Petrography, Palynology, and Organic Geochemistry of Neogene Paralic Coal, Mukah, Sarawak, Malaysia: Implications For Paleomires, and Peat-Forming Conditions

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Research Article

Keywords: Biomarker, Coal facies, Freshwater swamp, Lithotypes, Microlithotypes, Peat.

Posted Date: October 8th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-952318/v1>

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Abstract

The eight coal seams of Neogene paralic coals from Mukah coalfield, Sarawak, Malaysia, were investigated using petrographical, palynological, and organic geochemical analyses to describe coal-forming vegetation, conditions during peat development and precursor mires, and their associations in a sequence-stratigraphic context. The petrographic data of the coals implies the existence of oxygen-deficient and water-saturated conditions in the precursor mires. The condition of low mire oxidation was followed by biomass loss from the mires. The Mukah coals are suggested to be deposited in freshwater peat swamps, and the rich preservation of angiosperm pollens indicates that the organic matter in dense and lowland forest vegetation was mostly terrigenous. The overwhelming presence of *Casuarina* and *Calamus* types, suggesting the paleomires were closely linked to Kerapah/Kerangas peat forest and marginally bordered by rattan and supported by the biomarker data. Rheotrophic–ombrotrophic mires were temporarily formed because of water table fluctuations, which strongly depend on ever-wet climate changes and syn-depositional tectonic during the Neogene, resulting in balanced to high peat accumulation and preservation. A maximum thickness of 35m of peat deposits that formed between 10,000 and 175,000 years ago is suggested. The coals are proposed to be influenced by transgressive to initial highstand cycles within the paralic setting.

Introduction

The Mukah area forms the onshore region of the extensively investigated Balingian province, as it contains important petroleum sources and reservoir rocks¹ (Fig. 1a). This offshore, equivalent to the Sarawak basin's onshore stratigraphy, is thought to be between Cycles II and V². In general, the Mukah area is dominated by fluvial-, floodplain-, and estuarine-related coal-bearing deposits³.

The paralic coal from Mukah coalfield, Sarawak is of interest in this study and located between N02.78000° latitude and E112.37129° longitude (Fig. 1b). The coal is of the Balingian Formation and dates from the Early Miocene to Middle Miocene age^{1,3} of the Neogene coal-bearing sequence⁴. Previous work on Mukah coals has emphasized the quality and re-estimation of coal reserves^{1,5,6,7,8}. The main objective of this study is to provide significant insights into how the composition and stratigraphy of coal at a single locality changes over time in response to changes in accommodation space, compaction, paleoclimate, and/or tectonic subsidence, allowing for the prediction of coal quality and its corresponding relation to the basis of sequence stratigraphy study of the Neogene paralic Mukah coal seams, using petrographical, geochemical, and palynological studies.

Geological setting

The island of Borneo is located in East Malaysia, which is shared by the Malaysian states of Sarawak and Sabah, Kalimantan in Indonesia, and Brunei (Fig. 1a). The island is a product of multiple extensive tectonic events such as accretion of ophiolite, island arc, and microcontinental fragments that evolved during the Mesozoic^{9,10,11,12,13,14,15}. In the Cenozoic, the geology of Borneo was formed primarily by the collision between the continental crusts of Luconia Block and the Sarawak margin during the Late Eocene, followed by collision between the Dangerous Grounds and NW Sabah during the late Early Miocene^{12,16}. This former Late Eocene tectonic collision formed a major unconformity on onshore central Sarawak known as the Sarawak Orogeny, whereas the later late Early Miocene tectonic collision subsequently resulted in deep regional unconformity in offshore NW Sabah and the Sabah Orogeny on onshore western Sabah^{2,16,17,18}. Furthermore, a major accretionary wedge complex was formed during the Late Cretaceous to the Early Miocene, producing the Rajang-Crocker Fold-Thrust Belts and a peripheral foreland basin that extends from Sarawak to Sabah^{2,19,20} (Fig. 1a). The fold and thrust belts are also referred to as the Sibu Zone in onshore Sarawak^{7,21}.

Results

Coal petrography.

The results of petrographic and organic geochemical studies of coals being studied are reported in Tables 1 and detailed petrographic compositional variations in intra-seams in vertical profiles and coal-bearing succession are illustrated in Fig. 2. The Mukah coals are dominated by the huminite group (41.9–91.9%) and mainly consist of humotelinite of textinite (1.5–26.2%) and ulminite (9.5–55.1%). The composition of liptinite does not significantly vary with an average of 2.0–25.3% for all samples. Minor amounts of inertinite (1.4–5.5%) are found and characterized by fusinite, semifusinite, funginite, and inertodetrinite. Mineral matter mainly occurs as clay minerals and is typically dispersed. High amounts of argillaceous mineral matter (up to 50.6%) are reported in certain intra-seam. The amount of pyrite was almost non-existent, so it was not recorded in this study. For microlithotypes, the Mukah coals are characterized mainly by clarite, humite, and duroclarite with an average of 3.5–88.7%, 5.5–61.1%, and 0.0–8.5%, respectively. Liptite, inertite, durite, huminertite, and huminertoliptite were discovered infrequently (<1%). Carbominerite occurs in certain intra-seams and depends on the mineral matter occurrences.

Table 1

The petrographic composition shows values in range and average (avg.) as total (vol.%), and mineral-free basis (vol.%, m.m.f.)/ carbominerite free basis (vol.% Mukah coals. IV factor and correlation coefficients of variables are also shown.

Coal section	MC 01						MC 12						MC 05					
Seams	01/ 04	01/02- 01/03	01/ 01	01/ 04	01/02- 01/03	01/ 01	T	M	B	T	M	B	05/ 03	05/ 02	05/ 01	05/ 03		
Maceral	(vol. %)			(vol. %, mmf)			(vol. %)			(vol. %, mmf)			(vol. %)			(vol. %, n		
Textinite	12.8- 46.7	0.0- 39.8	17.5	12.8- 46.7	0.0- 39.8	17.5	3.8- 34.3	13.6- 38.7	12.4- 34.4	3.8- 36.0	13.6- 39.3	12.4- 34.4	3.2- 14.1	1.5	0.0- 27.4	3.2- 14.1		
Ulminite	4.6- 34.3	8.9- 84.8	41.6	4.7- 34.3	8.9- 84.8	41.6	12.4- 86.9	1.7- 62.8	2.4- 68.4	13.0- 86.9	1.7- 62.8	2.5- 68.4	16.6- 48.6	9.5	2.7- 98.7	16.6- 48.6		
Humotelinite	19.5- 70.1	37.2- 84.8	59.1	20.0- 70.1	42.9- 84.8	59.1	33.3- 90.7	31.3- 76.3	20.5- 83.3	48.9- 90.7	41.0- 76.3	20.5- 83.3	30.7- 51.8	11.0	2.9- 98.7	30.7- 51.8		
Attrinite	0.0- 5.8	0.0- 13.7	0.0	0.0- 5.9	0.0- 14.2	0.0	0.0- 16.1	0.1- 3.1	0.0- 1.1	0.0- 24.1	0.1- 4.9	0.0- 1.5	0.0- 22.9	0.0	0.0- 22.8	0.0- 22.9		
Densinite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
Humodetrinite	0.0- 5.8	0.0- 13.7	0.0	0.0- 5.9	0.0- 14.2	0.0	0.0- 16.1	0.1- 3.1	0.0- 1.1	0.0- 24.1	0.1- 4.9	0.0- 1.5	0.0- 22.9	0.0	0.0- 22.8	0.0- 22.9		
Phlobaphinite	9.4- 24.4	0.0- 17.3	4.7	9.4- 25.0	0.0- 18.2	4.7	0.8- 9.6	8.7- 13.2	0.7- 12.3	0.8- 10.1	9.0- 13.7	0.7- 12.4	4.5- 58.4	25.8	0.0- 53.6	4.5- 58.4		
Porigelinite	4.2- 26.0	1.3- 9.6	12.4	4.2- 26.7	1.3- 10.2	12.4	0.9- 4.8	2.9- 7.6	0.7- 42.8	0.9- 4.8	4.6- 7.6	0.9- 42.8	4.9- 10.6	5.1	0.0- 19.6	4.9- 10.6		
Humocollinite	18.3- 50.4	5.0- 26.1	17.1	18.3- 51.7	5.0- 28.0	17.1	1.7- 12.7	11.7- 20.1	2.6- 47.0	1.7- 15.4	16.6- 20.4	2.6- 47.0	9.4- 69.0	30.9	0.0- 73.2	9.4- 69.0		
Huminite group	72.5- 88.7	51.9- 93.0	76.1	72.5- 88.7	55.4- 93.0	76.1	51.6- 92.4	46.1- 93.1	59.6- 86.2	62.5- 92.4	61.9- 93.1	60.2- 86.2	84.1- 99.7	41.9	71.3- 99.2	84.1- 99.7		
Fusinite	0.0- 1.5	0.0- 7.8	0.0	0.1- 15	0.0- 9.0	0.0	0.0	0.0	0.0- 0.7	0.0- 0.1	0.0	0.0- 0.7	0.0	0.0	0.0- 0.3	0.0		
Semifusinite	0.1- 8.1	0.0- 7.5	1.2	0.0- 8.3	0.0- 7.5	1.2	0.0- 2.7	0.0- 1.1	0.0- 5.3	0.0- 2.7	0.0- 1.3	0.0- 5.3	0.0- 1.8	0.7	0.0- 2.2	0.0- 1.8		
Micrinite	0.0- 0.1	0.0	0.0	0.0- 0.1	0.0- 0.6	0.0	0.0- 0.3	0.0- 0.2	0.0- 0.4	0.0- 0.3	0.0- 0.3	0.0- 0.4	0.0	0.0	0.0- 0.0	0.0		
Macrinite	0.0	0.0	0.0	0.0	0.0	0.0	0.0- 0.3	0.0	0.0- 0.1	0.0- 0.3	0.0- 0.1	0.0- 0.1	0.0	0.1	0.0- 4.3	0.0- 0.1		
Secretinite	0.0- 0.5	0.0	0.0	0.0- 0.5	0.0	0.0	0.0	0.0- 0.2	0.0	0.0	0.0- 0.3	0.0	0.0	0.0	0.0- 0.0	0.0		
Funginite	0.0- 3.1	0.0- 4.9	0.7	0.0- 3.1	0.0- 5.0	0.7	0.1- 0.9	0.1- 1.9	0.5- 1.8	0.1- 0.9	0.1- 1.9	0.5- 1.9	0.0- 1.6	4.7	0.0- 2.1	0.0- 1.6		
Inertodetrinite	0.0- 0.3	0.0- 1.0	0.2	0.0- 0.3	0.0- 1.0	0.2	0.0	0.1- 0.3	0.0- 0.5	0.0- 0.2	0.0- 0.3	0.0- 0.5	0.0	0.0	0.0- 0.4	0.0- 0.1		
Inertinite group	0.6- 10.4	0.0- 10.5	2.0	0.6- 10.7	0.0- 11.1	2.0	0.1- 1.6	0.1- 3.3	1.2- 9.2	0.1- 1.7	0.1- 3.4	1.6- 9.2	0.0- 3.7	5.5	0.0- 8.2	0.0- 3.7		
Sporinite	0.0- 0.8	0.0- 0.2	0.4	0.0- 0.8	0.0- 0.2	0.4	0.3- 6.1	0.0- 3.7	0.0- 6.3	0.1- 6.4	0.0- 3.8	0.0- 6.3	0.1- 1.6	0.1	0.0- 3.0	0.1- 1.6		
Cutinite	0.1- 3.9	0.0- 13.4	7.7	0.1- 3.9	0.0- 13.4	7.7	0.4- 7.4	0.0- 11.4	0.0- 21.3	0.4- 7.8	0.0- 11.5	0.0- 12.8	0.0- 0.7	0.0	0.0- 5.7	0.0- 0.7		
Resinite	0.1- 11.0	1.3- 29.0	3.7	0.1- 11.0	1.5- 31.0	3.7	0.6- 5.5	0.5- 4.4	3.6- 19.1	0.6- 5.5	0.5- 4.5	2.4- 20.6	0.0- 4.3	0.7	0.3- 6.7	0.0- 4.3		
Alginite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
Liptodetrinite	0.0- 3.1	0.3- 3.6	6.1	0.0- 3.1	0.3- 3.8	6.1	0.7- 12.4	0.8- 6.6	1.2- 13.2	1.4- 13.0	1.3- 6.7	1.3- 13.2	0.1- 4.5	0.6	0.1- 2.9	0.1- 4.5		
Suberinite	0.1- 6.0	0.0- 5.0	1.9	0.1- 6.0	0.0- 5.8	1.9	0.4- 8.0	2.0- 5.4	0.3- 6.6	0.4- 8.0	2.0- 8.5	0.0- 6.6	0.0- 0.2	0.2	0.0- 3.5	0.0- 0.2		
Exsudatinite	0.0- 10.9	0.0- 8.9	2.0	0.0- 10.9	0.0- 9.5	2.0	0.1- 4.1	0.6- 6.2	0.2- 6.1	0.2- 4.1	0.6- 8.0	0.2- 6.2	0.1- 0.9	0.3	0.0- 6.4	0.1- 0.9		

T – Top, M – Middle, B – Bottom; IV factor: Inertinite – huminite/vitrinite factor by (inertinite x 100)/(inertinite + huminite).

Coal section	MC 01						MC 12						MC 05				
Liptinite group	0.3-18.4	7.0-41.5	21.8	0.3-18.4	7.0-44.4	21.8	7.5-34.2	6.8-34.2	10.2-36.6	7.5-35.98	6.8-34.7	10.2-37.0	0.3-12.2	2.0	0.8-20.5	0.3-12.2	
Mineral matter	0.0-2.5	0.0-13.3	0.0	-	-	-	0.0-33.6	0.0-36.1	0.0-26.4	-	-	-	0.0	50.6	0.0-8.9	-	
IV FACTOR	-	-	-	0.7-12.1	0.0-13.4	2.6	-	-	-	0.1-5.5	0.1-5.2	1.9-12.3	-	-	-	0.0-3.54	
Microolithotypes	(vol. %)			(vol.%, cmf)			(vol. %)			(vol.%, cmf)			(vol. %)			(vol.%, cr	
Humite	4.5-28.9	5.6-36.6	5.5	5.1-28.9	6.5-36.6	5.5	5.2-68.1	5.7-40.2	1.8-12.5	4.6-68.2	6.0-40.2	1.8-12.5	25.7-96.5	22.9	5.6-96.3	25.7-96.5	
Liptite	0.0-0.6	0.0-3.9	0.0	0.0-0.6	0.0-4.4	0.0	0.0-1.5	0.0	0.0-3.8	0.0-1.7	0.0	0.0-4.3	0.0-0.3	0.6	0.0-3.9	0.0-0.3	
Inertite	0.0-1.3	0.0-2.4	0.0	0.0-1.3	0.0-3.5	0.0	0.0-0.3	0.0-0.5	0.0-0.7	0.0-0.5	0.0-1.1	0.7-0.7	0.0-0.4	1.2	0.0-5.1	0.0-0.4	
Clarite	55.6-88.1	39.5-86.3	88.7	55.6-88.1	57.1-89.7	88.7	19.4-80.8	37.7-80.8	50.3-88.2	31.7-86.2	59.7-84.7	74.5-88.7	3.3-63.5	3.5	3.4-76.4	3.3-63.5	
Durite	0.0-7.5	0.0-6.7	0.0	0.0-8.4	0.0-6.7	0.0	0.0-0.2	0.0-0.2	0.1-1.4	0.0-0.2	0.0-0.4	0.1-1.4	0.0-0.7	3.1	0.0-3.6	0.0-0.7	
Huminertite	0.0-1.6	0.0-1.1	0.1	0.0-1.6	0.0-1.3	0.1	0.0	0.0	0.0-0.1	0.0	0.0	0.0-0.1	0.2-1.3	0.7	0.0-3.0	0.2-1.3	
Duroclarite	1.4-13.7	0.0-14.5	5.7	1.4-13.7	0.0-17.0	5.7	0.1-8.4	0.1-8.4	1.1-18.7	0.1-7.2	0.1-8.8	1.7-18.7	0.0-7.8	0.0	0.0-8.2	0.0-7.8	
Clarodurite	0.0-0.5	0.0-0.3	0.0	0.0-0.6	0.0-0.3	0.0	0.0	0.0	0.0-0.2	0.0	0.0	0.1-0.2	0.0	0.0	0.0-0.1	0.0	
Huminertoliptite	0.0-1.7	0.0-1.5	0.0	0.0-1.9	0.0-1.5	0.0	0.0	0.0	0.0-2.8	0.0-2.0	0.0	0.0-2.8	0.0-0.4	0.0	0.0-0.8	0.0-0.4	
Carbominerite	0.0-11.0	0.0-37.5	0.0	-	-	-	0.1-74.6	0.0-4.8	0.0-43.2	-	-	-	0.0	67.9	0.0-14.5	-	
T – Top, M – Middle, B – Bottom; IV factor: Inertinite – huminite/vitrinite factor by (inertinite x 100)/(inertinite + huminite).																	

The huminite/vitrinite of the coals being studied ranged from 0.39 to 0.49 R%. The accuracy of thermal maturity assessment is also supported by the percentage of non-hydrocarbon compound and biomarker distributions^{22,23}.

Palynological composition.

Twenty-four of the 45 analyzed coal samples contained abundant and well-preserved palynomorphs, some of which are depicted in Fig. 3, and their vertical distribution is shown in Fig. 4. The distributions of the preserved palynomorphs are relatively sparse with only a few moderately rich coal seams. The total assemblage is dominated by angiosperm pollen, particularly from the families Casuarinaceae, Euphorbiaceae, Acanthaceae, Fabaceae, Tiliaceae, Elaeocarpaceae, Arecaceae, Fagaceae, Sapotaceae, Guttiferae, Sonneratiaceae, Crypteroniaceae, Verbenaceae, Anacardiaceae, Palmae, and Myrtaceae. The conifer pollen (gymnosperm) in the assemblage is represented by Podocarpus species in a small amount. The spores of Stenochlaena palustris, Acrostichum aureum, and monolete smooth are found in relatively small amounts in most of the samples, which are ascribed to the families Dennstaedtiaceae and Filicales. The herbs of Magnoliaceae and Poaceae as well as Alnus from montane were also recovered from the samples being studied and are of great importance. Within section MC05, pollens of Rhizophora type, Sonneratia caseolaris, Sonneratia alba, Excoecaria agallocha, Brownlowia type, Xylocarpus, Acanthus, and Avicennia type were not recovered in any of the samples being studied. However, a few of these pollens are present in minor quantities in a few samples within sections MC12 and MC01. Section MC12 displays a high frequency of palynomorph assemblages with a dramatic increase in their occurrence, as seen in sample Nos. 13 and 20. Pollen of Causarina type is found in abundance within the middle section of the seam (No. 20). The upper part of section MC01 shows palynomorph assemblages in considerable abundance, with Stenochlaena palustris, Elaeocarpus, and Arecaceae being the most frequent within this interval.

Bulk geochemical data.

The results of petrographic and organic geochemical studies of coals being studied are reported in Tables 2 and 3. High organic carbon values with TOC ranging from 37.62 to 75.8 wt% and high quantities of extractable organic matter (EOM) and hydrocarbon yields (HC), exceeding 29,000 and 18,000 ppm, respectively, were recorded. These results suggested that the analyzed samples are rich in organic matter and agree well with the plot of TOC content versus EOM (Fig. 5a) and, hence, are capable of producing a substantial amount of gas with little to no oil product (Fig. 5b).

Table 2

Total organic carbon content (TOC), extractable organic matter (EOM), relative percentages of saturates, aromatics and nitrogen-sulphur-oxygen (NSO) components of EOM, ultimate analysis data and atomic ratios (dried-ash free).

Sample ID	TOC	Bitumen extraction and LCC					Ultimate analysis (wt. %)					Atomic ratios (daf)				
	(wt.%)	(ppm of whole rocks)														
		EOM	Sat	Aro	NSO	HC	Sat/Aro	C	H	N	S	O	H/C	O/C	C/N	S/T
MC01																
01/04	37.94-42.68	7306-29788	388-14328	1019-5707	4713-14938	1407-18429	0.12-3.49	49.12-68.12	3.83-5.24	1.43-2.29	0.32-2.08	30.45-56.03	0.77-1.03	0.27-0.94	29.81-37.63	0.01
01/02-01/03	39.90-48.16	3953-12839	419-1182	855-2975	2635-10036	1317-4157	0.29-0.56	26.45-66.92	1.26-3.58	1.29-2.40	0.34-2.35	26.17-69.53	0.64-1.19	0.77-1.10	23.17-37.63	0.01-0.06
01/01	45.48	19367	1377	4367	13623	5743	0.32	64.46	4.22	2.64	1.33	27.35	0.92	0.32	28.48	0.03
MC12																
T	37.62-62.32	2467-9559	254-991	508-2939	1325-6352	763-3930	0.34-0.64	22.90-63.70	1.58-3.70	1.25-2.88	0.18-0.67	30.13-73.59	0.65-0.83	0.42-2.41	21.39-31.44	0.00-0.02
M	53.84-61.44	6233-18474	654-2329	1358-6595	4221-10012	2012-8463	0.29-0.70	54.97-68.47	3.20-3.86	1.96-2.79	0.24-0.34	24.59-39.23	0.76-0.86	0.47-0.54	28.31-32.67	0.00-0.01
B	43.38-62.76	5912-18057	695-2117	1216-7231	859-8709	1911-9348	0.29-1.23	52.28-73.23	4.07-4.39	2.01-2.84	0.24-0.31	19.60-41.08	0.67-1.01	0.20-0.59	30.03-34.20	0.00-0.01
MC05																
05/03	73.30-75.80	12746-14317	801-825	2434-2621	9511-10871	3235-3446	0.31-0.33	62.27-69.66	3.92-4.54	2.53-2.77	0.34-0.57	23.08-30.31	0.67-0.96	0.25-0.37	28.70-29.31	0.00-0.01
05/02	40.24	10369	1407	1889	7073	3296	0.74	38.13	3.08	1.72	0.20	56.87	0.97	1.12	25.91	0.01
05/01	39.68-54.48	10199-23647	736-3034	1963-5876	7500-15643	2699-8910	0.31-0.51	59.80-71.10	4.01-4.78	2.01-3.09	0.20-0.36	20.99-33.57	0.69-0.97	0.22-0.42	26.13-34.67	0.00-0.01
Min. Value	37.62	2467	254	508	859	763	0.12	22.90	1.26	1.25	0.18	19.60	0.65	0.20	21.39	0.00
Max. Value	75.80	29788	14328	7231	15643	18429	3.49	73.23	4.78	3.09	2.35	73.59	1.10	2.41	37.63	0.06
Average	65.68	11634	1410	2711	7513	4121	0.52	74.44	4.88	2.98	0.62	49.22	1.12	0.83	38.16	0.01

Table 3
Molecular composition of the studied coal. Compound number is stated in Appendix I.

Sample ID	m/z 85				m/z 123	m/z 191			m/z 217						
	Pr/Ph	Pr/C ₁₇	Ph/C ₁₈	CPI	R _{dit}	Tm/Ts	Ts/	C ₂₉ /C ₃₀	HCR ₃₁ /	C ₃₂ S/(S+R)	C ₃₁ S/(S+R)	C ₂₉ /C ₂₇ R	Regular steranes		
							(Ts+Tm)						HC ₃₀	C ₂₇	C ₂₁
MC01															
01/04	0.74-2.22	0.41-1.17	0.19-0.51	0.89-1.88	1.40	0.62-1.00	0.50-0.64	2.74-4.31	0.07-0.77	0.37-0.53	0.50-0.81	0.10-0.36	7.97-24.38	6.4-19.0	
01/02-01/03	0.86-3.33	0.92-6.67	0.32-1.00	1.51-3.66	-	0.57-3.00	0.25-0.60	2.80-4.50	0.07-0.36	0.31-0.54	0.55-0.82	0.12-0.59	9.25-34.17	5.2-12.0	
01/01	0.92-3.67	0.42-3.67	0.20-0.50	0.86-2.38	1.14	0.67-2.25	0.31-0.60	2.12-3.16	0.14-0.34	0.28-0.53	0.23-0.76	0.23-0.36	17.53-23.69	6.5-9.8	
MC12															
T	1.19	0.43	0.14	1.50	1.13	1.40	0.42	2.71	0.16	0.52	0.47	0.30	20.27	12.0	
M	2.79	1.06	0.18	1.23	-	0.71	0.59	3.38	0.38	0.48	0.38	0.36	23.05	12.0	
B	3.19-3.67	2.91-2.50	0.31-0.36	1.05-1.89	1.20	0.90-3.20	0.24-0.53	3.47-3.67	0.14-0.24	0.50-0.56	0.55-0.58	0.48-0.49	27.25-27.86	15.0-16.0	
MC05															
05/03	1.83	1.00	0.28	0.97	1.45	1.62	0.38	1.71	0.16	0.51	0.61	0.25	18.57	6.8	
05/02	3.32	4.20	0.46	2.44	-	1.00	0.50	3.97	0.18	0.54	0.73	0.33	19.32	21.0	
05/01	1.00-1.60	0.31-1.26	0.23-0.47	0.89-1.49	1.59	1.25-2.33	0.30-0.44	2.49-2.89	0.07-0.10	0.51-0.53	0.33-0.72	0.19-0.22	15.03-15.66	5.9-15.0	
Min. Value	0.74	0.31	0.14	0.86	1.13	0.57	0.24	1.71	0.07	0.28	0.23	0.10	7.97	5.2	
Max. Value	3.67	6.67	1.00	3.66	1.59	3.20	0.64	4.50	0.77	0.56	0.82	0.59	34.17	21.0	
Average	1.93	1.84	0.40	1.59	1.32	1.51	0.44	3.08	0.20	0.46	0.61	0.27	18.52	11.0	
Pr – Pristane; Ph – Phytane; CPI – Carbon preference index (1): {2(C ₂₃ + C ₂₅ + C ₂₇ + C ₂₉) / (C ₂₂ + 2[C ₂₄ + C ₂₆ + C ₂₈] + C ₃₀)};															
R _{dit} – (19-norisopimarane + isopimarane + 16α-kaurane) / (ent-beyerane + 16β-phyllocladane + 16α-phyllocladane)															
Ts– (C ₂₇ 18α(H)-22,29,30-trisnorneohopane); Tm– (C ₂₇ 17α(H)-22,29,30-trisnorhopane); C ₂₉ /C ₃₀ : C ₂₉ norhopane/ C ₃₀ hopane;															
HCR ₃₁ /HC ₃₀ : C ₃₁ regular homohopane/C ₃₀ hopane; C ₃₁ S/(S+R) = C ₃₁ Homohopane 22S/(22S+22R);															
C ₃₂ S/(S+R) = C ₃₁ Homohopane 22S/(22S+22R); C ₂₉ /C ₂₇ R = Regular steranes C ₂₉ /C ₂₇															

Elemental analysis.

Carbon, oxygen, hydrogen, nitrogen, and sulfur concentrations are 20.94–73.23 wt.%, 19.60–73.59 wt.%, 1.26–4.78 wt.%, 0.18–2.35 wt.%, and 0.18–2.35 wt.%, respectively. The H/C, O/C, and C/N ratios based on a dried-ash-free basis represent the mean value of 1.12 wt.%, 0.83 wt.%, and 38.16 wt.%, respectively.

Molecular composition.

n-Alkanes (m/z 85, Fig. 6a) are mainly distributed between the n-C₁₆ to n-C₃₃ of the coals being studied. n-C₂₇, n-C₂₉, and n-C₃₁ compounds show the highest abundance, suggesting a contribution of higher molecular plant compounds, resulting in a relatively high CPI range between 0.86 and 3.66 (mean 1.57). Pristane (Pr) being more abundant than phytane (Ph), with the ratio of Pr/Ph ranging from 0.09 to 3.67 (mean 1.82). Data show that the Pr/Ph ratio of most samples (80%) is higher than 3.0, whereas the remaining 20% is higher than 0.6, indicating a mainly oxic to a sub-oxic environment with dissolved oxygen in water between 1.0 and 0.1 ml/L. The ratio of Pr/n-C₁₇ varies from 0.31 to 6.67, with an average of 1.77, and Ph/n-C₁₈ ratio ranging from 0.14 to 1.00, with an average of 0.41. The cross plot of Pr/n-C₁₇ against Ph/n-C₁₈²⁴ (Fig. 7a) shows the organic matter source of the Mukah coals to be mainly composed of terrestrial input. Some plots indicate sources from mixed organic matter. This can be defined from the distribution of the n-alkanes and acyclic isoprenoids,

which show substantial occurrences of compounds of high molecular weight from $n\text{-C}_{23}$ upwards in most of the analyzed samples, implying that higher plant molecular compounds are the source inputs^{25,26}. This interference is also in line with the high CPI values, which indicate the paleodeposition in the terrestrial environment²⁵.

Diterpane (m/z 123) distributions were performed to the selected samples (Fig. 6b), indicating ranges from 1.13 to 1.59, with the majority falling into group 3. Samples from the lower section of the Mukah coals (MC05-08, 53) fall into group 2 with R_{dit} 1.59 ($>1.5 R_{\text{dit}}$). This finding implies the coals in the middle stratal section were deposited in mires influenced by a high-water table, whereas fluctuations in the water table may occur in the lower and upper sections of the Mukah coals, as represented by R_{dit} values ranging from 1.13 to 1.59 (mean 1.32). Thus, the climate was probably wetter during the coal formation, as proposed by^{27,28}.

Hopanes are found in significant amounts over tricyclic terpanes (m/z 191; Fig. 6c), predominantly over C_{29} -norhopane, C_{30} -hopane, and $\text{C}_{31}\text{-C}_{32}$ homohopanes. The ratio $\text{C}_{29}/\text{C}_{30}$ hopane values was found greater than 1 (1.17–4.50), indicating a typical source of terrestrial organic matter²⁴. The homohopanes of $\text{C}_{31}\text{-C}_{32}$ from the examined samples are dominated by C_{31} and decrease toward C_{32} homohopanes. The calculated ratio of $\text{C}_{31}\text{R}/\text{C}_{30}$ hopane was high for the low-rank coals of Mukah. 17α (H)-trishomohopane (Tm) and 18α (H)-trishomohopane (Ts) occur at low concentrations, with Tm concentration being slightly higher than Ts, in all analyzed Mukah coals. The ratios of Tm/Ts and Ts/(Ts + Tm) were subsequently calculated, resulting in Tm/Ts values being greater than 0.6 (mean 1.55), suggesting an origin from higher plants, which is further supported by the dominance of tetracyclic over tricyclic.

The distributions of steranes and diasteranes (m/z 217; Fig. 6d) are strongly concentrated. The results indicate a higher concentration of C_{29} sterane (56.50–79.74%), a moderate concentration of C_{27} (7.97–34.17%), and a low concentration of C_{28} (5.23%–21.52%), indicating a mixed land plant and planktonic/algae source²⁹ (Fig. 7b). A standard ratio of $\text{C}_{27}/\text{C}_{29}$ steranes provides values of generally <1 , further implying that the Mukah coals were primarily terrigenous.

Discussions

Thermal maturity of coal. The huminite/vitrinite values indicate lignite to sub-bituminous B for the Mukah coals. The high concentration of NSO compound (65%) obtained from the EOM supports the low to moderate thermal maturity of the Mukah coals (Fig. 8a). Concerning the biomarker distributions of homohopanes C_{31} to C_{32} (m/z 191) and their frequencies, most of the samples being studied display a relative dominance of the “R” over the “S” epimers, indicating a low to moderate degree of thermal maturity^{22,23}. The ratio of C_{32} homohopanes $22\text{S}/(22\text{S} + 22\text{R})$ values range from 0.28 to 0.56 (mean 0.46), suggesting an increase in thermal maturity from the upper to lower coal seams of the Mukah coals. The ratios of C_{29} $\beta\beta/(\beta\beta + \alpha\alpha)$ sterane ranging from 0.03 to 0.50 (mean 0.31) indicate low thermal maturity. The cross plot of $20\text{S}/(20\text{S} + 20\text{R})$ steranes C_{29} and C_{32} $22\text{S}/(22\text{S} + 22\text{R})$ homohopanes (Fig. 8b) shows that the samples being studied were immature to early oil window for the Mukah coals and consistent with the CPI values from odd to even carbon ratios of n -alkanes and $\text{Pr}/n\text{-C}_{17}$ vs. $\text{Ph}/n\text{-C}_{18}$ ^{22,30}.

Paleomires condition. The vertical profile (Fig. 9) shows the Mukah coals enriched with brighter coals, huminite maceral, and clarite from the base to the top seams. The richness of huminite maceral implies the existence of oxygen-deficient and water-saturated conditions in the precursor mire. The apparent lack of dull coal and extremely low inertinite content ($<10\%$) further suggests minimal wildfires or burning and oxidation of the peat. The uncommon occurrences of pyrite and alginite maceral in the coals being studied suggest peat accumulated in freshwater mires with little or no marine influence. Furthermore, the abundance of 80% angiosperm pollen from the coals being studied supports the depositional setting of the Mukah coals as freshwater peat swamp. Generally, arborescent types of plants are predominant, suggesting the characteristic of typified bog facies in the Mukah coals.

The plot of S vs. TOC (Fig. 10) may further describe the development of peat in freshwater mires within topogenous to ombrogenous mire facies, as suggested by³¹. The vertical changes in hydrological regimes (Fig. 9) under which the precursor mires accumulated indicate that the peat-forming mires began with predominantly ombrotrophic mires and eventually ended in rheotrophic mires because of the moderate to rapid rise of the water table during peat accumulation. Temporary development of rheotrophic–ombrotrophic mires may have occurred because of the water table fluctuations. Here, the mires were fed by rainfall and groundwater levels that formed during low to moderate water floods. In most cases, the intervals suggest that waterlogged and rheotrophic origins are related to the occurrence of increased mineral matter, which was probably influenced by the clastic influx from the fluvial input into the mires with rising water table levels. Furthermore, the biomarker distribution and concentration of n -alkanes, high $\text{Pr}/n\text{-C}_{17}$, low $\text{Ph}/n\text{-C}_{18}$, high CPI, high $\text{C}_{29}/\text{C}_{30}$ hopane, high Tm/Ts, high tetracyclic, and high C_{29} sterane support the fact that the source of the organic matter in the Mukah coals is mainly terrestrial. In addition, the plots of $\text{Pr}/n\text{-C}_{17}$ vs. $\text{Ph}/n\text{-C}_{18}$ and atomic ratios of H/C and O/C support the interpretation of organic matter source input, within the sub-oxic to oxic (mainly) condition³² [100] and mainly from Type III kerogens and mixed Type II/III. The ratio of C/N is reported to be greater than 20 and 40 for the investigated samples, further representing the organic input from higher plants³².

Peat-forming vegetation. References of peat-forming vegetation were made to the known ecological data of ancient peats in Malaysia and Brunei indicated by^{33,34,35,36,37}.

The vertical profile (Fig. 4) appears to be predominated by the freshwater peat swamp communities. Meanwhile, the riparian, strand forest, ferns, and mangrove swamp vegetation, which are present in low frequencies, support the ecology within the main lowland forest. The rich preservation of angiosperm pollens suggests that mostly terrigenous inputs are fed into the organic matter in dense and lowland forest vegetation. Overall, the plant communities appear to be represented mainly within freshwater-influenced swamps. The presence of Calamus type, Barringtonia, Palaquium, Pandanus, and Stenochlaena palustris in a few coals being studied represent a former riparian fringe type of forest. The occurrence of mangrove pollens in sections MC12 and MC01 in

small quantities suggests the mangrove pollens were within proximity to the peat swamp forest communities. In contrast, no indication of mangrove influence is recorded in section MC05. Although pteridophytic spores of *monoete* smooth and *Stenochlaena palustris* are found in the entire coals being studied, they are not abundant, suggesting that the plant types were slightly influenced by fern taxa. Moreover, the significant occurrence of *Casuarina* type in the middle part of section MC12 and the small amount of pollen in most of the samples suggests that the Mukah coals were deposited close to the sea under the influence of the strand forest.

The assemblage list recovered in this study is similar to that provided by². Compared with their work, this study yielded approximately similar assemblages of palynomorphs, but in slightly different proportions. The overwhelming presence of *Casuarina* type and *Calamus* type found in Mukah coals further suggests that the peat swamp vegetation was closely linked to Kerapah/Kerangas peat forest and marginally bordered by rattan² even though these pollens were found restricted to certain seam intervals of the coals being studied.

Controls on peat formation. Following the coal-forming models^{38,39,40,41,42,43,44,45}, the authors surmised that different characteristics, architecture, and thicknesses of coal seams are governed by the height of the mire water table, which can be correlated with the transgressive–regressive cycles and, hence, may reflect different system tracts and the significance of key surface of sequence-stratigraphic development in coal-bearing strata. Since the Mukah coals were deposited in a low-lying coastal setting, the groundwater and seawater are hydrologically connected. Thus, the rise in relative sea level can cause the groundwater table to rise in coastal mires, resulting in accommodation space for peat accumulation and upstream deposition of siliciclastics in the study area as the accumulation of peat requires a balance between the rate of accommodation space and peat accumulation (AR/PPR).

Overall, the Mukah coal formation initially occurred at a low water table that allowed the peat to form in peat-forming mires. The peat growth progressed within an overall rising water table (base level). During the peat formation, the creation of accommodation space was moderate to high in response to the rate of change in the base level. A gradual decrease in the rate is expected at the end of peat growth, which allowed the peat to accumulate and maintain a steady pace with the rise in the water table (Fig. 9). In some cases, in particular the upper section of the Mukah coals, the coal formation occurred in the mires during a high-water table, which resulted in high peat accumulation, followed by stable water table conditions, and balanced peat accumulation (Fig. 9). Since the Mukah coals were located in a coastal setting, peat accumulation and preservation were, therefore, associated with the sea-level rise in the paleo-mires, as indicated by the balanced to high AR/PPR. The balance in AR/PPR may cause partially expose paleo-peat bodies in the mires, whereas high AR/PPR may cause the drowning and inundations of paleo-peat bodies. Therefore, it is suggested that the proposed vertical variations in the lithotypes, microlithotypes, and macerals have been controlled by fluctuations in the groundwater level in ancient freshwater mires, thereby resulting in different accommodation/peat preservation rates (Fig. 9). High huminite, low inertinite, and high humite and clarite contents in most of the coals being studied indicate permanently water-saturated peat with balanced to high accommodation creation⁴⁶. The increased liptinite content in the middle section of the Mukah coals indicates a loss of biomass and poor preservation of woody tissues. This may reflect the high preservation of herbaceous vegetation (unstructured material) in the mires. The moderate detrital-mineral matter content in topogenous peats may imply the association of fluvial input with the mires when peat accumulation was unable to keep up with the high rates of accommodation.

In this study, a large number of thin and clean coal seams topped by the tidal flat Begrih Formation⁷ indicates that frequent changes in the peat-forming mires occurred during the accumulation of peat, as evidenced by the temporary development of paleo-peat bodies from ombrotrophic to mesotrophic to rheotrophic and vice versa (Fig. 9). Based on the compositional variations of macerals, sub-macerals, and detrital-mineral matter, these changes were controlled by the moderate to high eustatic rise in sea level that led to a continuous rise in the base level of the region and subsequent rise in the water table of the coastal plain. The variations of coal lithotypes from being coarsely banded to dull in nature support intermittent moderate to high flooding of the fluvial areas, resulting in moderate to high diversification of the macerals/submacerals and moderate to no amount of mineral matter (Fig. 9). Once the mires were formed, they were shielded from substantial clastic deposition, as shown by the moderate to low amounts of clastic material in the seams (Fig. 9). On the basis of these observations, it is suggested that the anticipated stability of the tectonic setting should be excluded during the development of peat. This is supported by the study conducted by⁴⁷, which showed that shifts in the base-level from the Middle Miocene to the Pliocene were highly influenced by eustasy, whereas during the Late Oligocene to Early Miocene, the effects of global sea-level changes were significantly obscured by major tectonic movements. Moreover, the syn-collision between Luconia Block–Dangerous Grounds and Borneo in a rapidly subsiding basin that influenced the formation of Early Miocene Mukah coals² may be more important locally within the depositional basin in controlling the properties of coal seams (i.e., thickness, composition, continuity, and geometry)⁴⁸ and is comparable according to structural characteristics and overall subsidence that occurred on land within the Sarawak basin⁴⁹.

The water table fluctuations in the study, however, are strongly dependent on climate changes, as the influence of relative sea level on the position of regional water tables diminishes further inland^{38,50,51}. The compositional variations of coal lithotypes in Mukah coals have most likely been affected by climatic conditions as the changes may be attributed to the relative sea-level variables of the region. In this study, the obvious absence of major of fire-generated inertinite coal seams, uncommon dull coal, and dulling-upward succession from the base to top coal seams could be related to the ever-wet climate during the Neogene, as the coals being studied may have experienced a widespread rise in rainfall^{52,53,54,55}, which corresponded to the Asian monsoon from the earliest Miocene onward. As previously reported, the structured huminite maceral content (humotelinite) is predominant in the Mukah coals; thus, this observation supports permanently water-saturated mires with a minimum oxidation level during peat accumulation and was influenced by the rise in the water table. Furthermore, the high content of humite-clarite in the entire coals being studied implies that the paleomires have experienced a prolonged rise in sea level, as the signatures are typical of “transgressive” coal⁴⁶. From the petrographic evidence, the Mukah coal peat mires evolved on a wet, low-relief coastal plain in low-lying areas with continuously intermittent moderate to high flooding. The relationship between low inertinite (<10 vol. %), moderate to high R_{dit} ratio (m/z 123), palynology signatures, and low IV factor suggests that a moderate to high-water table had influenced the development of peat in the wet mires while the climate was probably more wet during these periods. The scarcity of gymnospermous pollen (*Podocarpus*) in the coals being studied may further indicate a low contribution from vegetation in the drier or upland areas. This is further supported by², who reported the abundance of *Casuarina*-type pollen associated

with common occurrences of *Dacrydium* in the Kerapah peat swamps, indicating an extremely wet climate. The presence of *Casuarina* type in high frequency is also the case of this study.

Peat accumulation rates vary considerably, particularly with respect to geographical latitudes⁴³. It is proposed in this study that the average peat accumulation rate for low-lying Holocene peats at low latitudes (<10°) ranges from ~2 to ~5 mm/year. According to⁵⁶, the compaction ratio to form low-rank coal seams from their original peats varies between 1.4:1 and 30:1. A ratio of 10:1 has been most commonly used^{57,58,59,60}. Considering that the coals being studied are low in rank and accumulated in a tropical climate, a ratio of 10:1 and peat accumulation rates of 2–5mm/year have been used as conservative estimations, resulting in the original thickness of the peat deposits in the Mukah coals of the Balingian Formation to be between 5 and 35 m and that records peat-forming environments were established between 10,000 and 175,000 years ago. The calculation is strongly dependent on the assumed peat–coal ratio; thus, it shows that the deposition of peat for the Mukah coals occurred within a short time interval.

The Mukah coals in a sequence-stratigraphic context. Some of the key sequence-stratigraphic surfaces have been proposed in the paralic coal beds being studied of the Balingian Formation (Fig. 9). The coal that initially formed at a low water table, overlies the paludification surface (PaS); meanwhile, the gradual termination of the peat represents a give-up transgressive surface (GUTS) in response to an increasing accommodation rate. Furthermore, the coal bed overlies a terrestrialization surface (TeS) at its initiation of peat formation in response to a decreasing accommodation rate, resulting in a GUTS during a stable water table. An accommodation reversal surface (ARS) was identified during the transition of accommodation from decreasing to increasing (balanced to high AR/PPR) or increasing to decreasing (high to balanced AR/PPR).

In this study, the creation of peat accumulation is observed from the difference in the thickness of the coals, which could be linked to the period of the base level changes in the mires. A shorter period of rising base level is assumed to have occurred in the middle and top parts of the section. The lowest coal seam (05/01) within the lower stratal section (MC05) is thicker than the upper and middle coal seam, suggesting that the initial transgressive stage occurred during the formation of the peat³⁸, as the increasing base level increases the rate of accommodation, resulting in the formation of a moderately thick coal bed (Fig. 11). Meanwhile, the development of the middle (05/02) and upper (05/03) coal seams in section MC05 is suggested to occur during the middle transgressive stage (Fig. 11), as their thicknesses are relatively thin and isolated owing to the high accommodation rate during peat accumulation in the mires³⁸. The increase in the rate of change in the base level is supported by the transition to a coarsening-upward unit, which indicates the gradual decrease in the growth of the peat-forming environment into a more clay- and sand-rich deposition (Fig. 11). The greater thickness of the middle section coal at MC12 indicates an overall increase in base level with a moderate water table in the initial stage, and that a late transgressive stage (Fig. 11) may have influenced the formation of peat in the mires³⁸. From the associated sedimentary deposits within the coals, the overall fining upward succession further supports an upward decrease in depositional energy in the mires, thereby decreasing the rate of change in the base level. The occurrences of thin coal seams in the upper section (MC01) indicate that shifts in the base level have occurred over a relatively short period under stable peat-forming conditions (Fig. 11). The continuous formation of thin coal seams of the upper stratal section may suggest that the initial highstand stage (Fig. 11) controlled the low to moderate accommodation rate during the accumulation of peat in the mires³⁸. The overall fining upward cycle indicates that hydraulic energy is low during deposition, thereby supporting the interpretation of gradual overgrowth peat in the mires.

In this study, the overall rising water table level during the growth of paleo-peat bodies suggests that the Mukah coals are deposited in a fluvial system. In the sequence-stratigraphic framework, the architecture of the Mukah coals from the lower to upper section could represent the transition from transgressive (TST) to initial highstand (HST) cycles (Fig. 11). This interpretation is supported by the high content of humite/vitrite + clarite in the entire coals being studied (Fig. 11), which corresponds to a transgressive event influencing the growth of peat in the mires⁴⁹. The interpretation may also be linked to Sarawak's stratigraphic framework analysis⁶¹, the detailed offshore reservoir geological assessment in the Balingian province^{62,63}, and the paleogeographic study of the Balingian Formation⁷, which suggested that shales and coals of offshore Cycles I–II were deposited in an overall transgressive environment^{61,62,63}, while two deposition stages, comprising an early transgressive event, followed by a late regressive episode, influenced the onshore Balingian Formation⁷.

Data And Methods

A total of 45 coal samples were collected from eight coal seams found from the three mining boreholes (MC01, MC05, and MC12) in the Mukah coalfield, Balingian Formation, with bed thicknesses ranging from 1 to 3.5 m (Fig. 2). Prior to sample selection, a detailed analysis of the lithologic and coal lithotypes from the base to the top of the seams was performed in high-resolution observation based on the brightness system indicated by^{64,65}.

Organic petrographic analysis was performed under a plane-polarized reflected light using a Leica DM 6000M microscope and Leica CTR6000 photometry system equipped with fluorescence illuminators. Huminite/vitrinite reflectance measurements were performed in reflected white light under oil immersion with a refractive index (ne) of 1.518 at 23°C. Calibration was performed with a Leuco Sapphire standard with a 0.589% reflectance value. Reported vitrinite reflectances (%Ro) are the averages of 100 measurements per sample and mean random vitrinite reflectance values were calculated using Hilgers Diskus Fossil software. Coal rank determination and maceral classification were based on the technique discussed by⁶⁶. Maceral and combined maceral-microlithotype analyses were used to determine the petrographic composition of polished blocks, as described by⁶⁷. Polished blocks were prepared following the work described by the International Committee for Coal and Organic Petrology⁶⁸. At least 1000-point counts of both analyses were performed, and the identification follows terminology for brown coals developed by ICCP for huminite⁶⁹, liptinite⁷⁰, and inertinite⁷¹ nomenclature. Fluorescence was used for liptinitic maceral identification. Samples with a high sporinite percentage were used for palynological investigation. Analysis procedure and identification of 100–200 counts of palynomorphs on each slide was recorded, following the standards⁷².

Organic geochemistry was performed on the samples' total organic carbon content (TOC, wt.%), using a Multi N/C 3100 analyzer, and element concentrations of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) were studied using an Elementar Analysensysteme GmbH (vario MICRO cube) analyzer.

Selected samples were analyzed for bitumen extraction and biomarker analysis. Source rock characteristic assessments using TOC, bitumen, and hydrocarbon yields are based on the work by^{73,74}. The aliphatic fractions of coal extracts were collected for gas chromatography and gas chromatography–mass spectrometry. Biomarker traces were based on the published work by^{27,28,75,76,77}.

Conclusion

The following conclusions can be drawn from the above:

1. Lignite to sub-bituminous B is defined for the Mukah coals. A high huminite and clarite typified the coals. Little or no alginite and pyrite was observed. The vertical changes in coal-forming vegetation and temporary development of rheotrophic–ombrotrophic mires, as represented by the changing petrographic compositional variation, may have occurred because of the water table fluctuations, which resulted in various ecological groups of plants.
2. The source of the Mukah coals is suggested to have been derived mainly from arborous vegetation, which appears to be predominated by the freshwater peat swamp communities.
3. Rapid subsidence and an ever-wet climate may be attributed to the relative sea-level variation in the region, which may have resulted in the water table fluctuations, balanced to high peat accumulation and preservation ratios during the peat formation in mires, moderate diversification of the composition in the coals, and a large number of thin and clean coal seams coarsely banded to dull coal lithotypes with moderate mineral matter and low inertinite.
4. Two patterns of key sequence-stratigraphic surfaces are mainly proposed in this study: PaS–ARS–GUTS, in response to the increasing accommodation rate (balanced to high AR/PPR), and TeS–ARS–GUTS, in response to the decreasing accommodation rate (high to balanced AR/PPR) during periods of a stable water table.
5. Within the fluvial setting, the formation of peat in the mires could be influenced by TST to initial HST cycles. The Mukah coals may correspond to a minimum thickness of ~5 m of peat deposits, which are expected to have formed between 10,000 and 175,000 years ago.

Declarations

Acknowledgments

The authors are very thankful to the Sarawak Coal Resource coal mining company in the Balingian coalfield, Sarawak, for providing borehole samples. The first author is most fortunate for financial assistance from the research grant YUTP-FRG (Cost Center 0153AA-E82) from Universiti Teknologi PETRONAS. The financial help from the University of Malaya research grant IPPP PG315-2016A is appreciated.

Author contributions

N.S., take part in data analysis and interpretation, wrote the main manuscript text, results and discussions, and funding the work. K.A., W.H., take part in reviewing the manuscript. Z.K, take part in the palynological analysis.

Competing interests

The author (s) declare no competing interests.

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Figures

Figure 1

(A) Geological map of Borneo (modified from Widodo et al., 2010). (B) Location map of the Mukah coalfield and borehole location of this study. Note the red stars represent the sampling locations taken by Sia and Abdullah (2011), Sia et al. (2014), Hakimi et al. (2013), and Murtaza et al. (2018).

Figure 2

Complete vertical profile of the eight coal seams from Mukah coalfield shows upward compositional changes in lithotypes, maceral groups, macerals, mineral matter, and microlithotypes. Note coal seam is labeled as 01/04.

Figure 3

Some of the pollen and spores recovered from the Mukah coal samples being studied. A-B, D, I-M, O-P. fungus, C. Casuarina type, E. Chepalomappa, F. Brownlowia type, G. ?Chepalomappa type, H. Blumeodendron, N. Acrostichum aureum.

Figure 4
Vertical distribution of different palynotaxa recovered in the Mukah coal samples being studied. The palynomorphs have been grouped into peat/freshwater swamp, mangrove, ferns, and others. The coal lithotypes are also shown.

Figure 5
(A) Distribution of extractable organic matter (EOM) and (B) hydrocarbon yield (HC), showing source potential rating and hydrocarbon

Figure 7

Plots of (A) Pr/n-C17 vs. Ph/n-C18 (modified after Lijmbach, 1975) and (B) C27, C28, and C29 of regular steranes, showing the organic matter source input for the analyzed Mukah coals, Sarawak.

Figure 8

Diagrams illustrate (A) ternary diagram of saturates (SAT), aromatic (ARO), and NSO compounds and (B) cross plot of $20S/(20S + 20R)$ C_{29} steranes against $22S/(22S + 22R)$ C_{32} homohopanes, showing their distribution and the thermal maturity level of the Mukah coal samples being studied.

Figure 9

Vertical compositional variations shown are vitrinite (mineral free), inertinite (mineral free), liptinite (mineral free), detrital-mineral matter, and microlithotypes, and interpreted accommodation curves for the Mukah coals, Balingian Formation. On the coal facies diagrams, the solid line represents an accommodation reversal surface (ARS).

Figure 10

A plot of sulfur (wt. %) vs. TOC (wt. %) for the analyzed Mukah coals (after Jasper et al., 2010) shows the peat development within topogenous to ombrogenous mire facies.

Figure 11

Construction of the accumulation progress during different stages in the evolution of the analyzed Mukah coal seams, Balingian Formation, Sarawak.

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