Bulletin of the Geological Society of Malaysia, Volume 78, November 2024, pp. 75 - 90
DOI: https://doi.org/10.7186/bgsm78202407

Observations on palynology of the Tukau Formation in northwest Sarawak, Malaysia

Yi Ning Fong, Dominique Dodge-Wan*, Prasanna Mohan Viswanathan

Department of Applied Sciences, Faculty of Engineering and Science, Curtin University Malaysia, CDT 250, Miri, Sarawak, Malaysia
* Corresponding author email address: dominique@curtin.edu.my

Abstract: This palynological study analysed 15 samples of the Tukau Formation, comprising intensely bioturbated sandy mudstone and organic-rich mudstones. Diverse vegetation types, including hinterland, mangroves, back mangroves, and montane regions, characterise the landscape of the region during the Tukau sediment deposition. Certain palynomorph types, such as *Rhizophora* type, *Laevigatosporites* sp., *Elaeocarpus* type, Euphorbiaceae, and *Verrucatosporites usmensis* (Stenochlaena), dominated the pollen assemblage, which represents the ancient landscape at that time. The influx of non-mangrove palynomorphs from the hinterland, likely transported by water, underscores the role of fluvial processes in controlling pollen distribution. Notably, the presence of age-specific marker pollen, such as *Florschuetzia levipoli, Florschuetzia meridionalis*, and *Florschuetzia trilobata*, confirms the age of the formation as Middle Miocene or younger. The presence of *Acrostichum aureum* pollen suggests a warm and humid tropical climate. Recognition of mangrove pollen from both front and back mangrove vegetation suggests deposition in the seaward region of the coast with significant tidal influences.

Keywords: Tukau Formation, palynomorphs, clastic sediments, palaeoclimate, Sarawak

INTRODUCTION

Onshore Sarawak is subdivided into three tectonostratigraphic zones: Kuching, Sibu, and Miri Zones (Madon, 1999). These three zones are separated by the Lupar Line and the Tatau-Mersing Line, and their age gets younger northward, the Miri Zone being the youngest (Upper Eocene to Recent) (Liechti *et al*., 1960; Madon, 1999). The formations in the Miri zone include Rajang Group, Mulu, Kelalan, Tatau, Melinau Limestone, Nyalau, Setap Shale, Subis Limestone, Lambir, Belait, Tukau, Miri, Seria, Bergrih and Liang Formation (Jong & Kessler, 2019). According to Lee *et al*. (2004), the Tukau Formation is of Late Miocene to Pliocene age.

Previous research on the Tukau Formation focused on the provenance, weathering, sedimentology, palaeoenvironment, and tectonic settings of the sediment source based on fieldwork, petrology, and geochemistry analyses (e.g., Banda & Honza (1997); Hutchison (2005); Nagarajan *et al*. (2014); Kessler & Jong (2015); Togunwa (2015); Togunwa *et al*. (2015); Kessler & Jong (2016; 2017a; 2017b); Nagarajan *et al*. (2017a; 2017b); Togunwa & Abdullah (2017); Dayong (2018); Collins *et al*. (2020)). Although the Tukau Formation has been extensively studied in most aspects, not much has been done on the palynology of the Tukau Formation. Fossil pollen in the Tukau Formation has garnered limited attention. A study of the palynomorphs in the Tukau Formation may resolve some research questions raised by other authors, e.g., the processes responsible for the rapid sedimentological shifts within the Tukau sequence (Kessler *et al*., 2023). While extensive palynological research has been conducted in various parts of Sarawak and on different formations (e.g., Jones & Pearce (2015); Murtaza *et al*. (2018); Konjing *et al*. (2022)), more investigation should focus on the Tukau Formation. Hence, based on palynological data, this study aimed to better understand the palaeo-ecological history and depositional environment of the Tukau sediments.

GEOLOGICAL SETTING OF THE TUKAU FORMATION

The Tukau Formation is part of the Neogene succession in the Baram Delta Province (BDP), which comprises the Setap Shale, Lambir, Miri, Tukau and Liang formations (Togunwa *et al*., 2015). The Neogene successions comprise a 9 to 12 km thick sequence of primarily progradational to strongly aggradational coastal-deltaic to shelf deposits (Sandal, 1996), which is possibly a storm-flood-influenced deposition (Collins *et al*., 2017; 2018). The BDP evolved as a deltaic province from the Middle Miocene to the present day, from a foreland basin to a shelf margin (Morley *et al*., 2003; Collins *et al*., 2017; 2018). Some researchers combined the

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

Lambir and Tukau formations due to their lithostratigraphic similarities and uncertain ages (e.g., Banda & Honza (1997); Collins *et al*. (2020)). In this study, the formation boundaries mapped by Liechti *et al*. (1960) are used to differentiate Lambir and Tukau as separate formations. Kessler & Jong (2017a) summarised the prominent unconformities in the greater Miri area. Two unconformities occur between the Tukau Formation and the younger sediments: 1) an Intra-Pliocene Unconformity (IPU) between Tukau and the overlying Liang Formation; (2) and a Lower Pleistocene Unconformity (LPU) between Tukau and overlying coastal terraces of coffee rock and lignitic materials.

The age of the Tukau Formation was reported as T_f to T_{gh} (equivalent to Middle Miocene to Pliocene) based on the strike correlation with the fossiliferous Miri and Seria formations (Wilford, 1961). Hutchison (2005) assumed the Tukau Formation was deposited during the Late Miocene to Early Pliocene. Stratigraphically, it is the time equivalent of the *Triloculina 16* zone and the *Bolivinita 1* horizon A of the Seria Formation based on Rotalias, *Bolivina 1,* and other forms found in the upper part of the formation in the Miri-Tudan area (Liechti *et al*., 1960). The thickness of the Tukau Formation, as determined in borehole sections, varies considerably (Liechti *et al*., 1960; Wilford, 1961); approximately 2700 m in the Bakong Hills, 1160 m in the Bakam area, and 850 m in the offshore exploration wells, Siwa-1 and -2 (Liechti *et al*., 1960; Wilford, 1961) (well locations are shown in Figure 1). Bakong Hills is approximately 70 km south of Miri.

The Tukau Formation is relatively heterolithic compared to other Neogene formations in the Baram Delta Province and was deposited in a coastal plain environment with fluvial and tidal influences (Collins *et al*., 2020). The formation comprises mudstone, massive silt/sandstone, and mud/siltstone containing irregular quartz pebbles (Nagarajan *et al*., 2017b; Togunwa & Abdullah, 2017). Carbonaceous materials are common (Collins *et al*., 2020). The Tukau Formation was previously named 'the Barren Series' because it is generally barren of foraminifera, except for some brackish-water fauna with no chronostratigraphic value: *Ammobaculites* sp., *Glomospira* sp., *Haplophragmoides* sp. and *Trochammina* sp. (Liechti *et al*., 1960; Wilford, 1961). Collins *et al*. (2020) listed the ichnofossils found in the formation (combining Lambir and Tukau formations). Abdul Hadi *et al*. (2017) and Nasir *et al*. (2018) studied the sedimentology and palynological aspects of the Lambir Formation, which we recognise as the Tukau Formation based on the geological boundaries of Liechti *et al*. (1960) (see Figure 1). Based on the acme of *Zonocostites ramonae* (*Rhizophora*) and a high concentration of back mangrove pollen, the authors concluded that the sediments were deposited in a back mangrove swamp. Previous pollen analyses also suggest a Middle to Late Miocene age for the sediments (Abdul Hadi *et al*., 2017; Nasir *et al*., 2018).

MATERIALS AND METHODS

Fieldwork was carried out across the Miri region from September 2021 to April 2023. All beds were measured at

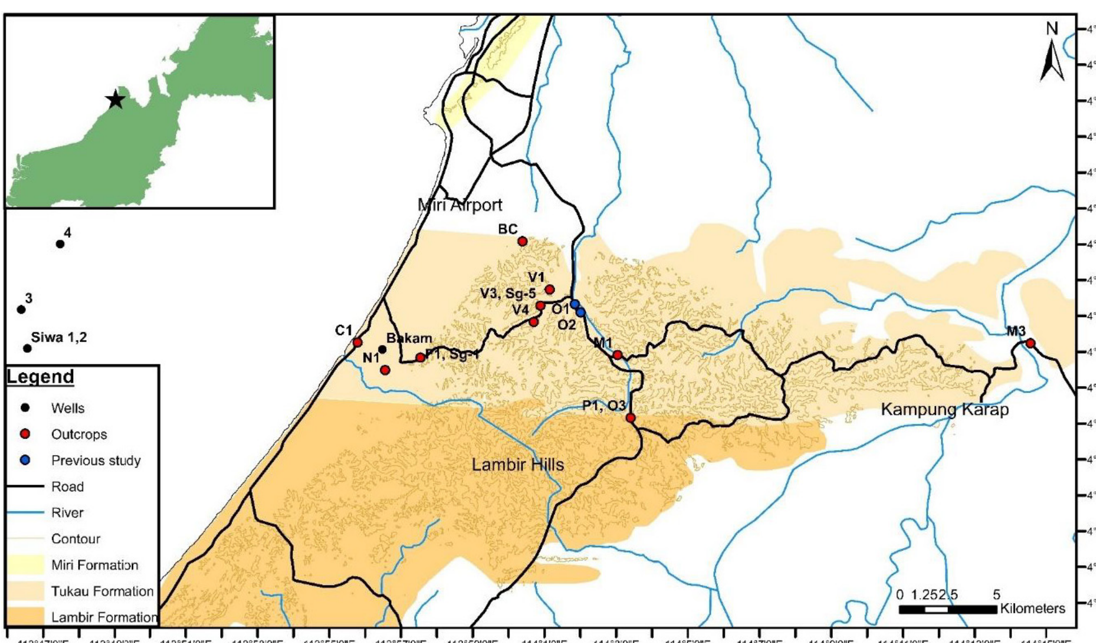

Figure 1: Location of the study area in the Miri region, NW Sarawak. Geological details were modified after Liechti *et al*. (1960). The red dots are outcrops sampled for this study. The blue dots are the location of outcrops from previous studies (Abdul Hadi *et al*., 2017; Kessler *et al*., 2023). Locations of Sg-1 and Sg-5 are on the map as per Kessler *et al*. (2023), and the location of O1, O2, and O3 are following Abdul Hadi *et al*. (2017).

each site, and the sedimentary structures and ichnofossils were carefully examined and recorded as part of a broader sedimentological study of the Tukau Formation. Bioturbation Index (BI) was utilised to quantify the degree of sediment bioturbation. These geological features were systematically recorded to their respective log heights, ensuring a precise correlation between observed characteristics and the vertical positioning within the stratigraphic sequence. The graphic logs of the studied outcrops are shown in Figure 3. Log heights represent the cumulative true bed thicknesses measured upwards from the base of the oldest bed in the outcrop.

For palynology, fifteen samples weighing 20g each were collected from 10 outcrops (see Figure 1 and Figure 3). The outcrop descriptions are included in Section 4, where the sample origins and geology of each outcrop are summarised. All the samples were collected from carbonaceous mudstones, where palynomorphs are more likely to have been preserved (Bercovici & Vellekoop, 2017), except one sample which was collected from an intensely bioturbated sandy mudstone. Only fresh rock beneath the soil and weathered surfaces were sampled. Different clean spoons were used for sampling across various beds and outcrops to prevent cross-contamination.

The samples were prepared, identified, and analysed by Orogenic Resources Sdn. Bhd. Hydrofluoric and hydrochloric acids were used to remove all silicates and carbonates in the rock samples, whereas the heavy liquid separation method was used to separate organic material from the residue. The presence and quantity of each palynomorph in the sample were recorded (during the analysis by Orogenic Resources). Photomicrographs of some palynomorphs were captured using a light microscope equipped with a 100x oil immersion objective lens and a 10x eyepiece (by the first author). Palynomorph colours were visually compared to Munsell colour standards (Pearson, 1984). Thermal alteration index ranging from 1 to 5 (Staplin, 1969) was utilised, whereby lower values reflect low thermal alteration and higher values indicate increased thermal alteration.

The study area shows a northward-younging trend with an average strike and dip of [069/19NW]. The youngest sample in this study is from the Bluepond outcrop (BC). The oldest is from the Lambir 1 Outcrop (P1), probably the same outcrop numbered O3 by Abdul Hadi *et al*. (2017).

OUTCROP DESCRIPTION

Bluepond outcrop (BC)

This site is located at the upper boundary of the Tukau Formation which is based on geological map in Liechti *et al*. (1960). The profile is 15.3 m thick and is characterised by alternating sandstone, mudstone and heterolithic beds at different intervals. The first 2 m of the section mainly comprised heterolithic beds containing plant materials and burrows. The central part of the section (until 9.5 m) comprises thick, parallel laminated sandstone, with minor bioturbation at the bottom, with a BI of 1 to 2. The sandstone is medium to coarse-grained, friable, and pale yellowish to greyish. The top portion of the section is characterised by alternation of sandstone, mudstone and heterolithic beds. Plant materials are common in heterolithic beds. Flaser, wavy and lenticular laminations and beddings are also regularly found. Sample S1 was collected from a laminated mudstone bed with carbonaceous materials.

Rait 1 outcrop (V1)

Outcrops along Sungai Rait Road are called the Upper Tukau Formation (Kessler *et al*., 2023). In this study, four sites along Sungai Rait Road were selected, including Rait 1 (V1), Rait 2 (V3), Rait 3 (V4), and Chicken Farm (F1). The profile is 20.7 m thick and consists of alternating sandstone, mudstone and heterolithic beds at different intervals. The sandstone is medium-grained to pebbly. Some lunate rippled surfaces were observed. See Figure 2A for the upper section of this outcrop. Plant materials are typically observed in mudstone and heterolithic beds. Iron concretions are common at the base of the section. The BI of this site is 0 to 2, except for an intensely bioturbated siltstone bed at a log height of approximately 7 m. Two samples (S2 and S3) for palynology analysis were collected from this site, and both samples are laminated mudstone with carbonaceous materials.

Rait 2 outcrop (V3)

The profile is 19.7 m thick, and the first 5.5 m of the section comprises heterolithic beds gradually changing into sandstone, followed by mudstone beds. The central part of the section (until 10.5 m) is characterised by thick sandstone. Parallel and planar cross-laminations are observed. The top portion consists of alternating sandstone, mudstone and heterolithic beds at different intervals. Plant materials are commonly present in mudstone and heterolithic beds. A shark tooth fossil was found in this outcrop at a log height of approximately 17.6 m. Samples S4 and S5 were collected from laminated mudstone beds with carbonaceous materials and BI of 1.

Rait 3 outcrop (V4)

The profile is 18.2 m thick, and the lower part of the profile is characterised by thick, parallel-laminated, medium-grained sandstone with simple burrows. The upper part of the profile comprises an alternation of sandstone, siltstone, mudstone, and heterolithic beds at different intervals. Flaser, wavy and lenticular laminations and beddings are also regularly observed in heterolithic beds. Trace fossils are unidentifiable, especially in the intensely bioturbated beds. Plant materials are found in almost all beds. Sample S6 was collected from an intensely bioturbated mudstone bed with BI of 5.

Church outcrop (C1)

Outcrop C1 comprises mudstone, sandstone with different sedimentary structures, and heterolithic beds.

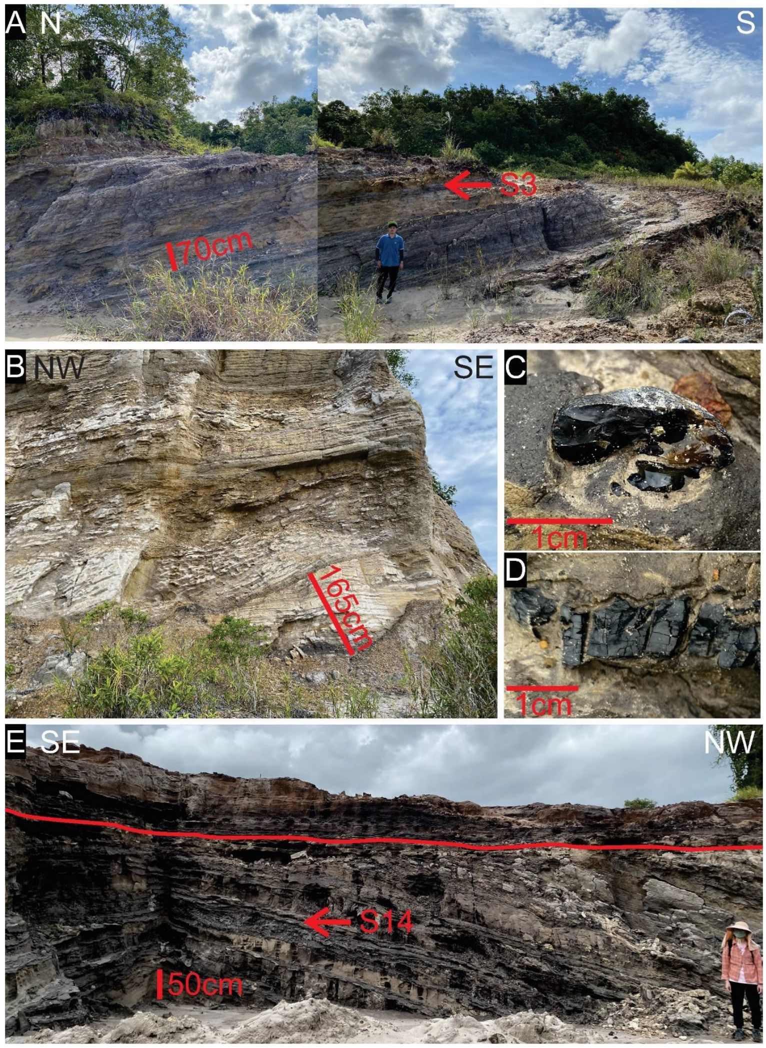

Figure 2: A, Photograph of the upper section of outcrop V1, with an arrow pointing to the bed where sample S3 was collected. **B,** Photograph showing the basal section of outcrop M3. **C&D,** photographs of plant materials (amber and lignite) in outcrop M1. **E,** Photograph of the outcrop N1 with the red line indicating the unconformity between the Tukau Formation and the younger Pleistocene deposits, with an arrow indicating the bed where sample S14 was collected.

Carbonaceous materials commonly occur in laminae. The first 12.5 m of the section is characterised by alternation of sandstone and mudstone. The sandstone is very fine-grained to pebbly, the majority with parallel laminations, some with trough cross laminations. The overlying section (until 27 m) mainly comprises mudstone with thin beds of sandstone and heterolithic. Some beds are intensely bioturbated. The upper part of the profile mainly consists of medium to coarser-grained sandstone with minor interbeds of mudstone and heterolithic at different intervals. Plant materials are commonly present throughout the sequence. Asymmetrical and lunate rippled surfaces were observed. Pleistocene deposits overlie the Tukau Formation rocks above an angular unconformity. Samples S7, S8, and S9 were collected from laminated mudstone beds with carbonaceous materials.

Marudi 3 outcrop (M3)

Outcrop M3 consists of an alternation of thick sandstone, mudstone and heterolithic beds. The sandstone is medium-grained to pebbly. A lunate rippled surface was found in one of the sandstone beds. Erosional surfaces were observed (see Figure 2B). Plant materials are typically observed in the mudstone beds. The colour change is observed throughout the sequence for different lithologies: light yellowish to greyish for sandstone, dark grey for mudstone, and reddish to brown for weathered beds. Flaser, wavy and lenticular laminations and beddings are regularly observed in the heterolithic beds. The BI for this site is 0 to 2. Samples S10 and S11 were collected from laminated mudstone beds with carbonaceous materials.

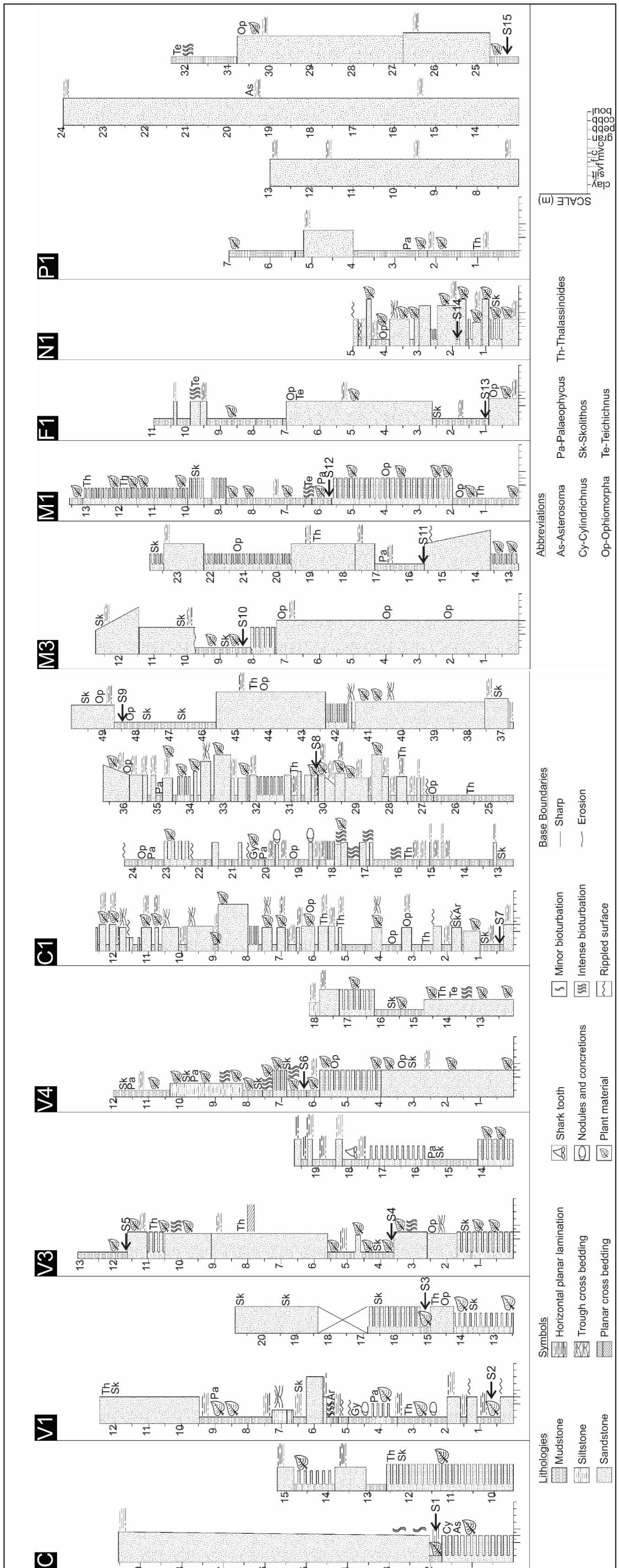

Figure 3: Sedimentary profiles of the studied outcrops in this study, arrows showing the log height of sample collection point for palynological study at each outcrop. See Table 1 for outcrop localities and names.

Table 1: Summary of outcrops and samples analysed in this study. The outcrops are listed from north to south (in approximate stratigraphic order from youngest to oldest from top to bottom). See Figure 3 for the graphic logs.

Outcrops	Sample number(s)	Location (Latitude N, Longitude E)	Remarks
Bluepond (BC)	S1	Sand quarry opposite cemetery, 15 km south of Miri city (4.3016,114.0066)	Sample at a log height of 1.7 m
Rait 1 (V1)	S2, S3	Along Sungai Rait Road, 18 km south of Miri city (4.2789,114.01915)	Sample at a log height of 0.8 m (S2) and 14.7 m (S3)
Rait 2 (V3)	S4, S5	Along Sungai Rait Road, 19 km south of Miri city (4.2714,114.0149)	Sample at log height of 3.5 m (S4) and 11.5 m (S5)
Rait 3 (V4)	S6	Along Sungai Rait Road, 20 km south of Miri (4.2638,114.0117)	Sample at a height of 6.2 m
Church (C1)	S7, S8, S9	In the Bakam area, 18 km south of Miri (4.2543,113.9298)	Sample at log heights of 0.4 m (S7), 30.3 m (S8), and 48.5 m (S9)
Marudi 3 (M3)	S10, S11	Along Sungai Arang-Marudi Road, 53 km southeast of Miri city (4.2539,114.2426)	Sample at log heights of 8.3 m (S10) and 15.6 m (S11)
Marudi 1 (M1)	S12	Along Sungai Arang-Marudi Road, 22 km south of Miri city (4.2485,114.0507)	Sample at a log height of 5.7 m
Chicken Farm (F1)	S13	Opposite a chicken farm, 20 km south of Miri city (4.2473,113.9591)	Sample at a log height of approximately 1 m
Construction (N1)	S14	At Kin Link Villa, 20 km south of Miri (4.2415,113.9427)	Sample at a log height of 1.7 m
Lambir 1 (P1)	S15	Along Pan Borneo Highway, 26 km south of Miri city (4.2193,114.05678)	Sample at a log height of 24.3 m

Marudi 1 outcrop (M1)

Outcrop M1 consists of dominantly dark grey mudstone and heterolithic beds with pale grey sandstone. Plant materials are commonly found (see Figures 2C&D) throughout the sequence as clasts and disseminated fragments in laminae. Flaser, wavy and lenticular beddings are common in the heterolithic beds. Some unidentified trace fossils were also found in M1. Sample S12 was collected from a carbonaceous laminated mudstone bed that has a BI of 2.

Chicken Farm outcrop (F1)

Outcrop F1 is the same as Sg-1/Chicken Farm Cliff in Kessler *et al*. (2023). It is 11 m thick and comprises an alternation of sandstone and mudstone. Plant materials were less observed throughout the sequence compared to other outcrops. The sandstone is fine to medium-grained with parallel laminations. Some simple burrows were observed in the sandstone and mudstone beds. The BI of outcrop F1 is between 0 to 1, except for a bed which is intensely bioturbated. Sample S13 was collected from a laminated mudstone bed with carbonaceous materials.

Construction outcrop (N1)

The profile is 5 m thick and comprises alternating sandstone, mudstone and heterolithic beds. Plant materials were regularly found throughout the sequence. The sandstone is fine-grained to pebbly with parallel and trough cross-lamination. Lunate rippled surfaces were observed in the sandstone and mudstone beds at the upper part of the profile. An angular unconformity was observed between the Pleistocene deposits and the underlying Tukau Formation rocks (see Figure 2E for the outcrop photograph). Sample S14 was collected from a laminated mudstone bed with carbonaceous materials and BI of 1.

Lambir outcrop (P1)

This outcrop is located at the lower boundary of the Tukau Formation (boundary based on geological map in Liechti *et al*. (1960)). It is easily accessible due to the Pan Borneo Highway construction excavation. The sequence comprises alternating thick beds of sandstone and mudstone. Plant materials were more commonly found in the mudstone beds. The sandstone is very fine to medium-grained with parallel laminations. Sample S15 was collected from a laminated mudstone bed with carbonaceous materials and BI of 1.

RESULTS

The studied outcrops are described in Section 4. Palynomorphs observed in the 15 Tukau rock samples are listed in Table 2 and Table 3. Seventy-four (74) different palynomorph types were identified, including 66 pollen types and eight spore types. These palynomorphs originate from diverse vegetation, including mangroves, back mangroves, and montane ecosystems. Figure 4 shows the photomicrograph of some palynomorphs found in sample S14, while Figure 3 shows the graphic log in each studied location.

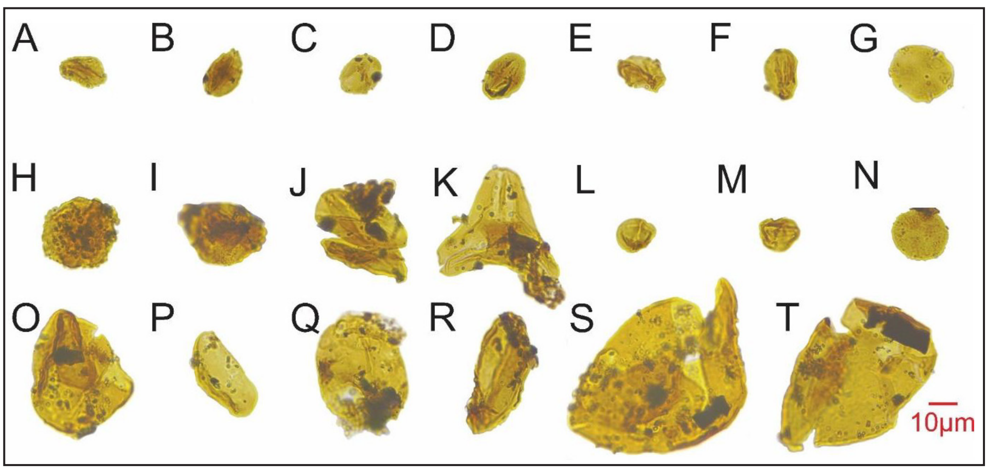

Figure 4: Microscopic images of some typical palynomorphs observed in this study. **A,** Euphorbiaceae. **B,** *Lithocarpus* type. **C,** *Stemonurus*. **D,** *Quercus*. **E,** *Elaeocarpus*. **F,** *Terminalia* type. **G,** *Alchornea*. **H,** *Gonystylus*. **I,** *Barringtonia*. **J,** Magnoliaceae. **K,** Loranthaceae. **L&M,** *Rhizophora* type. **N,** *Brownlowia* type. **O,** *Acrostichum aureum* (folded). **P&Q,** *Laevigatosporites* sp. (Polypodiaceae). **R,** *Polypodiisporites* sp. (Polypodiaceae). **S,** *Cyathidites* sp. (Cyatheaceae). **T,** Palmae (folded). **A-K** are derived from hinterland origins. **L-O** are derived from mangrove/back mangrove palynomorph origins. **P-S** are spores. **T** can be derived from hinterland or mangrove palms.

Table 2: Summary of palynomorph distribution in the analysed samples based on their ecological origins. The outcrops/samples are arranged in approximate order from youngest BC/S1 to oldest P1/S15.

Outcrop	BC	V1		V3		V4	C1			M3		M1	F1	N1	P1
Sample	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**
Mangrove/ Back Mangrove	16	32	24	7	6	23	22	6	20	8	20	17	12	27	75
Hinterland	69	72	72	12	17	106	19	10	52	31	59	76	65	67	24
Spores	19	26	14	3	6	25	17	7	28	14	20	22	14	11	7
Seasonal/ Montane	5	8	3	0	1	2	4	4	3	1	4	6	11	0	2
Total number of grains	109	138	113	22	30	156	62	27	103	54	103	121	102	105	108

Table 3: Detailed palynomorph distribution in the analysed samples, including the total grain counts for each species in each sample.

Group	Taxa/Species	BC	V1		V3		V4		C1		M3		M1	F1	N1	P1
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Mangrove / Back Mangrove	*Acanthus*						1							3	3	2
	Acrostichum aureum	1	2	4			1	1	2		1				3	
	Avicennia type	2	5	3	1		3	1		4	1	3	4			
	Brownlowia type	3	3	1			2	4	1		1	2			1	
	Camptostemon					1		1					1			
	Excoecaria agallocha	2														1
	Florschuetzia levipoli		1	2						1	1	3	1			
	Florschuetzia meridionalis		1	3			1		1	2	1	2	2		1	2
	Florschuetzia trilobata	1	1									1	2	2	2	
	Florschuetzia type	1	2								1	1	3	2	2	
	Nypa			1				1								
	Oncosperma		1					1		1						
	Rhizophora type	6	16	10	6	5	15	13	2	12	2	8	4	5	15	70
Hinterland	*Alchornea*					1	1						1	1		
	Alangium	1					1								2	
	Anacolosa	3		1						1		1	1	1	3	
	Arenga	1	2	3	1			1		1		1	2			
	Barringtonia		1	1					1	1		1		1	2	
	Blumeodendron	2	4	3		1	1	2		1		3	4	3	3	2
	Caesalpiniaceae	2		1			1		1		1	3	3		2	
	Calamus type	5	4	3	2	1	5	1	1	7		3	6		2	1
	Calophyllum type		2	3	1		3		1	3	1	1	5	4	3	1
	Campnosperma			2						1		1	1			
	Casuarina type	2	1	1			1			1		2	3	1		
	Chepalomappa type		3	4		1		1	1	1	1	4	2			
	Cycas	1														
	Cyrtostachys	3	2	5		1		1		2	2		4			
	Dactylocladus type	3	4	4		2	7	1		3	1	5	3	3	1	
	Dacrydium													1		
	Dillenia													1		
	Dipterocarpus	2	1	1		1	1			1		1	2	1		
	Durio type		1				1		1		1			1		
	Elaeocarpus type	11	2	3		2	20		1	6	1		4	4	15	1
	Eugeissona type	1	1						1		1		1	2	1	
	Eugeissona minor													1		
	Euphorbiaceae	7	6	6	2	2	4	1		5	1	2	5	5	7	5

Table 3: Continued

Hinterland	*Ficus*	2	1			1	5	2		2	2	1	1	2	1	1
	Garcinia		1	2	1							2	1			
	Gonystylus type		2	1			1		1		1	1		1	1	
	Hibiscus			1			3			1		1	1			
	Ilex type	2	3	3			3			2	1	1	2	2	2	
	Lithocarpus type		2	3			3	1		1	2		1	1	5	
	Loranthaceae															1
	Magnoliaceae	4	4	4			2	1		2	3	5	2	3		2
	Melanorrhoea type		2			1					3	1	2		1	1
	Meliaceae	4					20							7	2	
	Myrtaceae		4				9	2		3	1	4	2	4	8	2
	Nenga		1					1					1			
	Pandanus	1	3	4	1	1				2	2	5	4	1		2
	Papilionaceae	1	1	1		1	1				3		2			1
	Pometia		1	1						1			1			
	Proteaceae		1	3				2	1		1	1	1			
	Quercus type	1	1	2						1		1	3			
	Rubiaceae	1	2	1	1		3					2	1	1		
	Sapotaceae	2	4	3	1		1			1		2	1	3	3	
	Shorea	1												1		
	Stemonurus	4	3	2	2	1	3	1		2	2	3	2	4	3	3
	Taxodiaceae															1
	Terminalia	2					3							3		
	Timonius		2				3	1				1	1	2		
Spores	*Cyathidites* sp. (Cyatheaceae)		2	1					1	2	1	2	1	1	1	
	Stenochlaenidites papuanus							1								
	Laevigatosporites sp.	15	9	5	1	4	21	15	3	22	5	6	12	10	7	
	Lycopodium cernuum					1		1								
	Osmunda									1					1	
	Polypodiisporites sp. (Polypodiaceae)	2	3	3			2		1		1	4	2			
	Pteris type	1	2	2		1							1			
	Verrucatosporites usmensis (Stenochlaena)	1	10	3	2		2		2	3	7	8	6	3	2	7
Montane / Seasonal	*Alnus*	2	2					1		2			1	3		2
	Picea		1						1			1				
	Pinus			1		1										
	Podocarpus		1					2					1	1		
	Tsuga	1														
	Graminae/Poaceae	2	4	2			2	1	3	1	1	3	4	7		

Palynomorph abundance varies across all studied samples, ranging from 22 to 156 grains per sample. The percentage of palynomorphs derived from mangrove or back mangrove sources ranges from 11.8% to 69.4% of total grains per sample. In comparison, palynomorphs from hinterland sources account for 22.2% to 67.9% of the total grains per 20 g sample. Spores comprise between 6.5% and 27.4% of the number of grains per sample, and the percentage of seasonal or montane palynomorphs ranges from 0% to 14.8%. Figure 5 shows the percentage distribution of the palynomorph groups in each sample. The palynomorphs are mainly yellow-orange, with a Thermal Alteration Index (TAI) of 2, indicating they are immature.

A total of 1353 grains were observed in the 15 samples from the Tukau Formation. The dominant palynomorph types observed includes *Rhizophora* type (14%), *Laevigatosporites* sp. (cf. Schizaeaceae, cf. Polypodiaceae) (10%), *Elaeocarpus* type (5.2%), Euphorbiaceae (4.3%), and *Verrucatosporites usmensis* (Stenochlaena) (4.1%).

Rhizophora type pollen is generally used for the zonation of the seaward fringe of the shore. The parent plant of *Rhizophora*-type pollen (see Figures 4L&M) is the *Rhizophora* tree, the most representative mangrove genus. It is commonly found in the seaward part of the sheltered tropical and subtropical shorelines, more abundant in the intertidal zone (Kathiresan & Bingham, 2001; DeYoe *et al*., 2020). *Laevigatosporites* sp. (cf. Schizaeaceae, cf. Polypodiaceae). *Laevigatosporites* sp. represent spores from the modern families Dryopteridaceae, Aspleniaceae, Blechnaceae, Gleicheniaceae, Lomariopsidaceae, Polypodiaceae, and Pteridaceae (Frederiksen, 1980); see Figures 4P&Q for similar pollen from Polypodiaceae ferns. Schizaeaceae are typical terrestrial or epilithic ferns in tropical and warm temperature regions, varying from small to large-sized (Kramer, 1990). Polypodiaceae are predominantly found in tropical to subtropical environments with various habitats, usually small to medium-sized, with at least a terminal glandular cell (Hennipman *et al*., 1990). *Laevigatosporites* sp. are commonly derived from one of the freshwater swamp plants (Yap & Said, 2002). *Elaeocarpus* types are derived from flowering plants that belong to the *Elaeocarpus* genus. The trees of the *Elaeocarpus* genus can be found in various habitats depending on the species and produce a diverse range of fruit types and seeds (Coode, 2004). Euphorbiaceae is derived from a flowering plant commonly found in tropical regions (Webster, 1994) (see Figure 4A). *Verrucatosporites usmensis* (Stenochlaena) are fern spores derived from freshwater swamp habitats (Bolaji *et al*., 2020)

Less dominant species are *Cycas*, *Dacrydium*, *Dillenia*, *Eugeissona minor*, Loranthaceae (see Figure 4K for Loranthaceae), Taxodiaceae, and *Tsuga*, with one grain in each sample. Each species has distinct ecological characteristics and distribution patterns, briefly outlined below. *Cycas* is a genus of cycad, which is one of the oldest branches among the living seed plants, and has a diverse range of habitats, depending on the species in different regions (refer to Hill (1995); Hill & Yang (1999); Lindstrom *et al*. (2007, 2009); Zheng *et al*. (2017)). *Dacrydium* is a conifer from the Podocarpaceae family (Banks, 2004). The distribution of *Dacrydium* species can be affected by altitudinal gradients (Suratman *et al*., 2015). *Dillenia* species is a tree or shrub that commonly grows in warm tropical rainforests and is widely used as an indigenous medicinal plant (Lim, 2012). *Eugeissona minor* is a palm with unusual branching and stilt roots (Holbrook *et al*., 1985). Genus *Eugeissona* comprises six recognised species, four

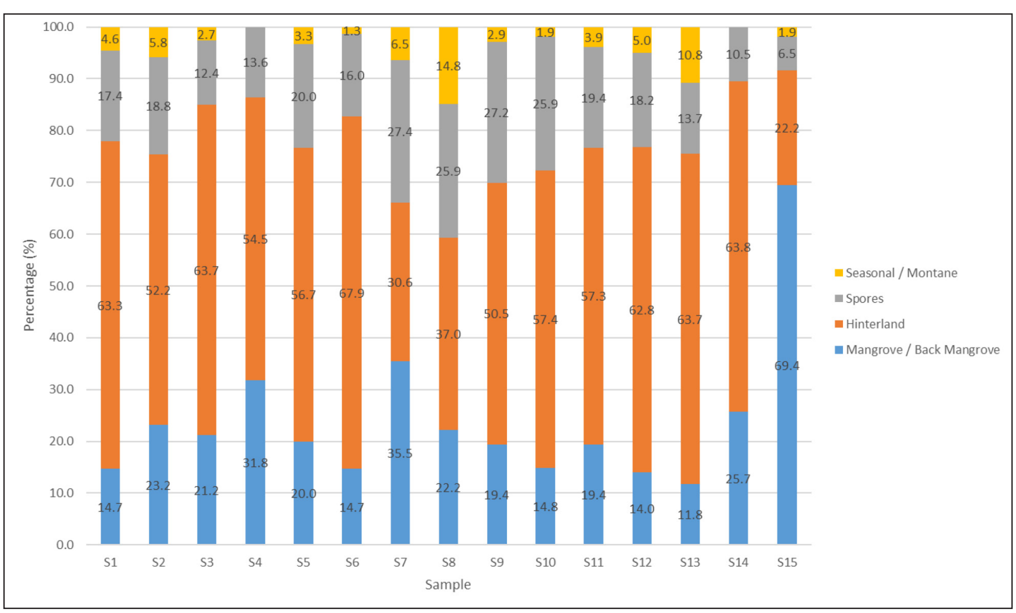

Figure 5: Summary of the percentage of total palynomorphs based on their ecological group. The samples are arranged in approximate order from youngest S1 to oldest S15.

are restricted to Borneo, with *E. minor* being one of them (Stauffer *et al*., 2016). The Loranthaceae family is known for its diversity, thriving primarily in tropical regions but with some representatives adapting to temperate habitats (Vidal-Russell & Nickrent, 2008). These plants are predominantly aerial parasites, attaching to branches or trunks, while only a minority are root parasites (Vidal-Russell & Nickrent, 2008). The resin-producing Taxodiaceae family consists of wind-pollinated coniferous trees, which bear male and female flowers on each tree (Page, 1990). *Tsuga* is a genus in the Pinaceae family, which is a resinous and monoecious pine tree (Simpson, 2010).

Folded grains of *Acrostichum aureum* and Palmae are shown in Figures 4O and T. The presence of *Acrostichum aureum*, which is a polypod fern restricted to the tropical climatic zone (Veldkornet, 2023), indicates that the Tukau sediments were deposited in a warm and humid tropical climate. Palmae pollen were derived from palms, e.g., *Calamus*, *Cycas*, *Nypa*, and *Pandanus*, which first appeared during the Triassic period but at present are mostly restricted to the tropics and subtropics (Mahabalé, 1967; Ferguson & Harley, 1993).

DISCUSSION

A total of 74 palynomorph taxa were recovered from different vegetation types (e.g., conifer, montane, palm), suggesting a diverse vegetation source during the deposition of the Tukau sediments. The palynomorphs are well-preserved, which indicate that they did not undergo thermal alteration (with TAI of 2) or intense weathering. This is consistent with the results of a previous study, which showed that the Lambir, Miri and Tukau Formations are thermally immature (Togunwa & Abdullah, 2017).

The pollen assemblage indicates deposition within a lower coastal plain setting with fluvial influences. The main mangrove pollen groups, including the *Rhizophora* type, *Avicennia* type, and Brownlowia-type, indicate that the ancient coastal environment was dominated by mangrove vegetation. Different mangrove associations can be identified in this study: the seaward pioneer genera (e.g., *Avicennia* and *Sonneratia*), the mid-high tidal flats (e.g., *Rhizophora* type), and the higher tidal zone (e.g., *Nypa*) (Corlett, 2005; Wong, 2005; Kamil *et al*., 2020; Setyadi *et al*., 2021; Konjing *et al*., 2022). The non-mangrove pollen and spores can be transported from the hinterland to the mangrove system either by upstream water or wind (Phuphumirat *et al*., 2016).

The mangrove pollen is tentatively classified as either front or back mangrove vegetation (see Table 4). In Table 4 and Figure 6, the samples S1 to S15 are shown approximately in younging order from south (S15) to north (S1). Different factors may affect the vegetation in these zones, i.e., the degree of tidal flooding, land elevation, and soil water salinity (Limaye & Kumaran, 2013), reflecting distinct ecological conditions in each zone. This contrasts with the observation by previous authors who noted "a high proportion of back mangrove pollen and the acme of *Zonocostites ramonae*" (Abdul Hadi *et al*., 2017; Nasir *et al*., 2018). Over the extended period of sediment deposition within the Tukau Formation, environmental changes may have occurred locally, influencing the distribution of the palynomorphs, as the vegetation diversity is highly dependent on environmental factors (Srivastava *et al*., 2021). Based on only 15 samples from 10 outcrops, we observed no consistent trend in vegetation changes over time. Further comprehensive sampling and in-depth analyses are requisite to ascertain the presence or absence of such trend.

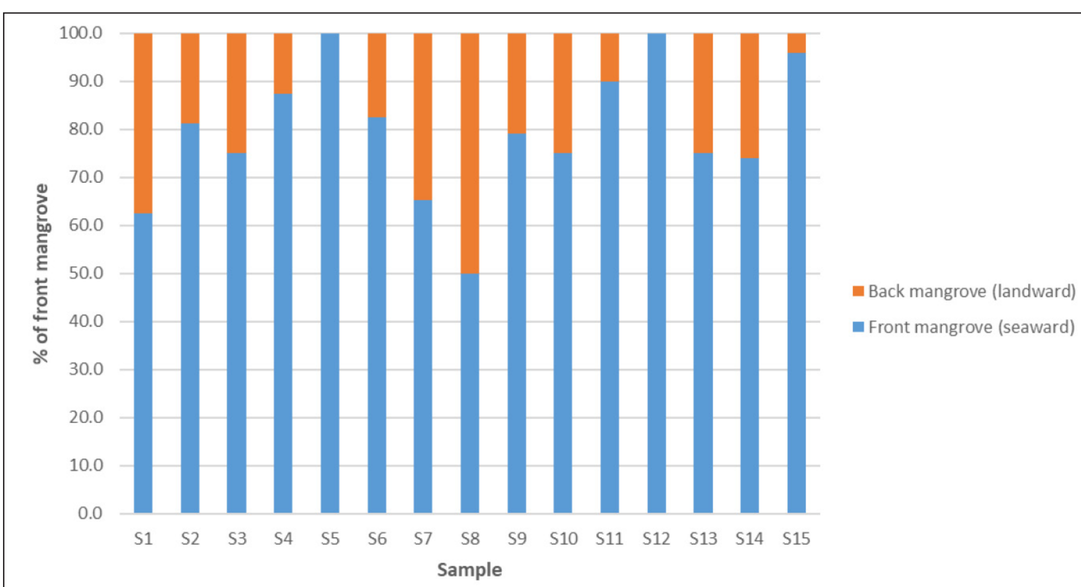

Figure 6: The percentage of front and back mangrove grains in each sample. The samples are arranged in approximate order from youngest S1 to oldest S15.

Table 4: Mangrove pollen in the samples were classified into front and back mangrove zonation.

	Sample	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Front mangrove	*Avicennia*	2	5	3	1		3	1		4	1	3	4			
	Camptostemon					1		1					1			
	Florschuetzia levipoli		1	2						1	1	3	1			
	Florschuetzia meridionalis		1	3			1		1	2	1	2	2		1	2
	Florschuetzia trilobata	1	1									1	2	2	2	
	Florschuetzia type	1	2								1	1	3	2	2	
	Rhizophora type	6	16	10	6	5	15	13	2	12	2	8	4	5	15	70
Total number of front mangrove grains		**10**	**26**	**18**	**7**	**6**	**19**	**15**	**3**	**19**	**6**	**18**	**17**	**9**	**20**	**72**
Back mangrove	*Achrostichum aureum*	1	2	4			1	1	2		1				3	
	Acanthus						1							3	3	2
	Avicennia type				1			1		4						
	Brownlowia type	3	3	1			2	4	1		1	2			1	
	Nypa			1				1								
	Oncosperma		1					1		1						
	Excoecaria agal-locha	2														1
Total number of back mangrove grains		**6**	**6**	**6**	**1**	**0**	**4**	**8**	**3**	**5**	**2**	**2**	**0**	**3**	**7**	**3**
Percentage of front mangrove grains		**63**	**81**	**75**	**88**	**100**	**83**	**65**	**50**	**79**	**75**	**90**	**100**	**75**	**74**	**96**

The pollen from the genus *Florschuetzia* has been widely used for dating in Southeast Asia, where the evolutionary appearance of *Florschuetzia levipoli* in the Early Miocene and *F. meridionalis* in the Middle Miocene is indicated (Morley, 1991). The published ranges of these pollen are shown in Figure 7 (Morley, 2018). The early pollen of *Florschuetzia* is commonly recognised as the ancestor of the mangrove *Sonneratia*. The chronological age and the modern pollen characteristics of these ancestral *Sonneratia* are listed and discussed by Mao & Foong (2013), wherein the *F. levipoli* is considered as an analogue to the modern pollen of *Sonneratia caseolaris*, and the *F. meridionalis* to *Sonneratia alba*. The presence of the age marker pollen of *F. trilobata (Sonneratioid), F. levipoli* (*Sonneratia caseolaris*)*,* and, in particular, *F. meridionalis* (*Sonneratia alba*) confirms that the Tukau sediments are of Middle Miocene or younger age.

CONCLUSION

Palynomorphs recovered from the Tukau Formation represent a diverse range of vegetation types, including hinterland, front and back mangroves, and montane vegetation, which reflects the diversity of the rich vegetation types in the region at that time. The dominance of specific palynomorph types, such as the *Rhizophora* type, *Laevigatosporites* sp., *Elaeocarpus* type, Euphorbiaceae, and *Verrucatosporites usmensis* (Stenochlaena), points to the prevalence of these plant groups in the ancient landscape during the deposition of Tukau sediments.

Acrostichum aureum suggests a warm and humid tropical climate, consistent with previous reports regarding regional climatic conditions. The non-mangrove palynomorphs from the hinterland were deposited into the mangrove ecosystem, suggesting the influence of fluid transport.

The front mangrove pollen is more dominant than the back mangrove, suggesting that the sediments were deposited in coastal areas with significant tidal influence. The presence of the age marker pollen, specifically *Florschuetzia levipoli, Florschuetzia meridionalis*, and *Florschuetzia trilobata*, aligns with previous findings and indicates that the Tukau Formation is Middle Miocene or younger age.

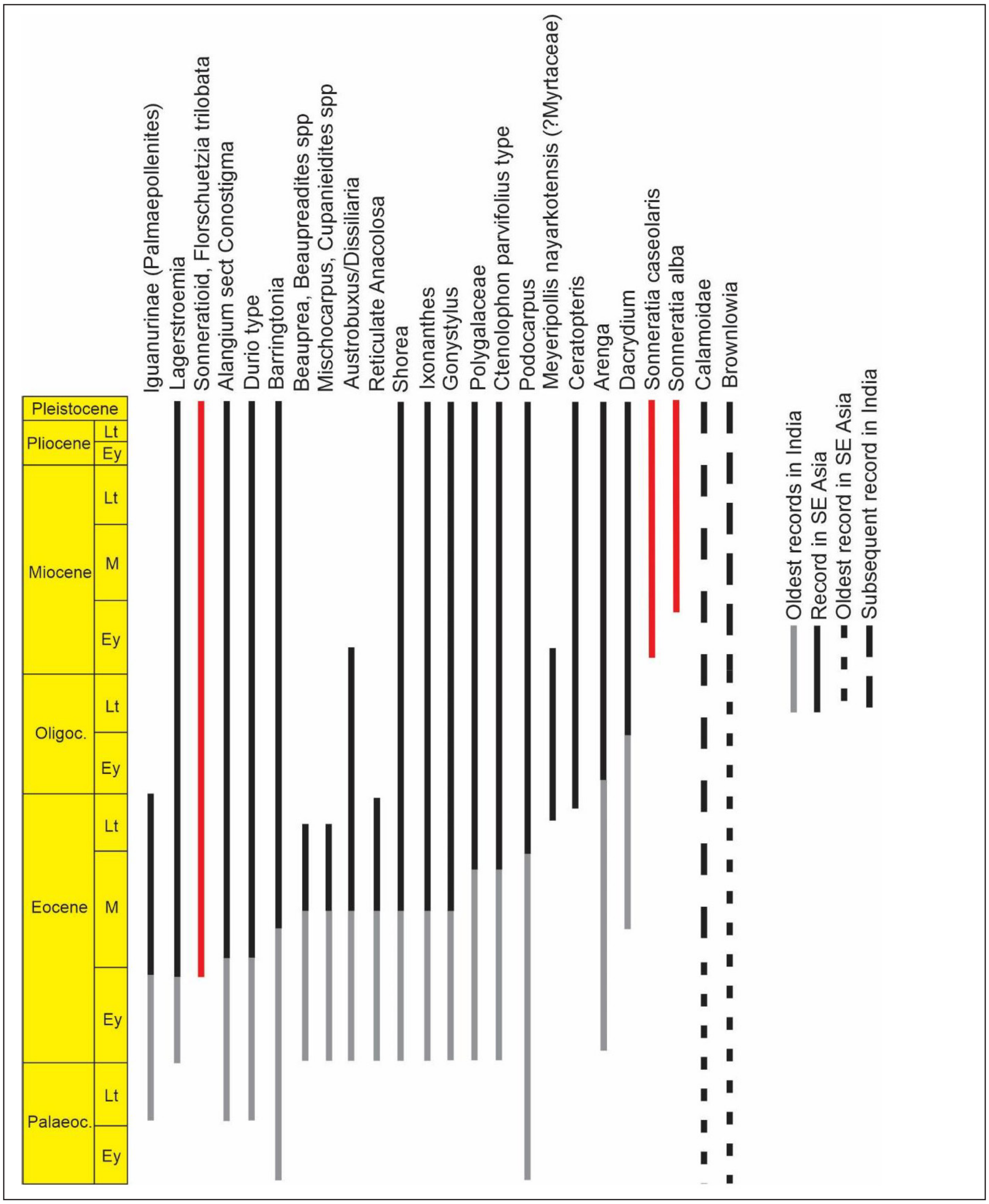

Figure 7: Stratigraphic ranges of pollen that occur in Southeast Asia and India (modified after Morley, 2018). The age marker pollen found in this study are highlighted in red, showing *F. trilobata* (*Sonneratioid*), *F. levipoli* (*Sonneratia caseolaris*), and *F. meridionalis* (*Sonneratia alba*).

This study has contributed to a better understanding of the palaeoenvironmental conditions and the vegetation diversity during the Tukau Formation deposition. A more comprehensive palynological biostratigraphy study could further enhance our understanding of the palaeoenvironment and provide a more detailed picture of the sedimentological, environmental, biostratigraphic and climatic conditions during deposition of the Tukau sediments.

ACKNOWLEDGEMENTS

The authors thank Curtin University for the Curtin Malaysia Postgraduate Research Scholarship (CMPRS) awarded to the first author and Curtin Faculty of Engineering and Science for supporting this study. Also, thanks to Mr. Zainey Konjing and Orogenic Resources Sdn. Bhd. for providing the palynology results. We also thank our esteemed reviewers for their helpful comments to enhance the paper.

AUTHORS CONTRIBUTION

YNF (70%): fieldwork (strata logging, sampling, sample preparation), data analysis, writing original draft; DDW (25%): manuscript review and editing; MVP (5%): manuscript editing.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare relevant to the content of this article.

REFERENCES

Abdul Hadi, A.R., Zainey, K., Ismail, M.S., & Mazshurraiezal, N., 2017. Sedimentology of the Lambir Formation (Late Miocene), Northern Sarawak, Malaysia. Paper presented at the ICIPEG 2016, Singapore.

Banda, R.M., & Honza, E., 1997. Miocene stratigraphy of Northwest Borneo Basin. Bulletin of the Geological Society Malaysia, 40(3), 1-11. https://doi.org/10.7186/BGSM40199701.

Banks, J.C.G., 2004. Tropical Ecosystems Southern Hemisphere Conifers. In: J. Burley (Ed.), Encyclopedia of Forest Sciences. Elsevier, Oxford. pp. 1712-1719. https://doi.org/10.1016/B0-12-145160-7/00185-X.

Bercovici, A., & Vellekoop, J., 2017. Methods in Paleopalynology and Palynostratigraphy: An Application to the K-Pg Boundary. In: K. E. Zeigler & W. G. Parker (Eds.), Terrestrial Depositional Systems. Elsevier, Amsterdam. pp. 127-164. https://doi.org/10.1016/B978-0-12-803243-5.00003-0.

Bolaji, T.A., Ndukwe, O.S., Oyebamiji, A.R., & Ikegwuonu, O.N., 2020. Palynological Age Control and Paleoenvironments of the Paleogene Strata in Eastern Dahomey Basin, Southwestern Nigeria. Sci. Rep., 10(1), 8991. https://doi.org/10.1038/s41598-020-65462-7.

Collins, D.S., Johnson, H.D., Allison, P. A., Guilpain, P., & Damit, A.R., 2017. Coupled 'storm-flood'depositional model: Application to the Miocene–Modern Baram Delta Province, Northwest Borneo. Sedimentology, 64(5), 1203-1235. https://doi.org/10.1111/sed.12316.

Collins, D.S., Johnson, H.D., Allison, P.A., & Damit, A.R., 2018. Mixed process, humid-tropical, shoreline–shelf deposition and preservation: Middle Miocene–Modern Baram Delta Province, Northwest Borneo. Journal of Sedimentary Research, 88(4), 399-430. https://doi.org/10.2110/jsr.2018.19.

Collins, D.S., Johnson, H.D., & Baldwin, C.T., 2020. Architecture and preservation in the fluvial to marine transition zone of a mixed-process humid-tropical delta: Middle Miocene Lambir Formation, Baram Delta Province, Northwest Borneo. Sedimentology, 67(1), 1-46. https://doi.org/10.1111/sed.12622.

Coode, M.J.E., 2004. Elaeocarpaceae. In: K. Kubitzki (Ed.), Flowering Plants Dicotyledons: Celastrales, Oxalidales, Rosales, Cornales, Ericales. Springer, Berlin Heidelberg. 135-144. https://doi.org/10.1007/978-3-662-07257-8_18.

Corlett, R.T., 2005. Vegetation. In: A. Gupta (Ed.), The Physical Geography of Southeast Asia. Oxford University Press, New York. pp 105-120. https://doi.org/10.1093/oso/9780199248025.003.0017.

Dayong, V.A., 2018. Geochemistry and mineralogy of clastic sediments of Tukau Formation: Implications on provenance and tectonic setting. (Master thesis), Curtin University, Malaysia. Retrieved from Espace, http://hdl.handle.net/20.500.11937/75247.

DeYoe, H., Lonard, R.I., Judd, F.W., Stalter, R., & Feller, I., 2020. Biological Flora of the Tropical and Subtropical Intertidal Zone: Literature Review for *Rhizophora mangle* L. Journal of Coastal Research, 36(4), 857-884. https://doi.org/10.2112/JCOASTRES-D-19-00088.1.

Ferguson, I.K., & Harley, M.M., 1993. The Significance of New and Recent Work on Pollen Morphology in the Palmae. Kew Bulletin, 48(2), 205-243. https://doi.org/10.2307/4117930.

Frederiksen, N.O., 1980. Sporomorphs from the Jackson Group (upper Eocene) and adjacent strata of Mississippi and western Alabama (Geological Survey Professional Paper 1084). U.S. Government Printing Office, Washington. 75 p. https://doi.org/10.3133/pp1084.

Hennipman, E., Veldhoen, P., & Kramer, K.U., 1990. Pteridophytes and Gymnosperms. In: K.U. Kramer & P.S. Green (Eds.), The Families and Genera of Vascular Plants. Springer, Berlin Heidelberg. 203-230. https://doi.org/10.1007/978-3-662-02604-5_41.

Hill, K.D., 1995. The Genus Cycas (Cycadaceae) in the Indian Region, with Notes on the Application and Typification of the Name Cycas circinalis. Taxon, 44(1), 23-31. https://doi.org/10.2307/1222674.

Hill, K.D., & Yang, S.L., 1999. The genus Cycas (Cycadaceae) in Thailand. Brittonia, 51(1), 48-73. https://doi.org/10.2307/2666557.

Holbrook, N.M., Putz, F., & Chai, P., 1985. Above-ground branching of the stilt-rooted palm, Eugeissona minor. Principes, 29(3), 142-146.

Hutchison, C.S., 2005. Geology of North-West Borneo. Elsevier, Amsterdam. 421 p. https://doi.org/10.1016/B978-044451998-6/.

Jones, S.E., & Pearce, K.G., 2015. A pollen morphology study from the Kelabit Highlands of Sarawak, Malaysian Borneo. Palynology, 39(2), 150-204. https://doi.org/10.1080/01916122.2014.940472.

Jong, J., & Kessler, F.L., 2019. The Setap Shale Formation on either side of the Baram Line Divide: Facies aspects and tectonic implications. Bulletin of the Geological Society of Malaysia, 67, 53-65. https://doi.org/10.7186/bgsm67201907.

Kamil, E.A., Takaijudin, H., & Hashim, A.M., 2020. Distribution of Mangroves in Kedah, Malaysia: A Remote Sensing and Ground-Truth Based Assessment. IOP Conference Series: Earth and Environmental Science, 549(1), 012005. https://dx.doi.org/10.1088/1755-1315/549/1/012005.

Kathiresan, K., & Bingham, B.L., 2001. Biology of mangroves and mangrove Ecosystems. Advances in Marine Biology, 40, 81-251. https://doi.org/10.1016/S0065-2881(01)40003-4.

Kessler, F.-L., & Jong, J., 2015. Northwest Sarawak: A complete geologic profile from the Lower Miocene to the Pliocene covering the Upper Setap Shale, Lambir and Tukau Formations. Warta Geologi, 41(3-4), 45-51. https://gsm.org.my/articles/702001-101671/.

Kessler, F.-L., & Jong, J., 2016. Shape parameters of clay and quartz clasts in the Neogene Tukau and Lambir Formations, NW Sarawak. Warta Geologi, 42(4), 63-68. https://gsm.org.my/articles/702001-100406/.

Kessler, F.-L., & Jong, J., 2017a. The roles and implications of several prominent unconformities in Neogene sediments of the greater Miri area, NW Sarawak. Warta Geologi, 43(4), 1-8. https://gsm.org.my/articles/702001-101726/.

Kessler, F.-L., & Jong, J., 2017b. Examples of fault architecture and clay gouging in Neogene clastics of the Miri area, Sarawak. Warta Geologi, 43(1), 15-20. https://gsm.org.my/articles/702001-101701/.

Kessler, F.-L., Jong, J., & Nagarajan, R., 2023. Synopsis of Upper Tukau Deposits along the Sungai Rait Road, Miri District, Sarawak, Malaysia. Bulletin of the Geological Society of Malaysia, 75, 73-84. https://doi.org/10.7186/bgsm75202307.

Konjing, Z., Abdul 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. https://doi.org/10.7186/bgsm74202202.

Kramer, K.U., 1990. Schizaeaceae. In: K.U. Kramer & P.S. Green (Eds.), Pteridophytes and Gymnosperms. Springer, Berlin Heidelberg. 258-263. https://doi.org/10.1007/978-3-662-02604-5_44.

Lee, C.P., Leman, M.S., Kamaludin, H., Bahari, M.N., & Rashidah, K., 2004. Stratigraphic lexicon of Malaysia. Geological Society of Malaysia, Kuala Lumpur. 162 p. https://gsm.org.my/articles/702001-101655/.

Liechti, P., Roe, F.W., Haile, N.S., & Kirk, H.J.C., 1960. The geology of Sarawak, Brunei and the Western part of North Borneo (1 ed.). Geological Survey Department, British Territories in Borneo. 360 p.

Lim, T.K., 2012. Edible Medicinal And Non-Medicinal Plants, Volume 2, Fruits. Springer, Dordrecht. 1100 p. https://doi.org/10.1007/978-94-007-1764-0.

Limaye, R., & Kumaran, N., 2013. Biogeographical and palaeoclimate appraisal of mangrove vegetation in South Asia and Southeast Asia in the post Himalayan uplift scenario. Chinese Science Bulletin, 58, 126-133. https://doi.org/10.1360/tb-2013-suppl009.

Lindstrom, A.J., Hill, K.D., & Stanberg, L.C., 2007. The genus Cycas (Cycadaceae) in The Philippines. Telopea, 12(1), 119-145. https://doi.org/10.7751/telopea20085805.

Lindstrom, A.J., Hill, K.D., & Stanberg, L.C., 2009. The genus Cycas (Cycadaceae) in Indonesia. Telopea, 12(3), 385-418. https://doi.org/10.7751/telopea20095826.

Madon, M.B.H., 1999. Geological setting of Sarawak. The Petroleum Geology and Resources of Malaysia, PETRONAS, Kuala Lumpur, 273-290. https://www.researchgate.net/publication/304132933.

Mahabalé, T.S., 1967. Pollen grains in Palmae. Review of Palaeobotany and Palynology, 4(1), 299-304. https://doi.org/10.1016/0034-6667(67)90199-6.

Mao, L., & Foong, S.Y., 2013. Tracing ancestral biogeography of Sonneratia based on fossil pollen and their probable modern analogues. Palaeoworld, 22(3-4), 133-143. https://doi.org/10.1016/j.palwor.2013.09.002.

Morley, C., Back, S., Van Rensbergen, P., Crevello, P., & Lambiase, J., 2003. Characteristics of repeated, detached, Miocene-Pliocene tectonic inversion events, in a large delta province on an active margin, Brunei Darussalam, Borneo. Journal of Structural Geology, 25(7), 1147-1169. https://doi.org/10.1016/S0191-8141(02)00130-X.

Morley, R., 1991. Tertiary stratigraphic palynology in Southeast Asia: Current status and new directions. Bulletin of the Geological Society of Malaysia, 28, 1-36. https://doi.org/10.7186/bgsm28199101.

Morley, R., 2018. Assembly and division of the South and South-East Asian flora in relation to tectonics and climate change. Journal of Tropical Ecology, 34, 209-234. https://doi.org/10.1017/S0266467418000202.

Murtaza, M., Rahman, A.H.A., Sum, C.W., & 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. https://doi.org/10.1016/j.jseaes.2017.11.033.

Nagarajan, R., Jong, J., & Kessler, F.-L., 2017a. Provenance of the Neogene sedimentary rocks from the Tukau and Belait Formations, Northwestern Borneo by mineralogy and geochemistry. Warta Geologi, 43(2), 10-16. https://gsm.org.my/articles/702001-101702/.

Nagarajan, R., Roy, P.D., Kessler, F.-L., Jong, J., Dayong, V., & Jonathan, M.P., 2017b. An integrated study of geochemistry and mineralogy of the Upper Tukau Formation, Borneo Island (East Malaysia): Sediment provenance, depositional setting and tectonic implications. Journal of Asian Earth Sciences, 143, 77-94. https://doi.org/10.1016/j.jseaes.2017.04.002.

Nagarajan, R., Roy, P.D., Jonathan, M.P., Lozano, R., Kessler, F.-L., & Prasanna, M.V., 2014. Geochemistry of Neogene sedimentary rocks from Borneo Basin, East Malaysia: Paleo-weathering, provenance and tectonic setting. Geochemistry, 74(1), 139-146. https://doi.org/10.1016/j.chemer.2013.04.003.

Nasir, M., Abdul Hadi, A.R., Konjing, Z., & Mohamed, M.A., 2018. Tertiary palynomorph from the Lambir Formation (Middle-Late Miocene), north Sarawak, Malaysia. Warta Geologi, 44(3), 230-231. https://gsm.org.my/articles/702001-101746/.

Page, C.N., 1990. Taxodiaceae. In: K.U. Kramer & P.S. Green (Eds.), Pteridophytes and Gymnosperms. Springer, Berlin Heidelberg. 353-361. https://doi.org/10.1007/978-3-662-02604-5_62.

Pearson, D.L., 1984. Pollen/Spore Color Standard, Version #2. Oklahoma Phillips Petroleum Company, Exploration Project Section, Bartlesville.

Phuphumirat, W., Zetter, R., Hofmann, C.-C., & Ferguson, D.K., 2016. Pollen distribution and deposition in mangrove sediments of the Ranong Biosphere Reserve, Thailand. Review of Palaeobotany and Palynology, 233, 22-43. https://doi.org/10.1016/j.revpalbo.2016.06.007.

Sandal, S.T., 1996. The geology and hydrocarbon resources of Negara Brunei Darussalam. Brunei Shell Petroleum Company, Brunei Darussalam. 243 p.

Setyadi, G., Pribadi, R., Wijayanti, D.P., & Sugianto, D.N., 2021. Mangrove diversity and community structure of Mimika District, Papua, Indonesia. Biodiversitas Journal of Biological Diversity, 22(8), 3562-3570. https://doi.org/10.13057/biodiv/d220857.

Simpson, M.G., 2010. 5 - Evolution and Diversity of Woody and Seed Plants. In: M.G. Simpson (Ed.), Plant Systematics (Second Edition). Academic Press, San Diego. 129-162. https://doi.org/10.1016/B978-0-12-374380-0.50005-1.

Srivastava, J., Manjunatha, B.R., Balakrishna, K., Prajith, A., Manjunatha, H.V., Jose, J., & Kumar, N., 2021. Quantitative pollen-based reconstruction of the vegetation diversity in response to the late-Holocene climate change near Karwar, south-west coast of India. Quaternary International, 599-600, 95-106. https://doi.org/10.1016/j.quaint.2021.03.026.

Staplin, F.L., 1969. Sedimentary organic matter, organic metamorphism, and oil and gas occurrence. Bulletin of Canadian Petroleum Geology, 17(1), 47-66. https://doi.

org/10.35767/gscpgbull.17.1.047.
Stauffer, F.W., Siegert, S., Silberbauer-Gottsberger, I., & Gottsberger, G., 2016. Floral structure in the Asian palm Eugeissona tristis Griff. (Arecaceae: Calamoideae), and description of a new nectary type in the family. Plant Systematics and Evolution, 302(6), 629-639. https://doi.org/10.1007/s00606-016-1292-8.
Suratman, M.N., Hamid, N.H.A., Sabri, M.D.M., Kusin, M., & Yamani, S.A.K., 2015. Changes in Tree Species Distribution Along Altitudinal Gradients of Montane Forests in Malaysia. In: M. Öztürk, K.R. Hakeem, I. Faridah-Hanum, & R. Efe (Eds.), Climate Change Impacts on High-Altitude Ecosystems. Springer International Publishing, Switzerland. 491-522. 10.1007/978-3-319-12859-7_19.
Togunwa, O.S., 2015. Petroleum source rock potential of submarine fan and deltaic cenozoic sequences of Western Sabah and Sarawak, Malaysia. (Doctoral thesis), University of Malaya, Malaysia. Retrieved from http://studentsrepo.um.edu.my/6830/.
Togunwa, O.S., & Abdullah, W.H., 2017. Geochemical characterization of Neogene sediments from onshore West Baram Delta Province, Sarawak: Paleoenvironment, source input and thermal maturity. Open Geosciences, 9(1), 302-313. https://doi.org/10.1515/geo-2017-0025.
Togunwa, O.S., Abdullah, W.H., Hakimi, M.H., & Barbeito, P.J., 2015. Organic geochemical and petrographic characteristics of Neogene organic-rich sediments from the onshore West Baram Delta Province, Sarawak Basin: Implications for source rocks and hydrocarbon generation potential. Marine and Petroleum Geology, 63, 115-126. https://doi.org/10.1016/j.marpetgeo.2015.02.032.
Veldkornet, D.A., 2023. The Influence of Macroclimatic Drivers on the Macrophyte Phylogenetic Diversity in South African Estuaries. Diversity, 15(9), 986.
Vidal-Russell, R., & Nickrent, D.L., 2008. Evolutionary relationships in the showy mistletoe family (Loranthaceae). American Journal of Botany, 95(8), 1015-1029. https://doi.org/10.3732/ajb.0800085.
Webster, G.L., 1994. Classification of the Euphorbiaceae. Annals of the Missouri Botanical Garden, 81(1), 3-32. https://doi.org/10.2307/2399908.
Wilford, G.E., 1961. The geology and mineral resources of Brunei and adjacent parts of Sarawak: With descriptions of Seria and Miri Oilfields. Geological Survey, Borneo Region, Malaysia. 319 p.
Wong, P.P., 2005. The Coastal Environment of Southeast Asia. In: A. Gupta (Ed.), The Physical Geography of Southeast Asia. Oxford University Press, New York, pp. 177-192. https://doi.org/10.1093/oso/9780199248025.003.0022.
Yap, S.F., & Said, U., 2002. Palynological study on a rock sequence at Bandar Tenggara, Johor. Bulletin of the Geological Society of Malaysia, 45, 185-192. https://doi.org/10.7186/bgsm45200228.
Zheng, Y., Liu, J., Feng, X., & Gong, X., 2017. The distribution, diversity, and conservation status of Cycas in China. Ecology and Evolution, 7(9), 3212-3224. https://doi.org/10.1002/ece3.2910.

Manuscript received 19 December 2023;
Received in revised form 11 January 2024;
Accepted 27 February 2024
Available online 30 November 2024