cycle I and Cycle II of Sarawak Cycle.

Sangan C section

Description

This section is positioned about 750 m to the northwest of the Sangan A section. A total of four samples were selected from laminated mudstone facies and heterolithic mudstone facies respectively (Table 2). The palynological composition within this section is somewhat similar to that of Sangan A section. *F. trilobata* shows slight reduction in terms of percentage but still occurs consistently throughout the section. However, the *Rhizophora* type marks abrupt decreased in number while back mangrove elements which is represented by *Nypa* marks it appearance in this section. Like Sangan A section, the *Brownlowia* type also occurs frequently but in low count. The seasonal element of Gramineae/Poaceae presents in all samples and usually made up about more than 5% from the total palynomorph. Pollen from peat swamp is well represented including riparian element such as Myrtaceae. Note, no marker such as *F. semilobata* and *F. levipoli* were recovered from the studied samples.

Interpretation and correlation

The palynomorph assemblage for this section is typical of FT-I zone. The consistent occurrence of *F. trilobata* throughout the studied samples without any occurrence of much younger marker such as *F. semilobata* and *F. levipoli* suggesting an age of Late Oligocene and/or earliest Miocene. The abrupt decreased in *Rhizophora* type is rather due to facies type. Based on facies analysis, the Sangan C section is positioned in a more proximal setting compared to Sangan A section (Zainey Konjing *In prep*). Thus, it can be expected that the frequency of the mangrove pollen is relatively lesser, while back mangrove elements showing significant presence throughout the section. In addition, the common presence of Myrtaceae pollen suggests a vicinity within riparian vegetation. The FT-1 zone of this section may correlatable with the *Brownlowia* pollen zone *sensu* Ho (1978) and old Sarawak Shell Berhad (SSB) palynological zone of Pcs 145 - Phc 88 *sensu* Hageman (1987). This characterizes the Late Oligocene to Early Miocene within Cycle I and Cycle II of Sarawak Cycle.

Sangan D section

Description

This section is located about 1 km to the northwest of the Sangan C section. Overall, five samples were collected from the mudstone interval (Table 2). The palynological composition marks abundant *F. trilobata* throughout the studied samples. In general, the occurrence of *F. trilobata* in each sample records more than 50% from the total pollen sum. *Rhizophora* type also occurs but never dominant and, in several samples, records zero occurrences while back mangrove taxa such as *Avicennia* type, *Brownlowia* type and *Nypa* show well representation even in relatively low number. Like previous section, seasonal elements of Gramineae/ Poaceae are regular and common in all studied samples.

Peat swamp pollen are well represented where the taxa such as *Blumeodendron* type, *Callophylum* type, *Calamus* type and *Dactylocladus* type are the major constituents in peat swamp pollen assemblage. In addition, samples from this section mark an increased abundance of montane pollen.

Interpretation and correlation

This section has similar palynological composition to that of Sangan A and Sangan C sections in which correlatable to local FT-I zone. The section is characterized by the absence of any younger marker in all analysed samples. In addition, the abrupt increased of *F. trilobata* allows this section to be correlated with the *Brownlowia* pollen zone *sensu* Ho (1978) and old Sarawak Shell Berhad (SSB) palynological zone of Pcs 145-Phc 88 *sensu* Hageman (1987). This characterizes the Late Oligocene to Early Miocene within Cycle I and Cycle II of Sarawak Cycle.

Rangsi section

Description

This outcrop is composed of thick conglomerate at base overlain by stacked sandstone with thinly intercalated dark grey mudstone. The interbedded mudstone displays slicken side features while sandstones are relatively hard with common centimetre to decimetre-scales of calcite vein. This rock succession was mapped as Rangsi Conglomerate and/or Tatau Formation based on Wong (2011) and the geological map of Jabatan Mineral dan Geosains Malaysia (2017). Five samples for palynological analysis were selected from the thin bedded mudstone intervals (Table 2). The selection of the samples from this outcrop was done for several reasons: i) To identify any potential palynofloral changes and signal from different formation in which serves as a control for the present study. ii) The position of the outcrop which is surrounded by predominantly Nyalau Formation may provide important palynofloral data which is crucial for palynostratigraphy determinations of the study area. The palynological composition within this section is relatively very poor. Only one sample (i.e., Rangsi-S1) contains palynomorph but in very low count. The recovered palynomorph grains are characterized by dark coloured with high thermal alteration index value (e.g., Staplin, 1968; Pearson, 1984). Several grains of Gramineae/Poaceae with taxa that may be originated from the family of Palmae and Magnoliaceae including Cyathidites sp. (Cyatheaceae) and *Alnus* were recovered from this sample. The presence of *Classopollis* sp. in sample Rangsi-S1 is classified as reworked form as this species is common species in much older deposits (e.g., Muller, 1968). Overall, all the analysed samples from this section are overwhelmed by black and dark brown woody fragments including unstructured amorphous organic matter.

Interpretation and correlation

Very poor and barren palynomorph in samples precluded any detailed interpretation and correlation for this section. The studied mudstone interval that characterized by low grade metamorphism might have undergone deeper burial before being uplifted. This condition may have destroyed any form of palynomorph and organic matter.

b. Sector II – Central Bintulu

Eighty-three samples were selected from three outcrops within this sector. The occurrence and distribution of selected palynomorphs are presented in Figure 3, 4 and 5.

SMK-I section

Description

The palynological composition in this section is characterized by abundant *F. trilobata* throughout and records slightly decreasing in number. Acme of this species is marked just above the coal bed (Figure 3). *F. semilobata* also sporadically occurs and never dominant. *Rhizophora* type showing increasing upward trend while back mangrove elements such as *Brownlowia* type, *Nypa* and *Excoecaria agallocha* are relatively scarce. Samples also contain variation in diversity and abundance of peatswamp and riparian elements where taxon such as *Calamus* type, *Calophyllum* type, *Dactylocladus* type, *Campnosperma* type, *Blumeodendron* type, *Stemonurus* type, Sapaotaceae, *Ilex* type, Myrtaceae and *Pandanus* are common. Another important characteristic from this section is the presence of kerapah element represented by *Casuarina* type pollen within coal bed of 10 m interval. Seasonal element such as Gramineae also presents throughout but only in small number of counts.

Interpretation and correlation

Two possible zone have been identified from this section which are FT-I Zone and FT-II zone (Figure 3). The FT-I zone is defined within the lower part of the section covering 0 m – 10 m interval, while FT-II zone is defined above the 10m interval. The FT-I is defined based on consistent occurrence and high percentage and acme of *F. trilobata* throughout the studied samples. The zone is also characterized by regular but low in percentage of *F. semilobata* which occurs in the lower part of the zone. The FT-II zone is defined based on slight decreases in percentage of *F. trilobata* and increases of *Rhizophora* type pollen. *F. semilobata* only presents in one sample at 22 m which suggests sporadic occurrence. Furthermore, the acme of *Casuarina* type pollen may also typify the FT-II Zone as a whole. The FT-1 and FT-II zone of this section may correlatable to the *Brownlowia* pollen zone *sensu* Ho (1978) and old Sarawak Shell Berhad (SSB) palynological zone of Pcs 145 - Phc 88 and/or PO3 79 *sensu* Hageman (1987). This characterizes the Late Oligocene to Early Miocene within Cycle I and Cycle II of Sarawak Cycle.

IKM-I Section

Description

This section is characterized by upward increases of *F. trilobata* and records its acme within interval of paleosol and

Table 2: Sangan A, C, D and Rangsi section (Sector I) palynomorph distribution.

		SAMPLE																	
GROUP	**TAXA/SPECIES**	Sangan A-S1	Sangan A-S2	Sangan A-S3	Sangan C-S4	Sangan C-S5	Sangan C-S6	Sangan C-S7	Sangan D-S8	Sangan D-S9	Sangan D-B10	Sangan D-B11	Sangan D-B12	Rangsi-S1	Rangsi-S2	Rangsi-S3	Rangsi-S4	Rangsi-S5	Rangsi-S6
MANGROVE	*Achrostichum aureum*	1	2	1						1	1		1		**BARREN PALYNOMORPH**				
	Avicennia type	3		1				2		2		3	1						
	Brownlowia type	1		1						3		1	1						
	Excoecaria agallocha			1															
	Florschuetzia trilobata	21	19	11	11	15	4	3	7	48	11	7	9						
	Nypa		1		2					1			1						
	Oncosperma							1				1							
	Rhizophora type	23	9	12			2			1			2						
HINTERLAND	*Alangium* type	2							1										
	Alchornea type																		
	Anacolosa			1															
	Arenga type		1				1												
	Barringtonia			2		1					1		1						
	Blumeodendron type	4						2		4									
	Caesalpiniaceae			1															
	Calamus type	5			3					3									
	Calophyllum type	4	1	3		1		1		3	1	2							
	Campnosperma	1																	
	Casuarina type	1	1	2	3				4	3		1							
	Chantium type					1		1											
	Chepalomappa type	2	1		2						1	1							
	Crudia type	1										1							
	Cycas type	1																	
	Cyrtostachys type			1			1		2			1							
	Dactylocladus type	4					3	1		2									
	Dipterocarpus type		1				1					1							
	Durio						1												
	Elaeocarpus type	1	1		5			1			1								
	Eugeissona type	1			1					2			1						
	Euphorbiaceae	1			3			1		2		3							
	Ficus	2			1			1		2									
	Garcinia				1		1												
	Gonystylus type						1			1									
	Hibiscus		2								1	2							
	Ilex type	1			2														
	Lithocarpus type	3			2		1			3									
	Loranthaceae			1							1								
	Magnoliaceae	2						1		5				4					
	Meliaceae			4	2		1			1		1							
	Melanorrhoea type	2				1				1			1						

(*Continued*)

Table 2 - *continued*

HINTERLAND	Myrtaceae		1		4		1								BARREN PALYNOMORPH
	Nenga type			1									1		
	Palaquium type		1							1					
	Palmae	1			1					2				5	
	Pandanus	1						2		2		1	3		
	Papilionaceae		1												
	Pometia							1							
	Protaceae					1		2			1		1		
	Quercus type			1							1				
	Rubiaceae	1							2						
	Shorea type								1						
	Stemonurus type	1			3										
	Sapotaceae		1	1		3			4						
	Taxodiaceae													1	
	Terminalia type	1								1					
	Timonius type		1												
SPORES	*Ceratopteris* type			1		2					1				
	Cyathidites sp. (Cyatheaceae)	1		1					1		1			1	
	Laevigatosporites sp. (Schizaeaceae)	8			3			`		6			`		
	Osmunda type	2										1			
	Polypodiisporites sp. (Polypodiaceae)	2													
	Pteris type							1				1			
	Selaginella									1					
	Verrucatosporites usmensis (Stenochlaena)	6	1	11	1	7		2	1	3	2	5			
SEASONAL/MONTANE	*Alnus*			3		4	1	1		2				1	
	Celtis	1													
	Ephedra					1			1			1			
	Picea	1	2	2		3		1		5	1		1		
	Pinus	1	4	2		2		1		4	1	2			
	Podocarpus	1			1										
	Tsuga			1		1									
	Graminae/Poaceae	5	2	1	4	6	3	5	3	1	2	5	1	9	
OTHERS	*Classopollis* sp.													1	
	Corsinipollenites sp.									1					
	Gemmatricolporites pilatus										1				
	Iugopollis sp.							1							
	Retitricolpites crucipori	1													
	Retitricolpites vulgaris	1									1				
	Tricolpites sp.	3													
	Tricolporites sp.													1	
	Triorites festatus	2							1						
	Zonalapollenites sp.	1								1					

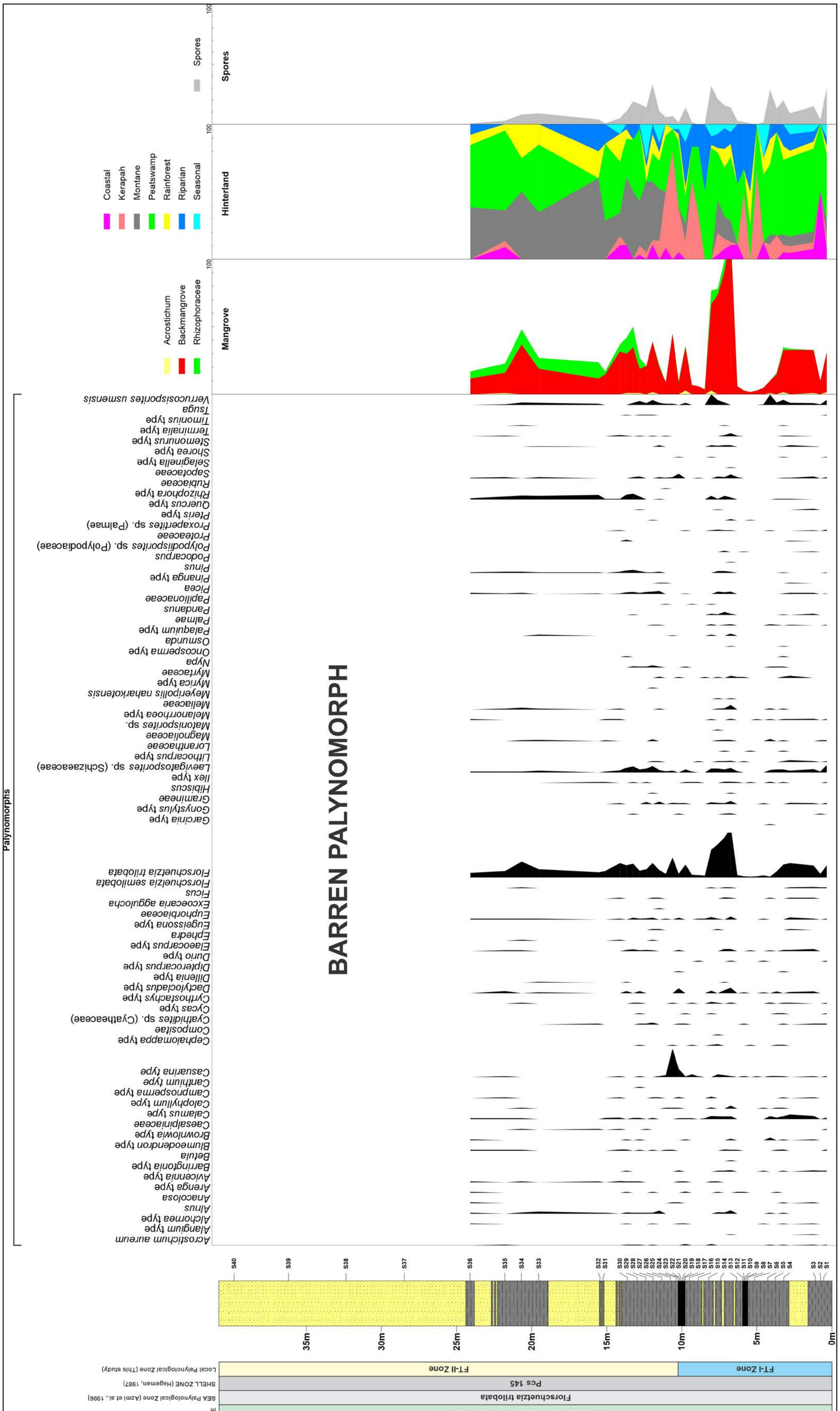

Figure 3: SMK-I section palynological succession, sector II.

carbonaceous mudstone between 14m-15m (Figure 4). *F. semilobata* occurs sporadically especially in the middle part of the section. Single grain of *M. naharkotensis* occurred in sample S-13 within paleosol interval. Mangrove and back mangrove are common throughout and record variation in abundance. *Rhizophora* type occurs consistently but in moderate count. While back mangrove element such as *Avicennia* type, *Brownlowia* type, *Oncosperma* and *Nypa* are all present but in low percentage. Gramineae pollen also common and presents continuously upward. Peat swamp elements records relatively high diversity where taxon such as *Blumeodendron* type, *Calamus* type, *Calophyllum* type, *Campnosperma* type, Sapotaceae and *Dactylocladus* type dominate the group. This section also marks moderate to low representation of riparian group of pollen which is represented by *Arenga* type, Myrtaceae, *Ilex* and *Pandanus*. Single grain of *M. naharkotensis* is recorded within carbonaceous mudstone.

Interpretation and correlation

Abundant *F. trilobata* throughout the section including common to sporadic occurrence of *F. semilobata* typify the FT-I zone. This is also supported by the presence of single grain *M. naharkotensis*. Based on the above evidence the section can be placed within the age of Late Oligocene to earliest Miocene in which correlatable to the *Brownlowia* pollen zone *sensu* Ho (1978) and old Sarawak Shell Berhad (SSB) palynological zone of Pcs 145-Phc 88 *sensu* Hageman (1987). This characterizes the Late Oligocene to Early Miocene within Cycle I and Cycle II of Sarawak Cycle.

TS-I Section

Description

The palynological composition within this section records an upward increases of *F. trilobata* with sporadic occurrence of *F. semilobata*. Single grain of *F. levipoli* also recorded within thick mudstone interval (Figure 5). *Rhizophora* type and Gramineae show increasing and continuous upward trend. Back mangrove element occurs in moderate count throughout the section. Pollen from peatswamp group shows strong variation in diversity and abundances. Among dominant taxon from this group are *Blumeodendron* type, *Calophyllum* type, *Campnosperma*, *Chepalomappa* type, *Calamus* type and *Stemonurus* type. Each of these taxa made up of more than 5% from total count. Riparian elements also present in moderate to low count and represented by *Ilex*, *Pandanus*, and Myrtaceae. Montane element such as *Alnus*, *Pinus* and *Picea* also present but in relatively low percentage. In addition, kerapah group which is represented by *Casuarina* type also presents in moderate percentage and showing continuous and sometime sporadic occurrence upward.

Interpretation and correlation

The palynomorph assemblage for this section can be placed within the FT-II zone and FT-III zone. This is based on the abundance of *F. trilobata* throughout and supported by sporadic *F. semilobata* and single grain of *F. levipoli*. Other evidence that supports the interpretation is the increasing in number of *Rhizophora* type and showing continuous occurrence and displaying upward increasing trend with moderate to low number of back mangrove element. Moreover, the continuous and sporadic occurrence of *Casuarina* type pollen may signify the FT-II zone**.** The FT-II and FT-III zone of this section may correlatable with the *Brownlowia* pollen zone *sensu* Ho (1978) and old Sarawak Shell Berhad (SSB) palynological zone of Phc 88 - Po3 79 *sensu* Hageman (1987). This characterizes the Early Miocene within Cycle II and III of Sarawak Cycle.

c. Sector III – Northeast Bintulu - Similajau

Twenty-three samples were selected from three outcrops from this sector and were analysed for their palynomorph content. The occurrence and distribution of selected palynomorphs are presented Table 3 and Figure 6.

SP-I Section

Description

The section records abundant and continuous occurrence of *F. trilobata* with low count of *F. semilobata*. *Rhizophora* type records continuous upward occurrence but in relatively moderate to low count. Seasonal element such as Gramineae and montane group such as *Alnus*, *Ephedra*, *Picea*, *Pinus*, *Podocarpus* and *Tsuga* are all present and records noncontinuous occurrence and occur in relatively moderate to very low percentage respectively. Back mangrove taxa are quite significant but not dominant and represented by *Avicennia* type, *Brownlowia* type, and *Excoecaria agallocha*, *Nypa* and *Oncosperma*. Peat swamp taxon are variably moderate to common. Taxon such as *Blumeodendron* type, *Calamus* type, *Calophyllum* type, *Chepalomappa* type, *Dactylocladus* type, *Menorrhoea* type, and Sapotaceae are the common peat swamp taxa recorded in this group where each of these taxa usually record more than 5% from the total count. Riparian element is relatively low and records non continuous occurrence throughout the section, while kerapah group is well represented by *Casuarina* type. Single grain of *M. naharkotensis* also occurred in one sample i.e., SP-S9 sample (Table 3).

Interpretation and correlation

The palynomorph assemblage for this section is typical of FT-I zone. This is shown by the abundance of *F. trilobata* throughout with common *F. semilobata*. In addition, the section also records the occurrence of *M. naharkotensis*. Other evidence includes variation of peat swamp pollen including continuous and gradual increases of *Rhizophora* type. This corresponds with the moderate representation of Gramineae pollen. Moreover, low representation of *Brownlowia* type also typify the zone in general. The FT-1 zone of this section may correlatable with the *Brownlowia*

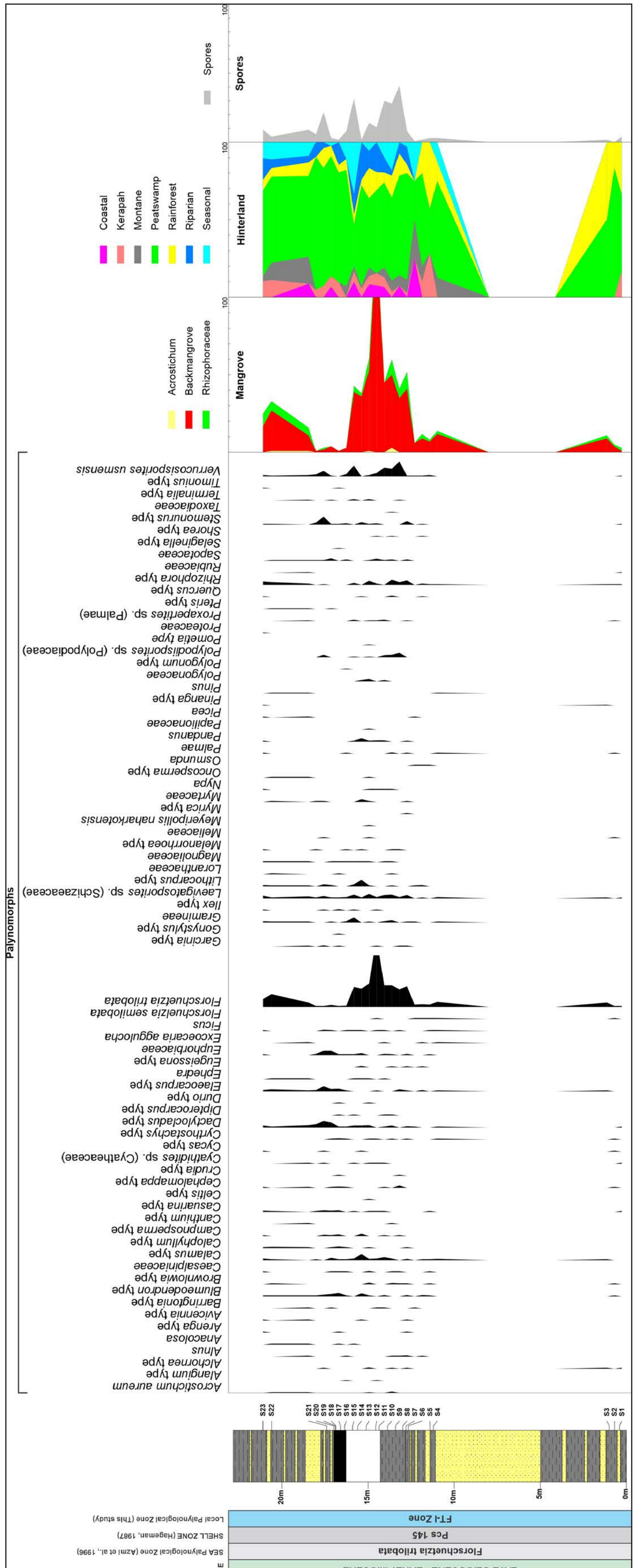

Figure 4: IKM-I palynological succession, sector II.

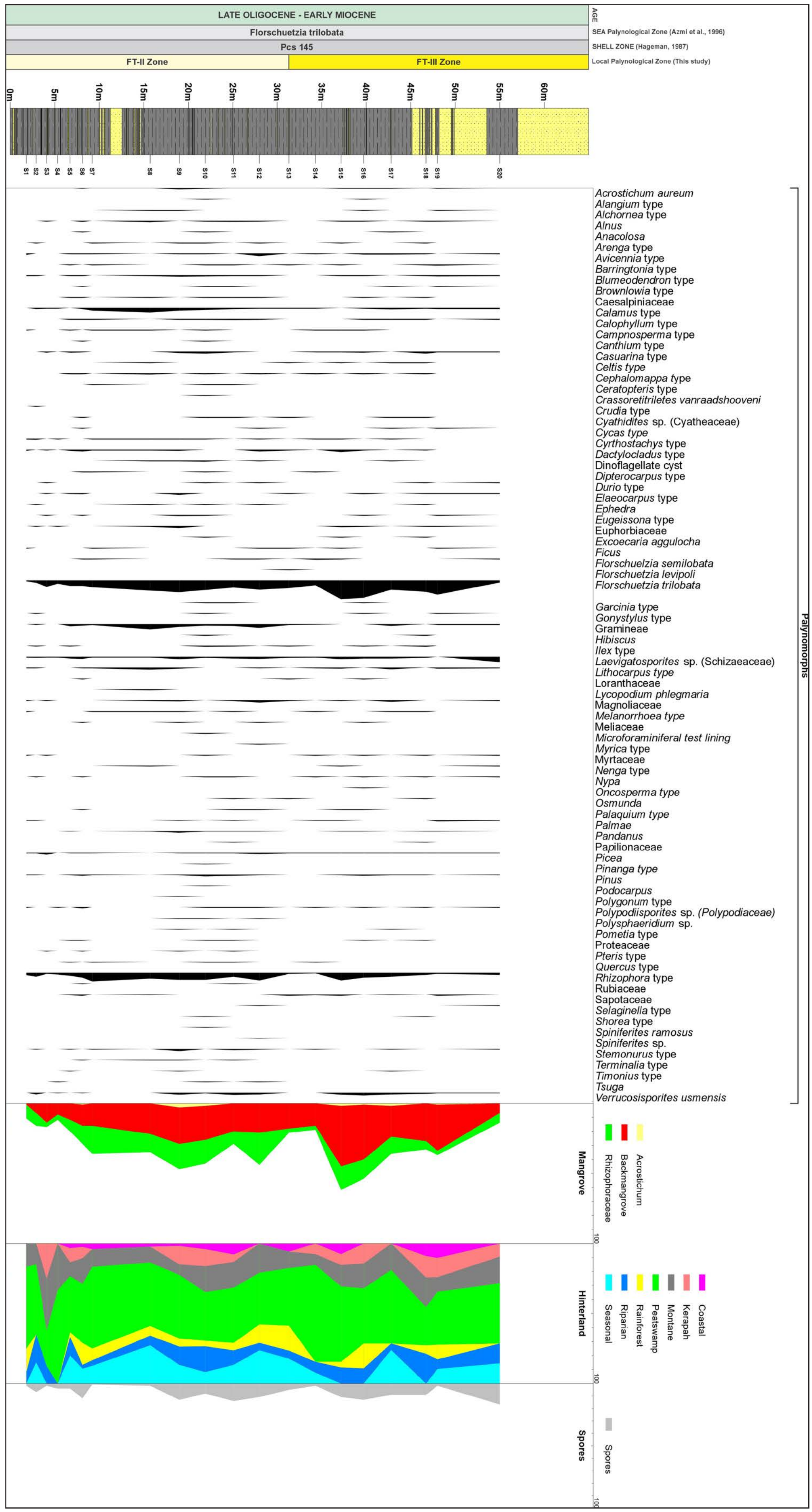

Figure 5: TS-I palynological succession, sector II.

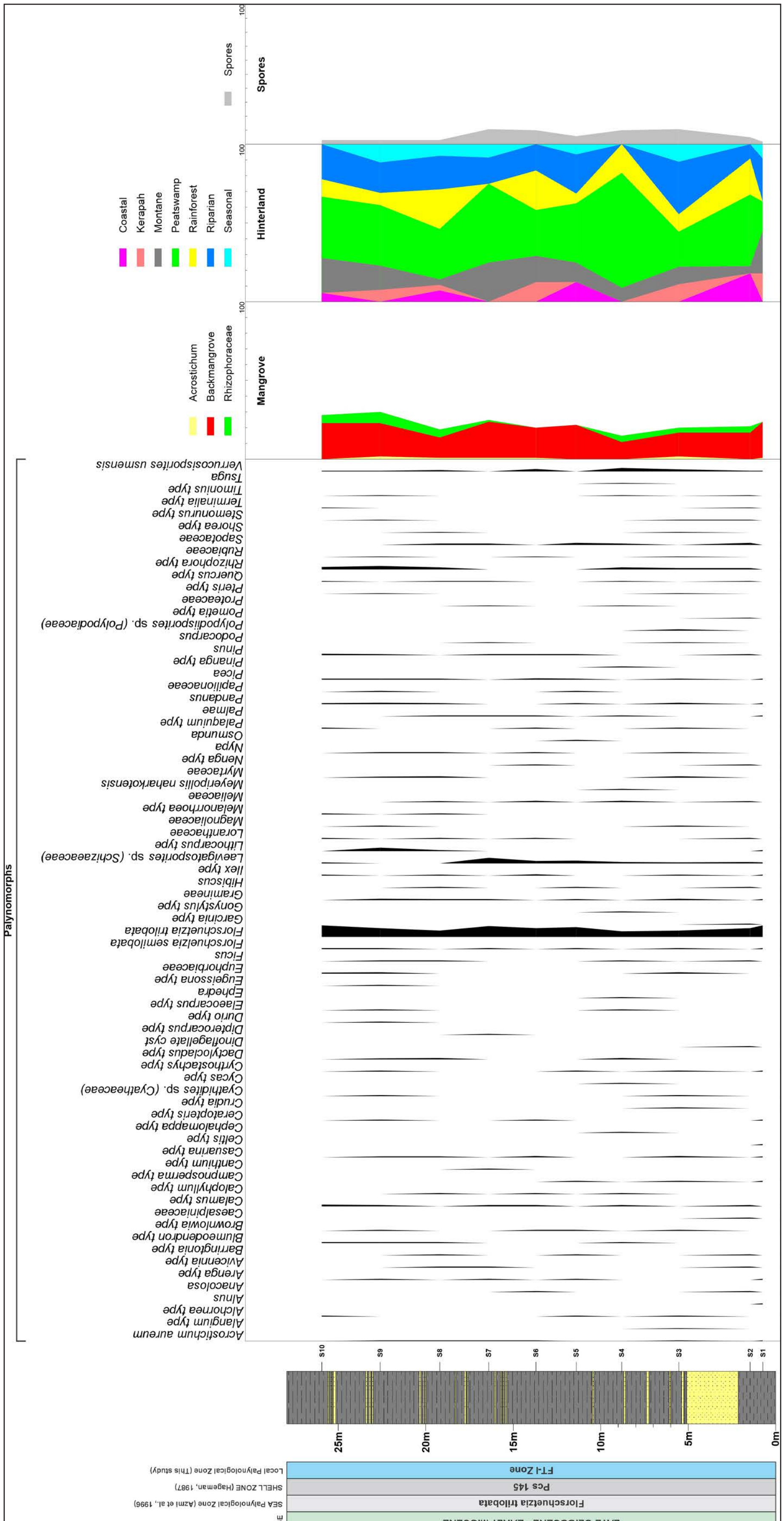

Figure 6: SMJ-II palynological succession, sector III.

Table 3: SP-I and SMJ-I section (Sector III) palynomorph distribution.

		SAMPLE												
GROUP	**TAXA/SPECIES**	SP1-S1	SP1-S2	SP1-S3	SP1-S4	SP1-S5	SP1-S6	SP1-S7	SP1-S8	SP1-S9	SP1-S10	SMJ1-S1	SMJ1-S2	SMJ1-S3
MANGROVE	*Achrostichum aureum*				1	2	1		1		1		5	3
	Avicennia type				2	1	1		2			2		1
	Brownlowia type					1		1			2			1
	Excoecaria agallocha										1		2	
	Florschuetzia trilobata	12	8	25	11	16	23	15	26	19	7	31	29	21
	Florschuetzia semilobata						1					1	2	1
	Nypa						1	1					1	
	Oncosperma										1	2		
	Rhizophora type	3	2	1	2	3	2	1	1	7	1	11	8	7
HINTERLAND	*Alangium* type									1				
	Alchornea type					1								1
	Anacolosa						1							
	Arenga type		1					1						1
	Barringtonia			1	1		2	1					3	
	Blumeodendron type					2	3	1	5		2			
	Caesalpiniaceae			1		1		1	2		1	4	1	1
	Calamus type			1	2	4	2	1	4	3		7	6	5
	Calophyllum type					1		1	3		1			1
	Campnosperma						1							1
	Casuarina type	1			3	2	3		2	3	1	3	1	4
	Chantium type							1						
	Chepalomappa type				1		1		2		1			1
	Crudia type					1						1		
	Cycas type							1						
	Cyrtostachys type					2	1	1						2
	Dactylocladus type			3		2	3		6	4		7		5
	Dipterocarpus type										1			
	Durio						1		1			1		
	Elaeocarpus type	1			1	1	2		3		3	1		3
	Eugeissona type												1	
	Euphorbiaceae				2	2		1	4	1	2	2	6	2
	Ficus	1			1					1		2	1	
	Garcinia			1			1	1			1		2	
	Gonystylus type					1							1	
	Hibiscus						1	1						
	Ilex type				2	2					1	1		
	Lithocarpus type	1	1			1	1		3	1		2		3
	Loranthaceae			1		2		1			1			

(*Continued*)

Table 3 - *continued*

HINTERLAND	Magnoliaceae				1		1		4	1	1	2		3
	Meliaceae		1				1							1
	Melanorrhoea type		1	1			1		3				3	
	Myrtaceae				1	3	1							2
	Nenga type							1		1			1	
	Palaquium type					1		1					2	
	Palmae	1									3			1
	Pandanus				1	2	1		5		2	3	6	
	Papilionaceae					1								
	Pinanga type							1						
	Polygonum type			1										1
	Pometia						1							
	Protaceae					2					1			1
	Quercus type	1			1		1							1
	Rubiaceae					1								
	Shorea type				1					1				
	Stemonurus type		1	1				1	3	4		3	4	1
	Sapotaceae	2		1		3			5		3			
	Terminalia type						1		3		1			
	Timonius type					1					1			
SPORES	*Ceratopteris* type													2
	Cyathidites sp. (Cyatheaceae)					1		1		1				1
	Laevigatosporites sp. (Schizaeaceae)	2	1	3	3		1	2	4	1	2	5	6	3
	Osmunda type						1							
	Polypodiisporites sp. (Polypodiaceae)			2			1		3	1				
	Pteris type				1		1					1		1
	Selaginella										1			
	Verrucatosporites usmensis (Stenochlaena)			1	1			2	3	3	4	7	6	5
SEASONAL/MONTANE	*Alnus*					1		1		1	1	1		1
	Ephedra								2					
	Myrica											1		
	Picea										1		1	4
	Pinus						1							3
	Podocarpus										1			
	Tsuga								1					
	Graminae/Poaceae	2		2				1	5	1		6	4	6
OTHERS	*Corsinipollenites* sp.		1											
	Gemmatricolporites pilatus										1			
	Iugopollis sp.			1										
	Retitricolpites vulgaris					1								
	Meyeripollis naharkotensis								1			1		
	Tricolporites sp.				1									

pollen zone *sensu* Ho (1978) and old Sarawak Shell Berhad (SSB) palynological zone of Pcs 145-Phc 88 *sensu* Hageman (1987). This characterizes the Late Oligocene to Early Miocene within Cycle I and Cycle II of Sarawak Cycle.

SMJ-I section

Description

Only three samples were selected from thin heterolithic mudstone of this section (Table 3). All the three analysed samples record abundant *F. trilobata* with low yields of *F. semilobata*. *Rhizophora* type occurs in each studied sample in relatively moderate percentage. Gramineae also presents in all samples and records approximately 5% in each sample analysed. Back mangrove element is relatively uncommon, while peat swamp element is variably moderate to common in which represented by *Calamus* type, *Dactylocladus* type, *Melanorrhoea* type, *Stemonurus* type and Sapotaceae. Riparian group of pollen also records moderate to low abundances whereas kerapah element is well-represented by *Casuarina* type. Single grain of *M. naharkotensis* is recorded in sample SMJ1-S1 (Table 3).

Interpretation and correlation

The consistent occurrence of *F. trilobata* throughout the studied samples including low number of *F. semilobata* are typify FT-I zone for all the analysed samples. This is supported by the occurrence of single grain *M. naharkotensis* including common Gramineae pollen. Based on the pollen evidence, a Late Oligocene and/or earliest Miocene is suggested for this section. The abundance of *F. trilobata* is consistent with other biostratigraphic evidence such as single occurrence of *M. naharkotensis* thus allows this section to be correlated with the *Brownlowia* pollen zone *sensu* Ho (1978) and old Sarawak Shell Berhad (SSB) palynological zone of Pcs 145 - Phc 88 *sensu* Hageman (1987). This characterizes the Late Oligocene to Early Miocene within Cycle I and Cycle II of Sarawak Cycle.

SMJ-II section

Description

A total of two samples were selected from bioturbated mudstone and another eight samples were sampled on the thick grey mudstone succession (Figure 6). The palynological composition obtained from this section is comparable to that of SMJ-I section. The *F. trilobata* occurs in abundant throughout the section and continuous. *F. semilobata* also marks continuous upward occurrence but in relatively low count. *Rhizophora* type shows strong variation in abundance while back mangrove element is relatively low in percentage. Taxon from back mangrove such as *Brownlowia* type, *Avicennia* type and *Nypa* are sporadically occur but never dominant. Peat swamp pollen group are common however, their occurrence is not continuous. This pollen group is well-represented by *Blumeodendron* type, *Calamus* type, *Cyrthostachys*, *Dactylocladus* type, *Stemonurus* type, and Sapotaceae. Strong variation of riparian pollen is recorded in which taxon such as *Arenga* type, *Ilex* type, Myrtaceae, and *Pandanus* record good representation although not in continuous occurrence. In addition, the seasonal and montane elements are also showing good representation. Gramineae occurs throughout while montane taxon such as *Pinus* and *Picea* are present continuously upward. Single grain of *M. naharkotensis* is recorded in one sample within dark grey mudstone interval.

Interpretation and correlation

The palynomorph assemblage for this section is typical of FT-I zone. The consistent occurrence of *F. trilobata* with low count of *F. semilobata* typify the zone. This is also supported by the occurrence of *M. naharkotensis*. In addition, the strong variation of peat swamp pollen and Gramineae throughout the section are also characterize the zone as a whole. The FT-1 zone of this section can be correlated to the *Brownlowia* pollen zone *sensu* Ho (1978) and old Sarawak Shell Berhad (SSB) palynological zone of Pcs 145-Phc 88 *sensu* Hageman (1987). This characterizes the Late Oligocene to Early Miocene within Cycle I and Cycle II of Sarawak Cycle.

DISCUSSION

Palynostratigraphic framework and correlation to Sarawak Basin

In the Sarawak Basin, the Cycle I and Cycle II consist of thick coastal plain, coastal and fluvio-marine sediments ranging from Late Eocene to Early Miocene. Ho (1978) addressed the problem of recognising the boundary between these cycles; in thick coastal sequences only, short-lived transgressive event have been identified and this is not an ideal candidate for regional stratigraphic surface. Recently, Lunt & Madon (2017) pointed out that the occurrence of an angular unconformity in the southwest of the Sarawak Basin was not marked as top Cycle I in many old well reports until 1987. In Hageman (1987), the top of Cycle I was placed at the top of Pcs 145 zone which represents the boundary between Cycle I and Cycle II. This boundary was suggested to represent a transgression in which the interpretation was based on changes in pollen assemblages from montane to hinterland, peat swamp and mangrove floras. This also marks the change in climate from relatively cool and temperate to hot and humid climate during the Late Oligocene to Early Miocene (Hageman, 1987).

Integration of the results derived from the palynological analysis of the ten outcrop sections namely Sangan A, Sangan C, Sangan D, Rangsi, SMK-I, IKM-I, TS-I, SP-I, SMJ-I and SMJ-II reveal three distinct informal and local palynological assemblage zone of the Nyalau Formation. This tentatively allows the studied section to be correlated within the regional context of the Sarawak Basin biostratigraphy by comparing to the existing palynostratigraphic zonation (e.g., Ho, 1978; Hageman, 1987). In this study four outcrops that display extensive facies succession were selected for local correlation based on the interpreted palynological zones (Figure 7). The present study shows that the pollen assemblage zones of FT-I, FT-II and FT-III can be broadly correlated to the Cycle I-Cycle II of the Sarawak Cycle (Ho, 1978). The abovementioned zone with abundant *F. trilobata*, common to sporadic *F. semilobata* including presence of *M. naharkotensis* corresponding to the upper Pcs 145 and Phc88 pollen zones. Several studied sections reveal acme and continuous occurrence of *Casuarina* type pollen which may coincide with the pollen zone of Po3 79.

Paleovegetation

The present study provides the basis of the terrestrial and coastal paleovegetation within the Oligocene-Miocene boundary in the Sarawak basin. Overall, three paleovegetation types have been recognized based on the palynological assemblages and these are: the mangroves (mangrove and back mangrove), the hinterland (coastal, kerapah, montane, peatswamp, rainforest, riparian and seasonal) and the spores (Figure 3, 4, 5 & 6). Comparison was made to the adjacent Oligocene and Early Miocene palynological succession such as Mohd Yakzan *et al.* (1997), Lelono & Morley (2011) and Sia *et al.* (2014). In addition, the areal extant of these assemblages have been compared to the modern-day vegetational zones studied by Anderson & Muller (1975) and Mohamad Zulkifley *et al.* (2016). The terminologies for the present days near shore vegetational zones especially mangrove is also following that of Somboon (1990) as shown in Figure 8.

Paleoclimate setting

The Oligocene to earliest Miocene paleoclimate for many areas in the Southeast Asia was seasonal and relatively lack in moisture (e.g., Morley, 1998; Morley, 2011) although certain area such as the southernmost part of the Natuna had experienced everwet climate (Morley *et al.*, 2007). The wettest climatic condition during the Oligocene had occurred in Java in which reflects a climatic fringe of the eastern margin of Sundaland (Lelono & Morley, 2011). The palynological successions from the Nyalau Formation show some similarity with other Oligocene and Early Miocene palynological records (e.g., Mohd Yakzan *et al.*, 1997; Lelono & Morley, 2011; Sia *et al.*, 2014; Morley *et al.*, 2020). The persistent occurrence of climate sensitive taxa such as Gramineae/Poaceae including certain taxa such as *Casuarina* type, *Rhizophora* type and variation in peat swamp pollen may delineate a regional climate variation during the Oligocene towards Miocene.

The zone FT-I with abundant *F. trilobata*, low *Rhizophora* type and regular to common occurrence of Gramineae including variably peatswamp taxa such as *Blumeodendron* type, *Calophyllum* type, *Stemonurus* type *Calamus* type and *Dactylocladus* type and relatively moderate to low riparian elements may reflect a period of wet climatic conditions with moderately seasonal climates (Figure 9). The zone FT-II is marked by gradual increases of *Rhizophora* type including regular to common back mangrove elements. The FT-II zone is also characterized by slight reduced in number of riparian pollen such as *Pandanus*, Myrtaceae and *Ilex*. The regular to abundance of *Rhizophora* type with common to abundant *Casuarina* type in which supported by decreasing of riparian elements suggest a period of everwet climate with occasional super wet climate for this zone.

The Zone FT-III which is characterized by strong variation in diversity and frequency of peat swamp pollen typifies everwet climate as a whole for the zone. However, the reduced frequency of *Rhizophora* type and slight reduction of *Casuarina* type including common montane elements may suggest a slightly less wet climate compared to FT-II zone with intermittent to marginally seasonal conditions.

Climate comparison to adjacent areas

In this study, the paleoclimate conditions based on pollen record can be positively correlated to some degree with the major climatic event in Southeast Asia region especially during the Oligocene to earliest Miocene. The Zone FT-I with regular seasonal elements can be correlated to the zone OL-2 *sensu* Lelono & Morley (2011) and PR3 of Mohd Yakzan *et al.* (1996) in which also consistent with the seasonal climatic condition in much of Southeast Asia during Oligocene (e.g., Morley, 1998; Morley, 2011).

The Zone FT-II that characterized by regular and intermittent acme of *Casuarina* type with common peat swamp taxa and low amount of riparian element can be correlated to the event of superwet to everwet climate recorded from the Zone OL-3 in the Java Sea *sensu* Lelono & Morley (2011) and PR3 to PR4 in the Malay Basin *sensu* Azmi Mohd Yakzan *et al.* (1996). This also coincides with the Java Sea palynological succession in which characterized by abundant "Kerapah" and peat swamp elements towards earliest Miocene. In addition, similar pollen assemblage also can be found in the Mukah-Balingian coal (e.g., Sia *et al.*, 2014) indicating this type of pollen assemblage that reflects wet to superwet with intermittent seasonal conditions may also occur in much younger succession.

In general, the *Casuarina* type was originated from the Gondwanaland and is native to Australia (e.g., Lelono & Morley, 2011). Its first appearance in Australian fossil records have been discussed by Morley (1998) in which occurred well after the separation of the India plate from Gondwana. *Casuarina* type is part of Kerangas vegetation or "heath forest" which usually occur in ombrotrophic namely Kerapah peat. In the present day such as in Borneo, this type of peat can be found on poorly drained soil (Brunig, 1990; Morley, 2000) where superwet climates are the favourable condition for development of this peat (Richards, 1996).

As addressed by Morley & Flenley (1987) a major climatic change occurred in the Early Miocene

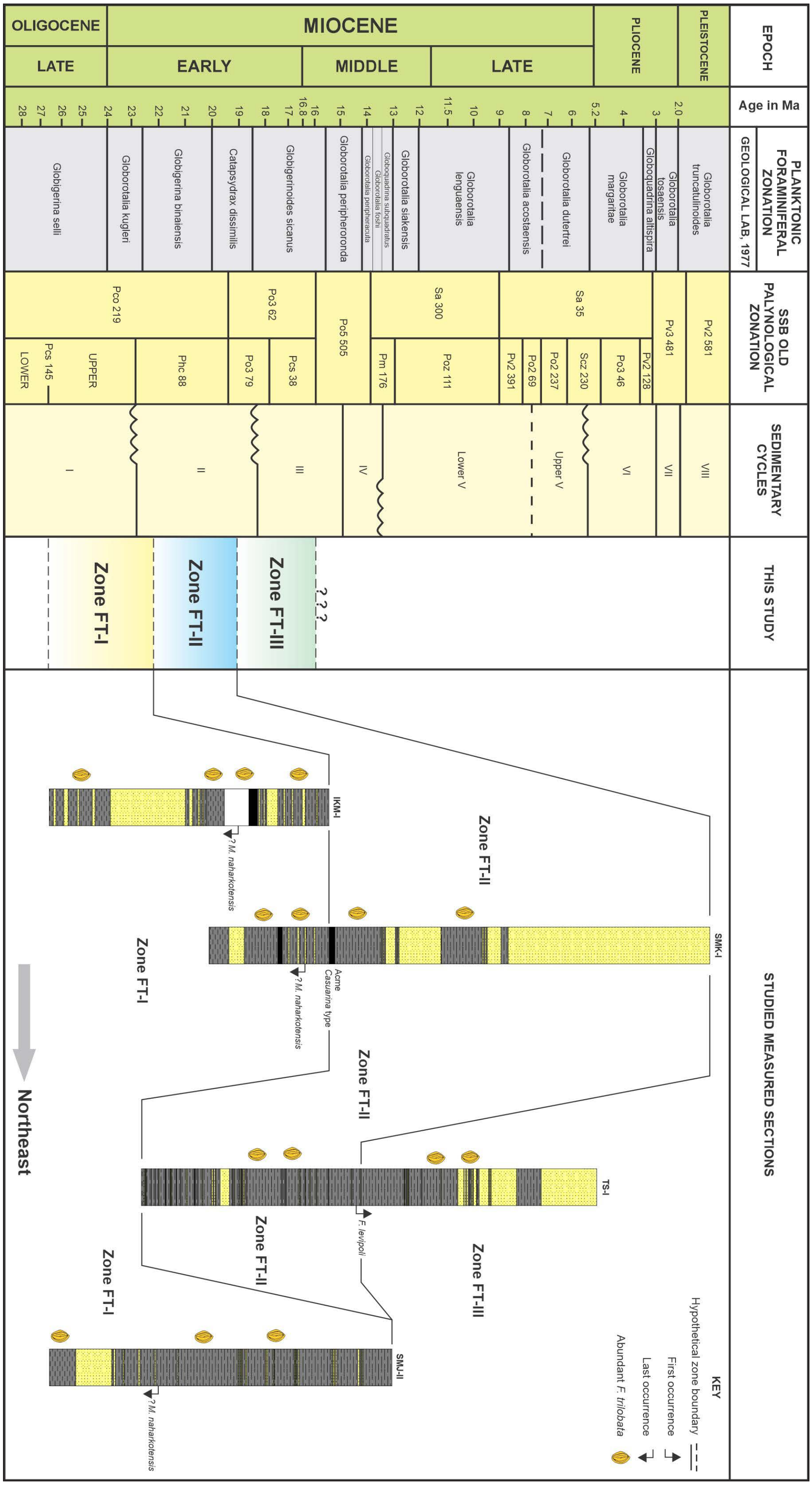

Figure 7: Hypothetical correlation of the studied sections from the Nyalau Formation based on the interpreted local palynological assemblage zones as recognized in the present study.

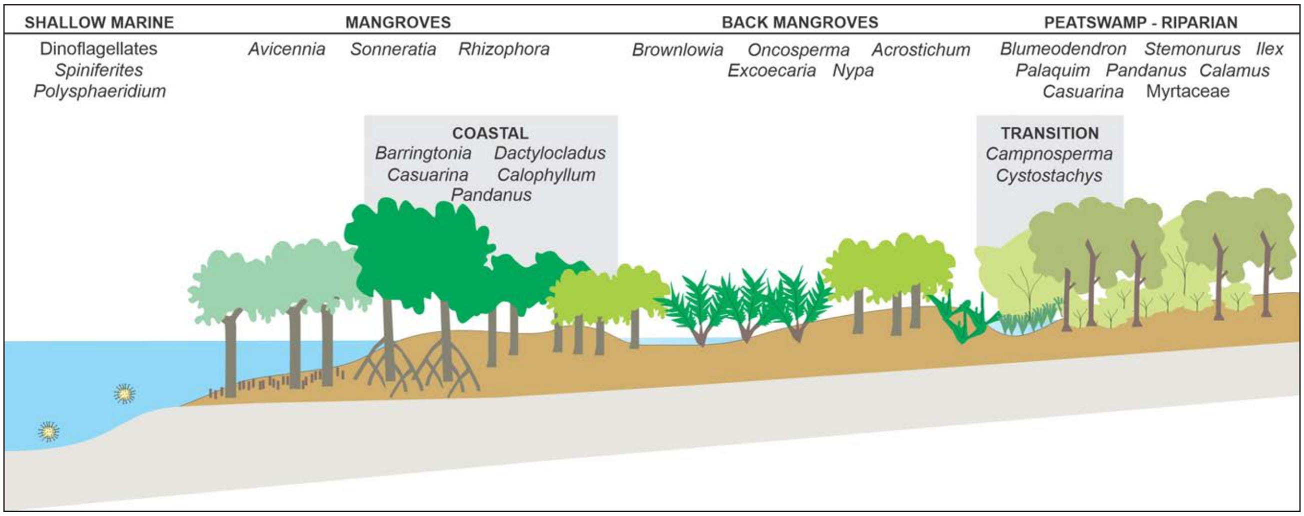

Figure 8: Interpreted palynofloral succession during Late Oligocene to earliest Miocene of the Nyalau Formation.

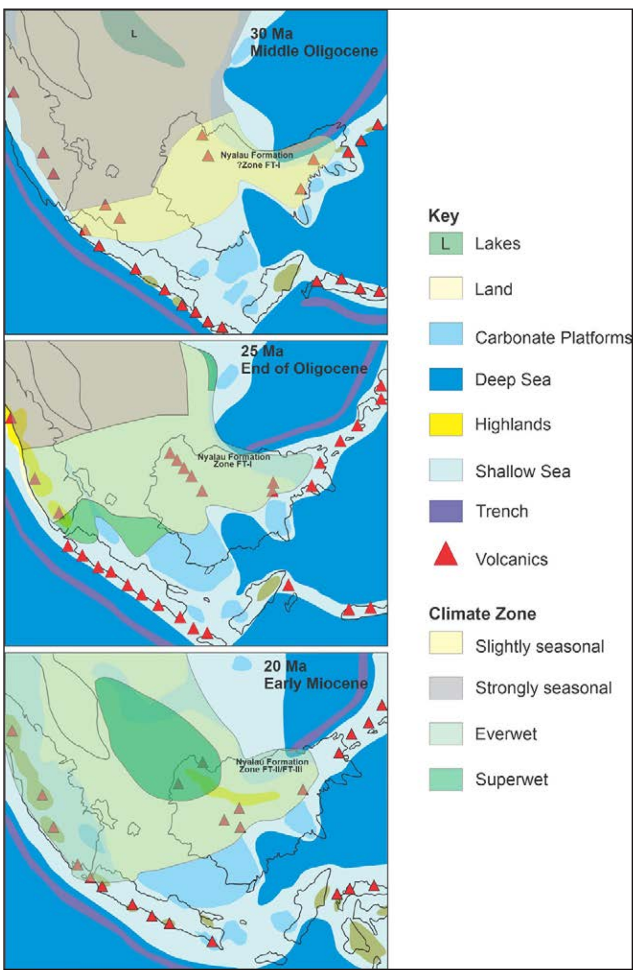

Figure 9: Paleoclimate distribution during Oligocene to Early Miocene, modified and redrawn from Lelono & Morley (2011), superimposed with paleogeographic maps of Hall (2009).

approximately 21ma. Subsequently coals that characterized by peat swamp taxa such as *Calophyllum* type, *Cephalomappa* type, *Durio* type and *Stemonurus* type became widespread in many areas of the Sunda region. This is consistent with the findings in this study where the above-mentioned taxa are well-represented in the samples especially within FT-II and FT-III zone. The widespread distribution of peat swamp taxa suggesting a prolonged wet to everwet climatic condition right after the seasonal Oligocene and lead to the expansion of the rain forest across the Borneo region.

CONCLUSIONS

- The Nyalau Formation provides important palynological records which is crucial for paleovegetation and paleoclimate reconstruction within the Oligocene-Miocene boundary of the Northwest Sarawak region. Despite the complexity of the marginal marine strata of the Nyalau Formation, at least three local palynological assemblage zones can be constructed namely FT-I, FT-II and FT-III. These palynological zones can be positively correlated to the high level palynostratigraphic framework in the Sarawak Basin, including other areas within Southeast Asia region such as in the Malay Basin and Java Sea of Indonesia.
- In the Sarawak Basin, the proposed palynological assemblage zones are correlatable to the Cycle I and Cycle II of Sarawak Cycle which typifies the Late Oligocene-Early Miocene. The interpreted palynomorph assemblage indicates that the mangrove and back mangrove including hinterland group were prevalent in which comparable to the modern-day plant communities.

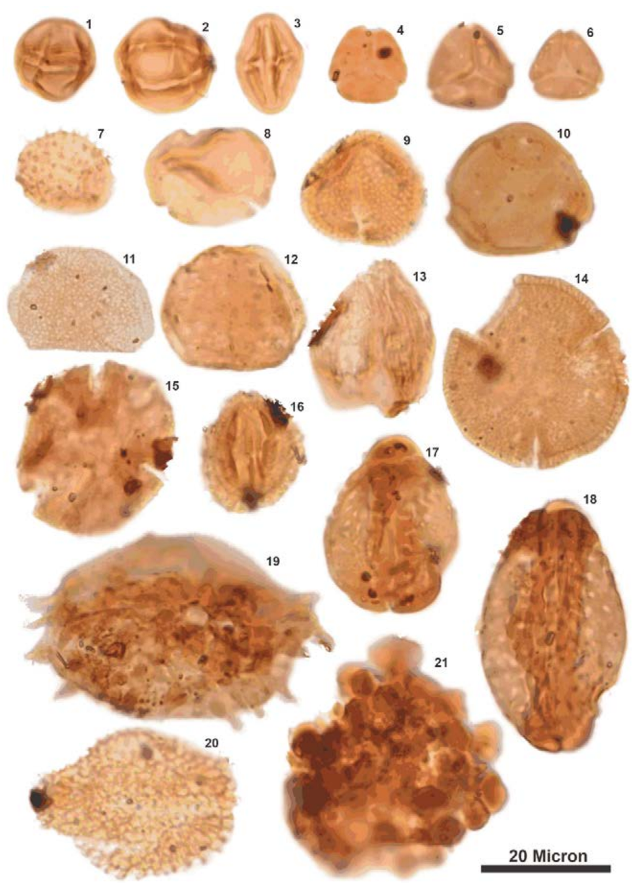

Figure 10: Photomicrograph of pollen grains observed in the Nyalau Formation samples. 1-2. *Rhizophora* type. 3. *Terminalia* type. 4-6. Myrtaceae. 7. *Pandanus.* 8. *Stemonurus* type. 9. *Avicennia* type. 10. *Casuarina* type. 11. *Calamus* type. 12. *Proxapertites* sp. (Arecaceae/ Palmae). 13. *Crudia* type. 14-15. *Brownlowia* type. 16. *Ilex* type. 17-18. Barringtonia. 19. *Nypa.* 20. *Timonius.* 21. *Meyeripollis naharkotensis* sp.

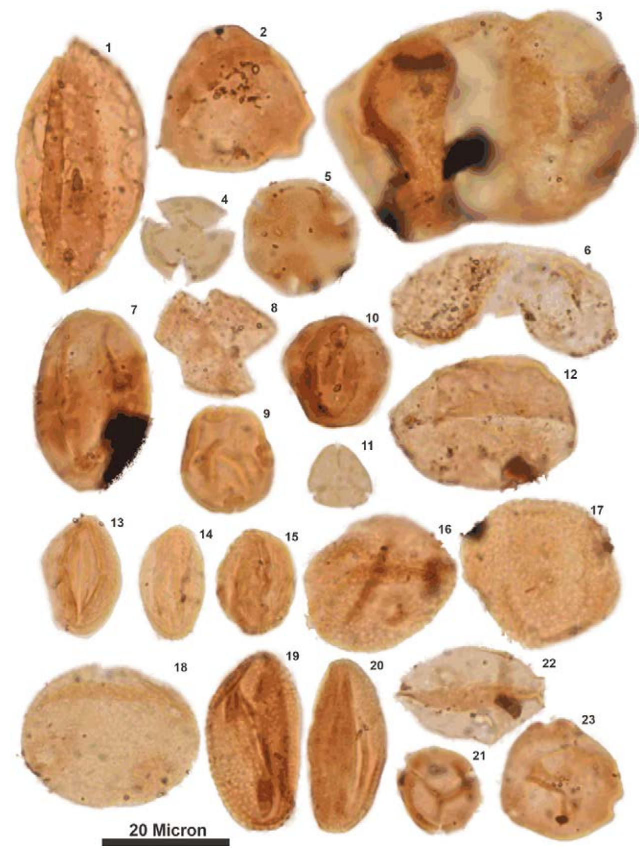

Figure 11: Light photomicrograph of pollen taxa recovered from the studied sections. 1. Magnoliaceae. 2. *Casuarina* type. 3. *Picea.* 4. Papilionaceae. 5. *Brownlowia* type. 6. *Pinus.* 7. Sapotaceae. 8. *Dipterocarpus*. 9. Meliaceae. 10. Euphorbiaceae. 11. Myrtaceae. 12. Palmae. 13-15. *Campnosperma*. 16-18. *Chepalomappa* type. 19-20. Euphorbiaceae. 21. *Rhizophora* type (Plan view). 22. Gramineae/ Poaceae. 23. *Casuarina* type.

- The climatic conditions based on the pollen records retrieved from the Nyalau Formation suggest a seasonally dry climate with well-pronounced wet climatic conditions throughout the Late Oligocene – Early Miocene as evident from regular occurrence of grass pollen i.e., Gramineae/Poaceae with common rain forest and peatswamp elements. Towards the Early Miocene, the climatic conditions may record intermittent superwet to everwet based on the acme of *Casuarina* type with common to abundant peat swamp including mangrove elements.

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AUTHOR CONTRIBUTIONS

ZK performed sampling, palynological analysis including interpretation and wrote the whole manuscript. AAR, MSI and NAS contributed to critically reviewing the manuscript and contributing ideas to improve the paper.

CONFLICT OF INTEREST

The authors declare there is no conflict of interest.

Figure 12: Light photomicrograph of *Florschuetzia* type recovered from the studied sections. 1-15. *Florschuetzia trilobata*. 16. *Florschuetzia semilobata*. 17. *Florschuetzia levipoli*.

Figure 13: Light photomicrograph of spores recovered from the studied sections. 1-5. *Laevigatosporites* sp. (cf. Polypodiaceae). 6-9. *Verrucatosporites* sp. (*Stenochlaena*).

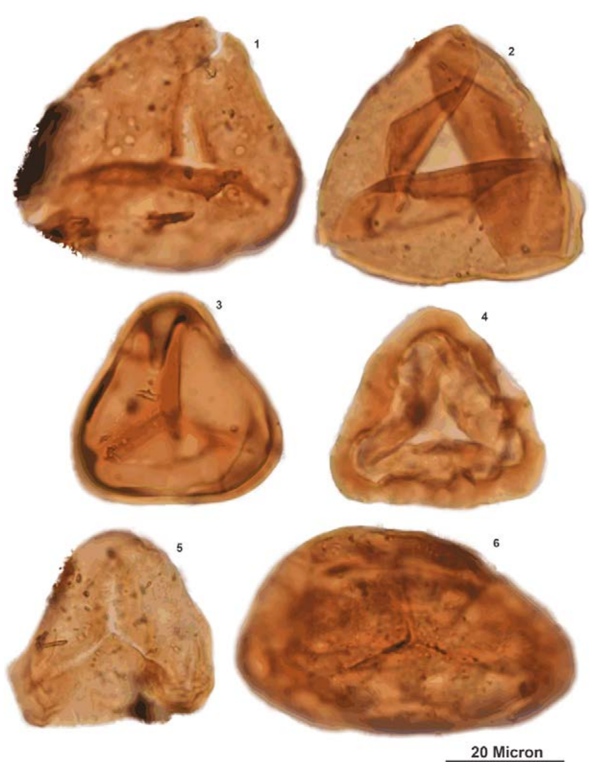

Figure 14: Light photomicrograph of spores recovered from the studied sections. 1-2. *Cyathidites* sp. (Cyatheaceae). 3. *Foveotriletes* sp. 4. Pteris type. 5-6. *Acrostichum aureum*.

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