



Geochemical and petrographical characteristics of low-rank Balingian coal from Sarawak, Malaysia: Its implications on depositional conditions and thermal maturity

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ARTICLE INFO

Article history:

Received 1 October 2011

Received in revised form 6 March 2012

Accepted 6 March 2012

Available online 14 March 2012

Keywords:

Calorific value

Maceral analysis

Proximate analysis

Raised mires

Ultimate analysis

Vitrinite/huminite reflectance

ABSTRACT

Geochemical and coal petrographical analyses were undertaken on low-rank Upper Pliocene Balingian coal from Sarawak, Malaysia, in an attempt to reconstruct the conditions during peat accumulation and the subsequent coalification processes. Chemically, the coal in this study is characterised by high moisture, low ash yield and low sulphur content. The low ash yield and low sulphur content, together with the lack of epiclastic partings clearly indicate that it was deposited in ombrotrophic raised bogs. The coal was plotted in the Type III terrigenous kerogen zone of the van Krevelen diagram, with H/C value below 0.9. This shows that the coal was derived from plant materials of terrigenous origin and is still immature for petroleum generation. The petrographical study reveals, nonetheless, the expulsion of early generated hydrocarbons from the disintegration of suberinite, and also from phlobaphinite and cutinite. Petrographically, the coal is dominated by huminite, with low to moderate amounts of liptinite and low amounts of inertinite, pointing to predominantly anaerobic deposition conditions in the paleomires, with limited thermal and oxidative tissue destruction. Most of the studied samples are characterised by low TPI and high GI values, and are plotted on the marsh field of the Diessel's diagram, or it could also originate from decomposed wood in forested swamps. Nevertheless, coals originating from both these sources usually generate high ash yield, which is not the case for the studied coal. This shows that the interpretation as suggested by the Diessel's diagram is not valid for the studied coal. The coal has a mean random huminite reflectance between 0.26 and 0.35%, suggesting a lignite coal rank for the coal. Nevertheless, geochemical classification based on total moisture and calorific value suggests a subbituminous C rank.

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1. Introduction

Coals in Malaysia are present in the Tertiary basins in all three geographical provinces, viz. Sarawak, Sabah and Peninsular Malaysia (Fig. 1). However, most of the coal resources are located in the states of Sabah and Sarawak. As at the end of 2011, total coal resources in Malaysia stood at 1819 Mt, of which 1468 Mt or 80.7% were located in Sarawak, 334 Mt or 18.3% in Sabah, and the remaining 1% in Peninsular Malaysia. The coals range from subbituminous (see also Sections 2 and 5.2.1) to anthracite in rank. Most of the coals are thermal coal; nonetheless coals with coking properties exist in the Bintulu, Silantek, Slimponpon and Maliau coalfields. Despite Malaysia having sufficient coal resources to meet the nation's demand, the country imported a total of 17.03 Mt of coal in 2010 (EIA, 2012), mostly from Indonesia, Australia and South Africa.

Coal was used to be mined from the Sadong, Slimponpon, Labuan, Batu Arang, Enggor, and Durian Chondong basins (Fig. 1), but the mining operations have long been ceased. Coal mining was resumed

in the country with the opening of the coalmine at the Merit-Pila coalfield in 1986. Currently, opencast coal mining is actively being carried out in the Merit-Pila, Mukah and Balingian coalfields, whilst underground mining is being carried out in the Silantek coalfield, producing about 2.5 Mt of coal per year (EIA, 2012).

Exploration for coal in this area was started by Sarawak Shell Bhd. in 1974. However, the company withdrew from the area owing to poor accessibility, and probably also because limited opencast reserves were found. The prospecting work was continued by Buroi Mining Sdn. Bhd. in 1981, but the company too relinquished most of its prospecting areas in 1999, except the area in the northeast corner of the coalfield that had a coal resource of 52 Mt (Yin, 1991). The Geological Survey Department of Malaysia (a government agency now known as the Mineral and Geoscience Department of Malaysia) started evaluating the coal resources in 1991 as a departmental project, and identified a total of 203 million tonnes of coal resources in the eastern part of the coalfield. The area relinquished by Buroi Mining Sdn Bhd. was subsequently taken over by Sarawak Coal Resources Sdn. Bhd. Using the existing data, the company started exploring the area in 2007, with mining being initiated in the same year. Currently, the coal extracted from this area is used to fuel the 270 MW capacity mine-mouth Mukah Coal-Fired Power Station that

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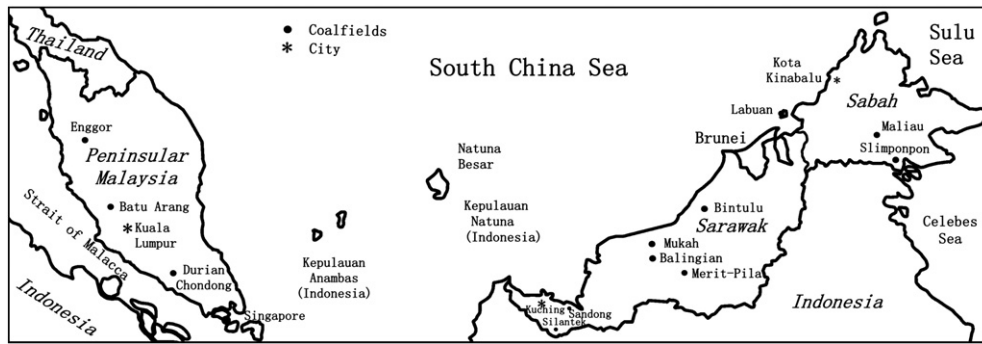


Fig. 1. Location map showing the coal bearing Tertiary basins in Malaysia.

started operation in 2009. The power station is expected to consume 1.2 Mt of Balingian coal a year.

Despite the importance of this coalfield, little is known about the coal, and little published information is available so far. The characterisation of the coal using the integration of conventional geochemical and coal petrographical approaches is the main objective of this study. The investigation is expected to elucidate the depositional conditions and thermal maturity (coal rank) of Balingian coal.

2. Geological setting

Balingian coalfield, covering an area of approximately 410 km², is located in the low-lying coastal plain between the Mukah and the Balingian Rivers of Sarawak, Malaysia. Accumulation of the Balingian coal took place in the Liang Formation during Upper Pliocene. The Liang Formation is unconformably underlain by the Lower Pliocene Begrih Formation in the north and by the Eocene Belaga Formation in the south (Figs. 2 and 3) (Hutchison, 2005).

The Liang Formation has a thickness of approximately 950 m (Fig. 3), and is made up of thick and massive clays, sands, tuffs, coal seams and gravel lenses. The fauna identified in the coal zone include *Ammodiscus* sp., *Glomospira* sp., *Haplophragmoides* sp., and *Trochammina* sp., which suggest a brackish-water environment of

deposition. Outside the coal zone, however, the sediments were deposited in a very shallow, near-shore type of marine depositional environment (Hutchison, 2005). Five coal seams with an accumulated thickness of 22.42 m have been identified in this study. The coal has been classified as lignite and represents the only minable lignite deposit reported in the country; however data of the present study indicates that it is subbituminous C in rank (see also Sections 5.1.1, 5.1.4 and 5.2.1).

The Begrih Formation consists of conglomerates, conglomeratic sandstones, mudstones, shales, tuffs and also a coal seam. The formation contains mixed marine and brackish-water fauna, suggesting depositional conditions that were probably predominantly littoral (Hutchison, 2005).

The Belaga Formation is a highly deformed deep-water turbidity deposit of the Upper Cretaceous to the Middle Eocene age (Hutchison, 2005). The sediments consist of intensely folded thinly interbedded sandstones with shales, mudstones, argillites, and slates.

3. Material and methods

A total of 24 coal samples were collected using the bench-by-bench channel sampling method from all the five coal seams identified in this study. The sampling method applied is in conformity

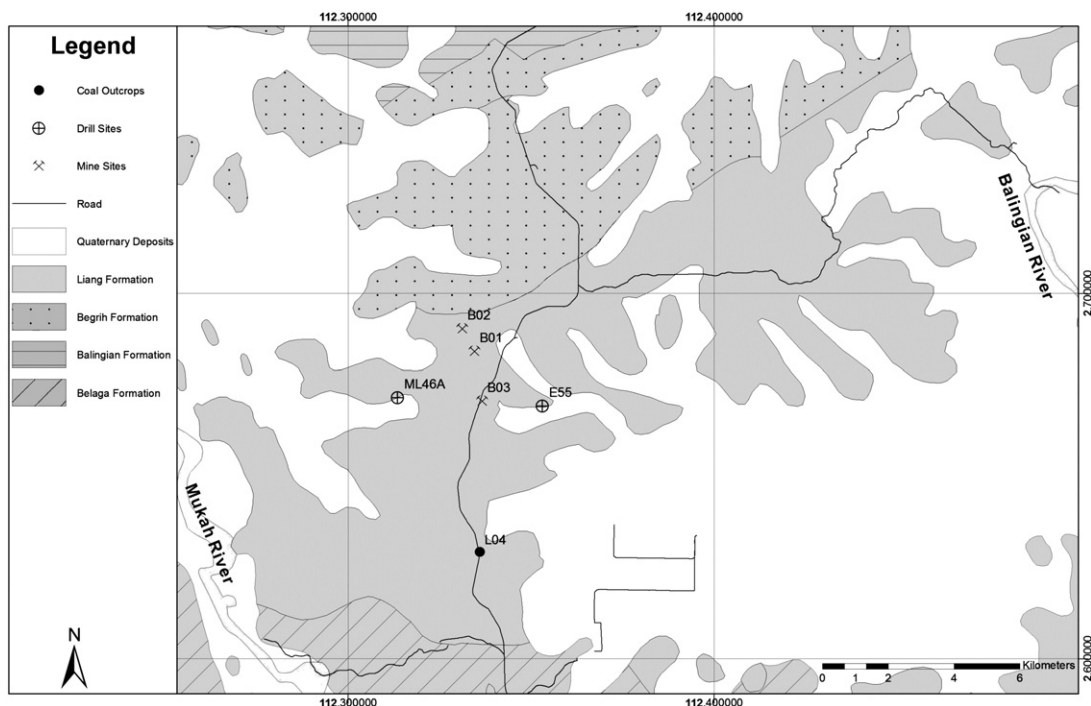


Fig. 2. The geology of the Balingian coalfield and the sampling points (location).

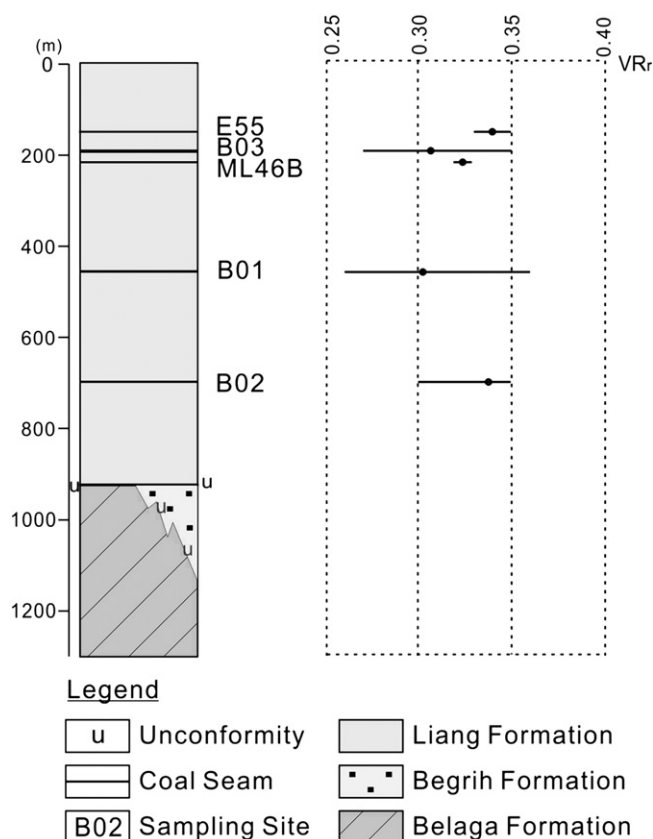


Fig. 3. Generalised stratigraphic column of the study area showing the relative stratigraphic level of the coal seams and the mean random reflectance measurement of ulminite (%).

with Standard Classification of Coals by Rank ASTM D388 (1990). The sampling interval was decided on the basis of changes in coal lithotypes, with each sample representing a single bench sample with a bench thickness of not more than 1 meter.

All the samples were petrographically examined, however only thirteen selected coal samples were geochemically analysed. Geochemical analyses, inclusive of proximate and ultimate analyses, as well as calorific value, were performed at the Accredited Coal Quality Testing Laboratory of the Mineral and Geoscience Department Malaysia (Sarawak). The proximate analysis carried out comprised determinations of moisture, ash and volatile matter using in-house test methods based on ASTM standard and fixed carbon values were calculated by difference.

Three forms of moisture in coal, namely total moisture, equilibrium moisture and air-dried moisture, can be measured by the prescribed standard methods. Information on the various forms of moisture is required for calculating the analysis results to other basis, especially equilibrium moisture which is used as bed moisture or for calculating the analysis results to moist basis for ASTM rank classification. Nevertheless, equilibrium moisture could not be determined in this study, as the laboratory was not equipped for this test. In this study, total moisture (which shows the closest results with bed moisture) was used to convert the analytical results into the moist basis for the purpose of ASTM rank classification. Nevertheless, the requirements of ASTM D388 (1990) were not met despite every attempt having been made in the field to collect samples that were relatively fresh, unoxidised and without visible surface moisture to reduce or eliminate the effect of surface moisture. As such, coal rank determined in this study is considered as an ASTM apparent rank, and not the definitive ASTM standard rank.

The ultimate analysis carried out comprised the determinations of carbon, hydrogen, nitrogen, and total sulphur using the ASTM

standard test methods, and oxygen was calculated by difference. The calorific value was also determined using the ASTM standard test methods for the ASTM coal rank classification system. All the geochemical analyses results were reported in as received basis, unless otherwise indicated.

Measurement of vitrinite/huminite reflectance was carried out using a LEICA CTR 6000 Orthoplan microscope under reflected white light, with $\times 50$ oil immersion objectives using immersion oil with a refractive index (n_e) of 1.518 at 23 °C. A sapphire glass standard with 0.589% reflectance value was used for calibration. Reflectance measurements were determined in the random mode (R_{rand}) on ulminite maceral at a wavelength of 546 nm, and the values reported were arithmetic means of at least 50 measurements per sample. Maceral composition analysis was carried out using the single scan method, where identification of maceral was done using white and blue light illumination in combination. The analysis was based on at least 500 counts on each sample and the results were reported as mineral free volume percentage, unless otherwise indicated. Classification of maceral was done according to System 1994 of the International Committee for Coal Petrology. Since petrographically the vitrinite/huminite reflectance indicates a lignite coal rank (see also Section 5.2.1), the classification for low-rank coal was used in this study.

The formulas proposed by Diessel (1986) to calculate TPI and GI are based on coal facies analysis on the Permian high rank coals in Australia. However, as pointed out by Amijaya and Littke (2005), Tertiary coals are very different in terms of vegetation and climate compared with the Permian coal; as such the formulas proposed by Diessel (1992) fail to show the development of the paleomire in detail. As a result of this, many formulas have also been proposed for application to Tertiary low-rank coals; among others are Davis et al. (2007), Flores (2002), Kalkreuth et al. (1991), Markic and Sachsenhofer (1997), and Singh et al. (2010). The low-rank nature of Balingian coal bears similarity in characteristics to the Tertiary coals from the Western Indonesia in terms of their low ash and low sulphur content, as well as low TPI and high GI values. Moreover, considering the proximity of the Balingian coalfield to the Tertiary Western Indonesian fields, both locations can be expected to have shared a similar climate. As such, the formulas proposed by Davis et al. (2007) for the Tertiary coals of Western Indonesia were used to calculate the TPI and GI in the present study:

$$TPI = \frac{(\text{telohuminite} + \text{semifusinite})}{(\text{detrohuminite} + \text{macrinite} + \text{inertodetrinite})}$$

$$GI = \frac{\text{huminite}}{\text{inertinite}}$$

The relationships between the analyses results were analysed using the SPSS statistical program (Version 16). The relationships between the petrographical parameters were based on all the 24 samples studied, whereas the relationships involve geochemical parameters, particularly the total moisture and total sulphur, were based on the 13 samples available. To eliminate the effect of moisture and mineral matter, total sulphur content used in the statistical analyses was converted into dry mineral-matter free basis prior to statistical analysis.

4. Results

4.1. Geochemistry

The results of the geochemical analyses and the calculated H/C and O/C atomic ratios for the 13 bench samples are shown in Table 1. The minimum, maximum, arithmetic mean and the standard deviations of the geochemical results and the calculated H/C and O/C atomic ratios are summarised in Table 2.

Table 1
Geochemical analyses and the calculated H/C and O/C atomic ratios of Balingian coal.

Sample number	Proximate analysis					Ultimate analysis					GCV	Atomic ratios	
	Moisture		Ash	VM	FC	C	H	O	N	TS		H/C	O/C
	(wt.%)	(wt.%)	(wt.%)	(wt.%)	(wt.%)	(wt.%)	(wt.%)	(wt.%)	(wt.%)	(wt.%)			
	ar	ad	ar	ar	ar	ar	ar	ar	ar	ar	ar	dmmf	dmmf
E55/4	29.9	14.9	3.3	33.0	33.8	47.2	3.29	44.89	1.00	0.27	17.87	0.84	0.23
E55/3	29.3	15.3	2.5	33.4	34.8	48.5	3.25	44.59	1.03	0.13	18.33	0.80	0.23
B03/9	25.5	13.2	1.7	37.3	35.5	51.0	3.49	42.64	0.97	0.24	19.26	0.82	0.25
B03/8	20.8	11.4	1.3	39.3	38.6	55.1	3.80	38.41	1.26	0.13	20.64	0.83	0.24
B03/7	24.2	11.2	1.7	37.4	36.6	51.4	3.44	42.14	1.21	0.11	18.90	0.80	0.26
B03/1	28.9	12.7	2.2	34.1	34.8	48.9	3.41	44.21	1.12	0.16	18.35	0.84	0.23
B01/6	32.7	14.9	3.0	31.0	33.4	45.6	3.08	47.07	0.90	0.35	17.34	0.81	0.23
B01/4	32.7	13.8	2.3	31.4	33.6	45.8	3.14	47.84	0.85	0.07	17.44	0.82	0.24
B01/3	34.6	14.3	2.2	30.1	33.1	44.8	3.00	49.06	0.85	0.09	17.02	0.80	0.24
B02/5	21.3	12.2	2.6	36.8	39.4	54.2	3.49	37.61	1.28	0.82	20.23	0.77	0.22
B02/4	24.8	12.7	2.3	35.0	37.8	52.1	3.32	40.63	1.24	0.41	19.38	0.76	0.22
B02/2	22.2	12.8	2.2	35.9	39.7	52.6	3.56	40.47	1.04	0.13	19.91	0.81	0.26
B02/1	25.9	13.2	2.3	34.2	37.6	50.1	3.38	42.93	1.05	0.24	18.96	0.81	0.25

VM volatile matter
 FC fixed carbon
 C carbon
 H hydrogen
 O oxygen
 N nitrogen
 TS total sulphur
 GCV gross calorific value
 ar as received
 ad air-dried
 wt weight
 dmmf dry, mineral-matter free

Proximate results indicated that the studied coal had relatively high total moisture content, ranging from 20.8 to 34.6 wt.%, with an arithmetic mean of 27.1 wt.% (Tables 1 and 2). The higher total moisture content in the studied coal was contributed by samples from coal seams at B01, ranging from 32.7 to 34.6 wt.%. Air-dried moisture varied from 11.2 to 15.3 wt.%, with an arithmetic mean of 13.3 wt.%. Ash yield was low, ranging from 1.3 to 3.3 wt.%, with an arithmetic mean of 2.3 wt.% (Tables 1 and 2).

The ultimate results indicated that the arithmetic means of carbon, hydrogen, oxygen, nitrogen and total sulphur content were 49.8 wt.%, 3.36 wt.%, 43.27 wt.%, 1.06 wt.% and 0.24 wt.% respectively. Gross calorific value of the studied coal ranged from 17.02 to 20.64 MJ/kg, with an arithmetic mean of 18.90 MJ/kg (Tables 1 and 2).

Table 2
Minimum, maximum, arithmetic means and standard deviations of the geochemical analytical results.

Parameter	Unit	Range		Arithmetic mean	Standard deviation
		Minimum	Maximum		
Moisture (ar)	wt.%	20.8	34.6	27.1	4.56
Moisture (ad)	wt.%	11.2	15.3	13.3	1.31
Ash (ar)	wt.%	1.3	3.3	2.3	0.53
Volatile Matter (ar)	wt.%	30.1	39.3	34.5	2.76
Fixed Carbon (ar)	wt.%	33.1	39.7	36.1	2.36
Carbon (ar)	wt.%	44.8	55.1	49.8	3.32
Hydrogen (ar)	wt.%	3.00	3.80	3.36	0.21
Oxygen (ar)	wt.%	37.61	49.06	43.27	3.49
Nitrogen (ar)	wt.%	0.85	1.28	1.06	0.15
Total sulphur (ar)	wt.%	0.07	0.82	0.24	0.20
Gross calorific value (ar)	MJ/kg	17.02	20.64	18.90	1.14
H/C (dmmf)	Atomic ratio	0.76	0.84	0.81	0.02
O/C (dmmf)	Atomic ratio	0.22	0.26	0.24	0.01

4.2. Coal petrography

The results of the vitrinite/huminite reflectance and maceral composition, along with the petrographic facies indices of the studied coal, appear in Table 3. The minimum, maximum, arithmetic mean and standard deviation of the petrographic analyses and the facies indices are summarised in Table 4.

The mean random reflectance measurement of ulminite maceral of the studied coal varied from 0.26 to 0.36% (Tables 3 and 4; Fig. 3). The studied coal was dominated by huminite (56.7–97.4 vol.%), with low to moderate amounts of liptinite (1.1–40.8 vol.%) and low amounts of inertinite (0.8–8.9 vol.%) (Fig. 4).

Huminite content in the studied coal ranged from 56.7 to 97.4 vol.%, and was represented mainly by detrohuminite. Ulminite prevailed detrohuminite only in samples B03/9, B03/3, B01/3, B01/2, B01/1 and B02/2 (Table 3). The detrohuminite (Fig. 5a and b) content varied greatly in the studied coal, ranging from 1.0 to 95.0 vol.% with an arithmetic mean of 53.7 vol.% (Tables 3 and 4). The ulminite (Fig. 5c) content, which also varied greatly in the studied coal, ranged from 0.0 to 92.7 vol.% (Tables 3 and 4). Textinite (Fig. 5c) was either absent or present in low concentrations in most of the studied samples (<1 vol.%), with the exceptions of only samples B03/8 and B01/2 having a relatively high content of textinite, at 5.6 vol.% and 48.3 vol.% respectively (Table 3). The studied coal contained low amounts of corpohuminite, usually below 5 vol.% (Table 3), except for 3 samples, namely B03/8, B03/1 and B01/2, which contained 15.0, 21.0 and 28.0 vol.% of corpohuminite respectively (Table 3). Corpohuminite occurred mainly as cell fillings in textinite (Fig. 5c and d). Porigelinite content in the studied coal was usually below 4 vol.%, but higher porigelinite content was seen in samples E55/2 (14.7 vol.%) and B03/1 (13.4 vol.%) (Table 3). The maceral was present within phlobaphinite, showing a microgranular appearance and bright internal reflectance (Fig. 5c).

Liptinite content in the studied coal ranged from 1.1 to 40.8 vol.%; higher liptinite content (>10 vol.%) was recorded in samples B03/4,

Table 3

Random vitrinite/huminite reflectance (%), maceral composition (mineral free, vol.%), and petrographic facies indices of the studied coal.

Sample no.	VR	Huminite						Liptinite						Inertinite						TPI	GI	
		Tx	U	Dh	Ch	Pg	TH	Sp	Cu	Rs	Ld	Sub	Ex	TL	Fg	Idt	F	Sf	Ma			TI
E55/4	0.35	0.8	23.2	66.3	0.0	0.0	90.2	0.0	0.0	0.2	0.2	6.5	0.4	7.3	1.2	0.4	0.0	0.8	0.0	2.4	0.37	37.00
E55/3	0.33	0.0	1.5	95.0	0.2	0.0	96.7	0.0	0.2	0.7	0.7	0.7	0.7	2.2	0.0	0.9	0.0	0.2	0.0	1.1	0.02	89.00
E55/2	0.34	0.0	0.0	77.2	0.0	14.7	91.9	0.0	0.0	0.0	0.6	5.2	0.0	5.8	1.0	0.2	0.6	0.4	0.0	2.3	0.01	40.36
B03/9	0.32	0.6	61.0	31.0	1.0	0.0	93.6	0.2	0.4	0.0	0.0	3.9	0.0	4.5	0.4	0.2	0.4	0.8	0.0	1.9	2.00	50.33
B03/8	0.33	5.6	25.2	45.3	15.0	0.2	91.2	0.0	0.2	1.1	0.2	0.9	0.0	2.4	1.3	3.0	1.5	0.6	0.0	6.4	0.65	14.23
B03/7	0.30	0.0	11.5	84.3	0.0	0.0	95.9	0.0	0.0	0.2	0.9	1.5	0.0	2.6	0.2	1.1	0.0	0.2	0.0	1.5	0.14	62.86
B03/6	0.28	0.0	17.5	74.1	0.2	0.9	92.7	0.0	0.0	1.2	0.7	4.5	0.0	6.4	0.0	0.0	0.0	0.9	0.0	0.9	0.25	98.25
B03/4	0.35	0.0	9.2	52.3	3.8	0.4	65.7	0.0	0.2	0.0	0.6	31.8	0.0	32.6	0.0	0.4	0.4	0.8	0.0	1.7	0.19	39.25
B03/3	0.27	0.9	74.3	16.8	1.9	3.5	97.4	0.0	0.2	0.0	0.6	0.2	0.0	1.1	0.2	0.2	0.9	0.2	0.0	1.5	4.42	64.43
B03/2	0.30	0.0	8.4	65.5	0.6	0.0	74.5	0.0	0.0	1.8	0.0	22.7	0.0	24.5	0.0	0.0	1.0	0.0	0.0	1.0	0.13	74.20
B03/1	0.30	0.8	26.9	31.1	21.0	13.4	93.3	0.0	0.0	0.0	5.0	0.8	0.0	5.9	0.0	0.0	0.8	0.0	0.0	0.8	0.89	111.00
ML46B/2	0.33	0.0	0.2	52.1	4.4	0.0	56.7	0.0	0.2	0.0	0.9	39.6	0.0	40.8	1.4	0.0	0.7	0.5	0.0	2.5	0.01	22.36
ML46B/1	0.32	0.0	0.0	72.3	0.8	0.0	73.1	0.0	0.8	20.4	0.6	2.9	0.0	24.8	1.1	0.6	0.4	0.0	0.0	2.1	0.00	34.80
B01/6	0.26	0.0	44.0	47.4	0.0	0.0	91.4	0.0	0.2	0.4	0.6	1.1	0.0	2.4	0.4	2.6	1.5	1.5	0.2	6.2	0.91	14.69
B01/5	0.32	0.2	20.6	52.5	0.7	0.0	74.0	0.0	0.0	0.0	1.6	15.5	0.0	17.1	0.5	1.4	3.0	4.0	0.0	8.9	0.46	8.32
B01/4	0.29	0.0	46.4	47.4	0.8	0.0	94.7	0.0	0.0	1.6	0.4	1.8	0.0	3.9	0.0	0.4	0.2	0.8	0.0	1.4	0.99	65.86
B01/3	0.29	0.0	92.7	1.8	0.4	2.2	97.1	0.0	0.4	1.4	0.0	0.0	0.0	1.8	0.0	1.0	0.0	0.0	0.0	1.0	32.50	95.40
B01/2	0.36	48.3	18.5	1.0	28.0	0.0	95.8	0.0	2.4	0.2	0.2	0.4	0.0	3.2	0.0	1.0	0.0	0.0	0.0	1.0	33.20	95.20
B01/1	0.30	0.0	46.7	38.3	1.3	2.4	88.6	0.0	2.2	3.2	1.5	1.7	0.0	8.6	0.4	1.3	0.4	0.6	0.0	2.8	1.20	31.69
B02/5	0.35	0.3	4.7	74.8	1.3	0.3	81.3	0.3	1.0	2.9	0.8	12.2	0.0	17.1	0.5	0.0	0.0	1.0	0.0	1.6	0.08	52.17
B02/4	0.32	0.0	1.1	83.4	0.5	0.0	85.0	0.0	0.5	1.4	0.9	9.6	0.0	12.3	0.2	0.7	0.0	1.8	0.0	2.7	0.04	31.08
B02/3	0.34	0.0	1.0	85.5	1.2	0.0	87.7	0.0	0.0	0.2	0.5	7.1	0.0	7.9	0.7	1.2	0.5	1.2	0.7	4.4	0.03	19.83
B02/2	0.33	0.8	87.1	6.5	0.2	2.5	97.1	0.0	0.0	0.0	0.0	1.4	0.0	1.4	0.2	0.6	0.2	0.4	0.0	1.4	12.34	67.86
B02/1	0.35	0.0	1.8	87.4	4.7	0.0	93.9	0.0	0.0	2.4	0.6	0.6	0.0	3.7	1.4	0.0	0.2	0.8	0.0	2.4	0.03	38.42

VR	Vitrinite/huminite reflectance
Tx	Textinite
U	Ulminite
Dh	Detrohuminite
Ch	Corpohuminite
Pg	Porigelinite
TH	Total huminite
Sp	Sporinite
Cu	Cutinite
Rs	Resinite
Ld	Liptodetrinite
Sub	Suberinite
Ex	Exsudatinite
TL	Total liptinite
Fg	Funginite
Idt	Inertodetrinite
F	Fusinite
Sf	Semifusinite
Ma	Macrinite
TI	Total Inertinite
TPI	Tissue Preservation Index
GI	Gelification Index

B03/2, ML46B/2, ML46B/1, B01/5, B02/5 and B02/4, with liptinite content as high as 40.8 vol.% (Tables 3 and 4). High liptinite content in these samples was due mainly to the presence of high amounts of suberinite (up to 39.6 vol.%), and also resinite. Suberinite content varied greatly from non-existent to 39.6 vol.% in the studied coal (Tables 3 and 4). It occurred as cell wall tissues and was characterised by a yellow to brownish-yellow fluorescence (Fig. 6a and b). Resinite in the studied coal appeared mostly as cell-filling in textinite (Fig. 5e and f), but there were also some isolated small globular bodies. Except for sample ML46B/1 which contained 20.4 vol.% of resinite, its content in the studied coal was usually less than 3.2 vol.% (Table 3). The contents of cutinite and liptodetrinite were low, with arithmetic means of 0.4 vol.% and 0.8 vol.% respectively (Tables 3 and 4). Liptodetrinite in the studied coal was often present together with inertodetrinite which was finely dispersed in a groundmass of attrinite (Fig. 5a and b). Secondary liptinite macerals such as exsudatinite and fluorinite had also been observed in the studied coal, but they were either absent or were present in trace amounts (Tables 3 and 4). Exsudatinite in the studied coal appeared as crack fillings and was yellow in fluorescent light (Fig. 6c and d). Fluorinite in the

studied samples was always associated with cutinite and characterised by a greenish-yellow in fluorescent light (Fig. 6e and f).

The studied coal contained low contents of inertinite ranging from 0.8 to 8.9 vol.% (Tables 3 and 4). Inertinite in the studied coal was made up of funginite (<1.4 vol.%), inertodetrinite (<3.0 vol.%) (Fig. 5a), fusinite (<3.0 vol.%), semifusinite (<4.0 vol.%) and macrinite (<0.7 vol.%).

5. Discussion

5.1. Geochemistry

Proximate analysis, ultimate analysis, and calorific value are the conventional geochemical analyses carried out to determine the geochemical parameters of a coal. The information derived not only determines the suitability of coals for various industry uses (ASTM D3176, 1989), but also provides information on the depositional conditions and geologic history of the coal-bearing sequences and individual coal seams (Ward, 2002). Nevertheless, the suitability of coals for various industry uses is beyond the scope of this study.

Table 4

Minimum, maximum, arithmetic means and standard deviations of the petrographical analytical results.

Parameter	Range		Arithmetic Mean	Standard Deviation
	Minimum	Maximum		
Vitrinite/huminite reflectance	0.26	0.36	0.32	0.03
Textinite	0.0	48.3	2.4	9.84
Ulminite	0.0	92.7	26.0	28.14
Detrohuminite	1.0	95.0	53.7	28.02
Corpohuminite	0.0	28.0	3.7	7.21
Porigelinite	0.0	14.7	1.7	3.94
Total huminite	56.7	97.4	87.5	11.00
Sporinite	0.0	0.3	0.0	0.07
Cutinite	0.0	2.4	0.4	0.65
Resinite	0.0	20.4	1.6	4.11
Liptodetrinite	0.0	5.0	0.8	1.00
Suberinite	0.0	39.6	7.2	10.45
Exsudatinite	0.0	0.4	0.0	0.08
Total Liptinite	1.1	40.8	10.2	10.80
Funginite	0.0	1.4	0.5	0.50
Inertodetrinite	0.0	3.0	0.7	0.79
Fusinite	0.0	3.0	0.5	0.69
Semifusinite	0.0	4.0	0.7	0.85
Macrinite	0.0	0.7	0.0	0.15
Total inertinite	0.8	8.9	2.5	2.02
TPI	0.00	33.20	3.79	9.31
GI	8.32	111.00	52.44	29.8

Therefore only chemical parameters with significance to the peat-forming conditions and thermal maturity will be discussed in detail.

5.1.1. Total moisture

The vegetable debris from which coal was formed contained a high content of both physically and chemically bound water (Speight, 2005). The water content, however, decreases with the rise in coal rank through the coalification processes, which eliminates much of the moisture in the vegetable debris largely as a result of decreasing porosity (Stach et al., 1982). Moisture has been used as a rank indicator for low-rank coals (Stach et al., 1982) (see also Section 5.2.1). The classification made, using the total moisture arithmetic mean (27.1 wt.%), indicated a subbituminous C coal rank for the studied coal (see also Sections 5.1.4 and 5.2.1).

The total moisture of coal in this study had a significant negative correlation with the mean vitrinite/huminite reflectance (Fig. 7). The higher total moisture content for samples collected from the coal seam at B01 is believed to be of lower maturity, though the content of total moisture is also influenced by ambient conditions, particularly the temperature and water vapour pressure of the environment where the coal seams crop out, as well as the weathering stage of the coal sample (Sivek et al., 2010). This is evidenced by the relatively lower vitrinite/huminite reflectance of samples from this coal seam (Fig. 7), despite the fact that it is stratigraphically the second lowest coal bed identified (Fig. 3).

5.1.2. Ash yield

Minerals in coal represent material washed or blown into the accumulating peat deposit (Davis et al., 1984) by epiclastic and pyroclastic processes (e.g., Ruppert et al., 1991; Triplehorn, 1990). The minerals could also have been formed as a result of accumulation of skeletal fragments and other biogenic components within the peat deposits (Ward, 2002), as well as through syngenetic and epigenetic precipitation of minerals by crystallization in situ (Ward, 2002). The studied coal was characterised by low ash yield (see also Section 4.1) which could have been formed by three main processes, either the process of doming of the peat deposits, the leaching of mineral matter from previously deposited peat, or the deposition of peat on surfaces where inorganic sedimentation processes were not active (Amijaya and Littke, 2005). Although inorganic constituents in the coal-forming peat could

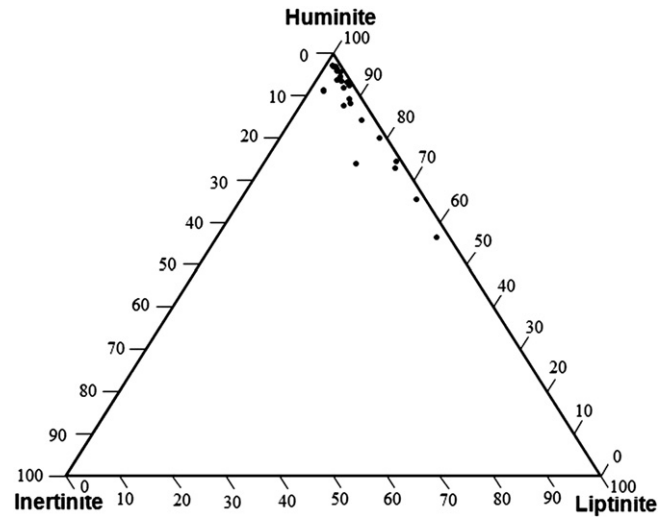


Fig. 4. Ternary diagram showing maceral group composition of the samples.

have been leached out during the coalification processes to produce low ash coals (Amijaya and Littke, 2005; Bustin and Palsgrove, 1997; Cohen and Stack, 1996; Diessel, 1992; Kisters and Bailey, 1983), this was unlikely to be marked (Wüst et al., 2002). Nevertheless, doming of peat deposits could restrict the introduction of detrital mineral matter and sulphur-containing waters into the deposit (Cohen and Stack, 1996; Esterle and Ferm, 1994). Studies carried out by Anderson (1964, 1983), Esterle (1990), Esterle and Ferm (1994) and McCabe (1987) on the prograding deltaic settings of the tropical coasts of Southeast Asian attributed the low ash coals (also with low sulphur content) to the ombrotrophic raised bogs. This inference is also agreed by many researchers, such as Amijaya and Littke (2005), Cohen and Stack (1996), Davis et al. (2007), Diessel (1992), Greb et al., 2002; Gruber and Sachsenhofer (2001), Obaje et al. (1994) and also Taylor et al. (1998). Therefore, we infer that the studied coal originated from ombrotrophic raised bogs.

Upon combustion, carbon, oxygen, sulphur and water (including water from clays) are driven off from the bulk mineral matter producing ash (ASTM D3174, 1987). Though mineral matter content in coal can be determined directly by analytical methods, the method is time consuming; hence, this is seldom carried out. Alternatively, mineral matter content can also be calculated using empirical formulas, many of which have been proposed for this purpose. However, in the present study, mineral matter of the studied coal was estimated by regression analysis carried out between GCV and ash yield as proposed by Gray (1983). The analysis shows that the relationship between the mineral matter and ash for the studied coal is: Mineral matter = 1.10 Ash. The mineral matter content developed in this manner is similar to that obtained by the simplified Parr's formula and the Standards Association of Australia formula. This mineral factor is used to calculate the ash free basis to mineral matter free basis for the ASTM coal rank classification (see also Section 5.1.4).

5.1.3. Total sulphur

The content of sulphur in the studied coal is low (see also Section 4.1). Low sulphur content is a result of both the limited sulphur input and the lack of sulphate-reducing bacteria in acidic conditions (e.g., Amijaya and Littke, 2005; Cameron et al., 1989; Casagrande, 1987; Cohen et al., 1984; Davis et al., 2007; Diessel, 1992; Gruber and Sachsenhofer, 2001; Neuzil et al., 1993; Phillips et al., 1994; Postma, 1982). The principal sulphur source was marine water. Raised bogs, which were fed by rainwater alone, were usually fresh-water with low sulphur content (Casagrande, 1987; Greb et al., 2002; Gruber and Sachsenhofer, 2001; Suárez-Ruiz et al., 2012) (see also Section 5.1.2). Therefore, the low sulphur content strengthens

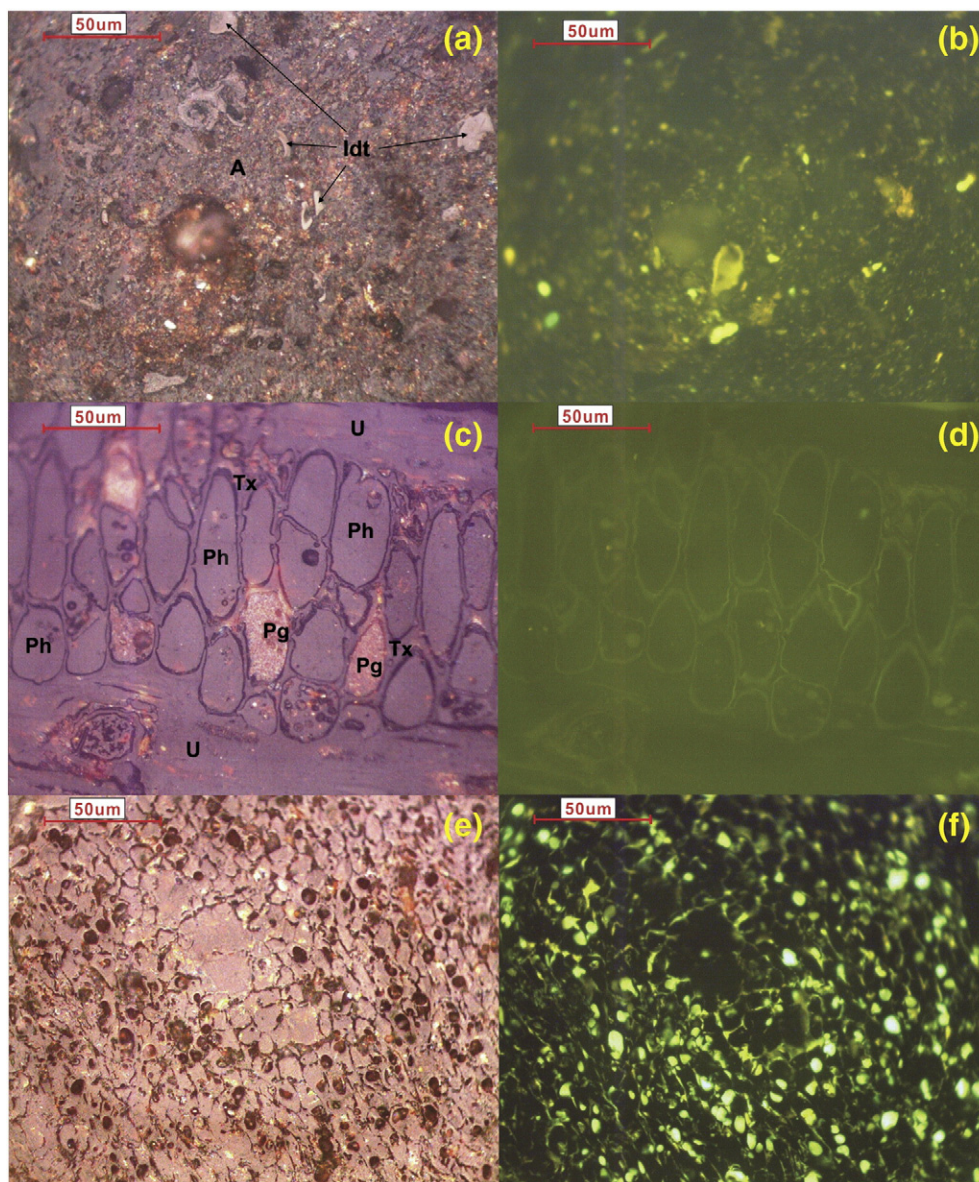


Fig. 5. Photomicrograph of (a) inertodetrinite (Idt) in the matrix of attrinite (A) of the detrohuminite maceral subgroup; reflected light (b) similar view of Fig. 5a under uv light showing the presence of liptodetrinite (c) the presence of textinite (Tx), ulminite (U), phlobaphinite (Ph) of the corpohuminite maceral and porigelinite (Pg); reflected light (d) vague fluorescing cell walls surrounding phlobaphinitic cells; similar field of Fig. 5c; uv light (e) textinite with cellular cavities filled with resin; reflected light (f) similar view of Fig. 5e; uv light. All photos were taken under oil immersion.

our inference that the studied coal accumulated in ombrotrophic raised bogs (see also Section 5.1.2). The proposition is further supported by the absence of syngenetic pyrites in the coal, though epigenetic cleat filling pyrites are common. The cleat filling pyrites are believed to be precipitated post-depositionally from descending solutions percolating through brackish-water strata which overlain the coal seam. This agrees well with the brackish-water depositional environment of the Liang Formation as indicated by the associated fossils (see also following discussion).

Many studies carried out also show the close relationship between marine roof rocks and higher sulphur content in coal (Cecil et al., 1979; Chou, 1984, 1997; Cohen and Stack, 1996; Diessel, 1992; Ferm et al., 1979; Spears and Zheng, 1999; Taylor et al., 1998; Williams and Keith, 1963). This is believed to be the result of the infiltration of sulphate-bearing seawater into the original fresh- to brackish-water peat mires during or after deposition resulting in the enrichment of sulphur and ash at the upper parts of the underlying coal seam (Altschuler et al., 1983; Cohen and Stack, 1996; Hunt and

Hobday, 1984; Mastalerz et al., 1997; Turner and Richardson, 2004; Williams and Keith, 1963). In the present study, three of the four coal seams where the coal sample were geochemically analysed, namely E55, B01 and B01, display these enrichments (see also Section 5.3). This is in agreement with the brackish-water depositional environment of the Liang Formation (see also Section 2). Nevertheless, the low sulphur content at the upper parts of the coal seam might indicate a barely to mildly brackish depositional environment for the overlying clastic sediments.

5.1.4. Atomic ratios of H/C and O/C

Van Krevelen's diagram is a well known approach for chemical characterisation of coals. The diagram plots the H/C–O/C atomic ratios which are used to classify kerogens and information about the evolution path of organic matter from different organic sources (Erik, 2011). The composition of kerogen also determines the genetic potential and the amount of hydrocarbons that can be generated during burial.

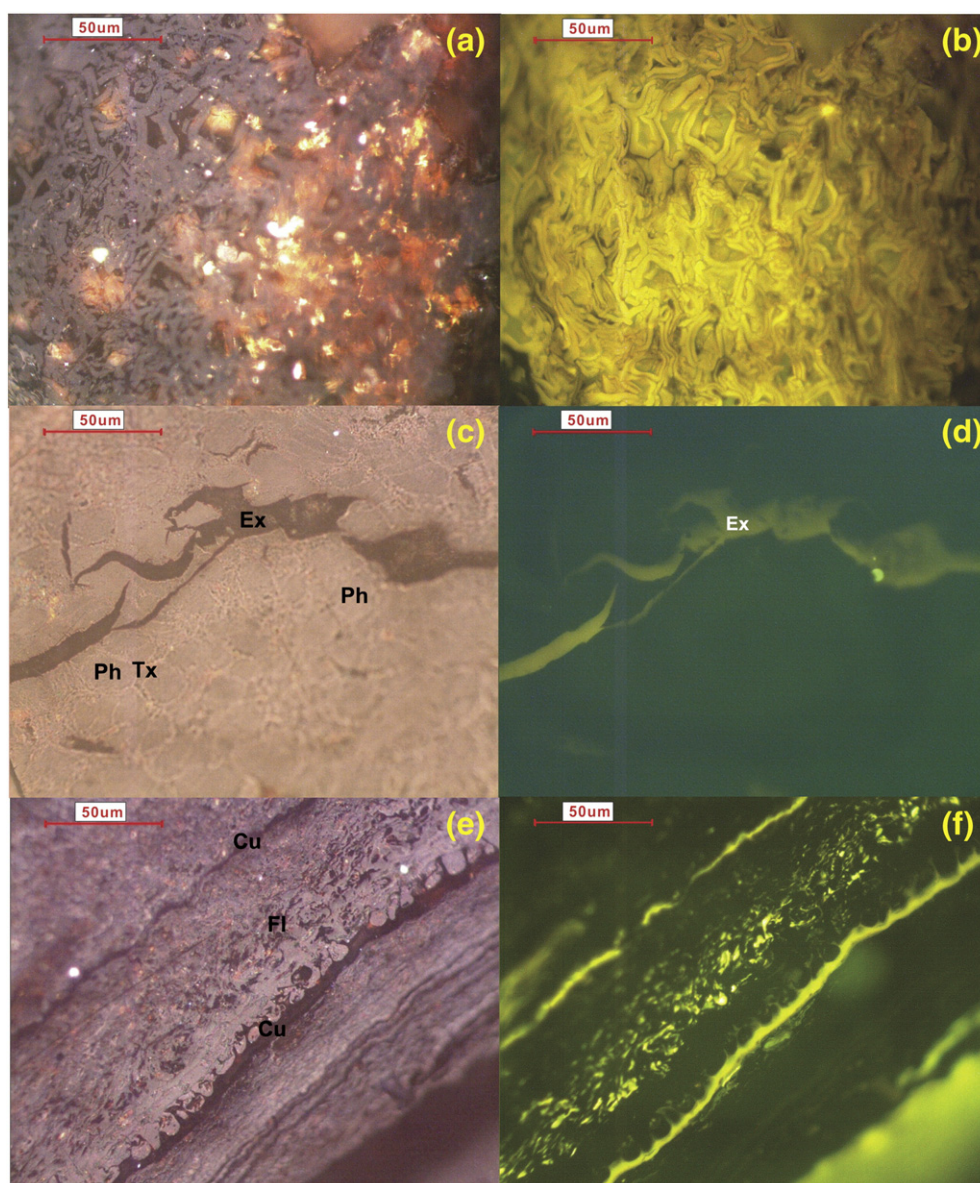


Fig. 6. Photomicrograph of (a) accumulation of colourful oil smears of early generated hydrocarbons as a result of disintegration of suberinite at a mean vitrinite/huminite reflectance of 0.28%; reflected light (b) similar view of Fig. 6a; uv light (c) exsudatinite representing early generated hydrocarbons and phlobaphinite (Ph) surrounded by textinite (Tx); reflected light (d) similar view of Fig. 6c showing yellow fluorescing exsudatinite; uv light (e) cutinite (Cu) sandwiching fluorinite (Fl); reflected light (f) similar view of Fig. 6e; uv light. All photos were taken under oil immersion.

The calculated H/C atomic ratio ranges from 0.76 to 0.84, whereas the calculated O/C atomic ratio ranges from 0.22 to 0.26 (Table 2). All the analysed samples fall within the van Krevelen's coalification band of subbituminous rank (Fig. 8). In agreement with the petrographical analysis (see also Section 4.2), the atomic H/C and O/C ratios of the studied coal are plotted in the Type III terrigenous kerogen zone on a van Krevelen diagram. The H/C values of the studied coal are all below the H/C value of 0.9 that is considered necessary for petroleum generation and expulsion from subbituminous coals (Erik, 2011). In spite of this, petrographical evidence shows the early hydrocarbon generation of the Balingian coal (see also Section 5.2).

5.1.5. Gross calorific value

Gross calorific value (GCV) is also an important rank parameter for low-rank coals (see also Section 5.2.1). With a mean total moisture of 27.1%, mineral matter content of 2.45% (converted using the mineral factor for the studied coal), and GCV of 18.90 MJ/kg on as received basis, a GCV of 19.56 MJ/kg (8408 Btu/lb) for the moist, mineral matter free was

obtained. This implies that the apparent rank of the studied coal fell within the range of subbituminous C of the ASTM coal rank classification. The coal was classified as lignite based on geochemical properties by previous workers (Wolfenden, 1960) (see also Section 2).

5.2. Coal petrography

Coal petrographical studies are commonly conducted on coal to measure its thermal maturity by vitrinite/huminite reflectance, and maceral composition analysis to reconstruct the peat-forming conditions.

5.2.1. Thermal maturity

Thermal maturity (coal rank) reflects the degree of metamorphism that had taken place since deposition of the peat, due primarily to the depth of burial, temperature, geothermal gradient, time, and pressure (Carpenter et al., 2007; Stach et al., 1982; Ward and Suárez-Ruiz, 2008). Various rank parameters have been proposed as indicators at different coalification stages, viz. bed moisture and

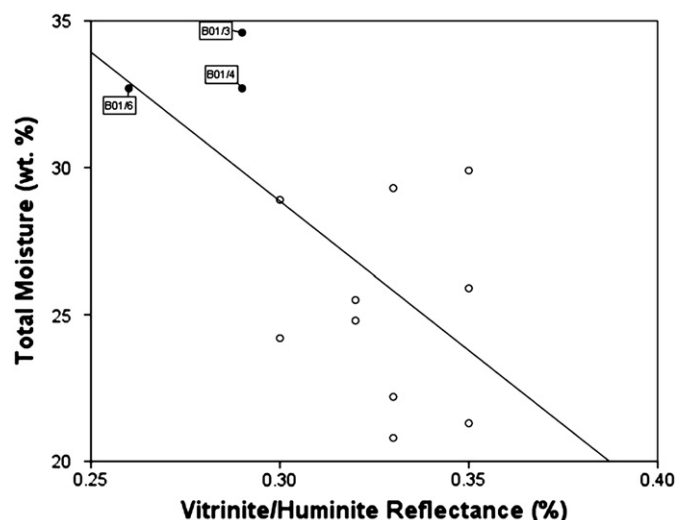


Fig. 7. Scatter plot showing the relationship between total moisture and vitrinite/huminite reflectance ($r = -0.61$). Solid circles are sample with high total moisture.

calorific value for low-rank coals, carbon for medium-rank coals and volatile matter and vitrinite reflectance for high-rank coals (Stach et al., 1982). Though vitrinite/huminite reflectance is not a reliable indicator for the low-rank Balingian coal (Gurba and Ward, 1998; Stach et al., 1982), it is, nevertheless, discussed together with other rank parameters, namely bed moisture and calorific value, as well as H/C and O/C atomic ratios for comparison purposes.

Based on the mean random vitrinite/huminite reflectance measurements (see also Section 4.2), the rank of the studied coal should settle at the lignite coal rank. Hence, the coal rank as determined using the vitrinite/huminite reflectance is lower compared with coal rank determined using the geochemical rank parameters (see also Sections 5.1.1 and 5.1.5). Although vitrinite/huminite reflectance is considered to be the most accurate rank parameter with the capacity to serve as an independent rank indicator (Ward and Suárez-Ruiz, 2008), this measurement is known to be suppressed, giving misleading results for perhydrous coal, marine-influenced coal, or if the coal contains abundant liptinitic maceral (Barker, 1991; Carr, 2000; Diessel, 1998; Diessel and Gammidge, 1998; Gurba and Ward, 1998, 2000; Iglesias et al., 2002; Mukhopadhyay, 1992, 1994; Price and Barker, 1985; Suárez-Ruiz et al., 1994a, 1994b; Taylor et al., 1998; Ward and Suárez-Ruiz, 2008; Wilkins and George, 2002). Nevertheless, as shown in Fig. 8, the

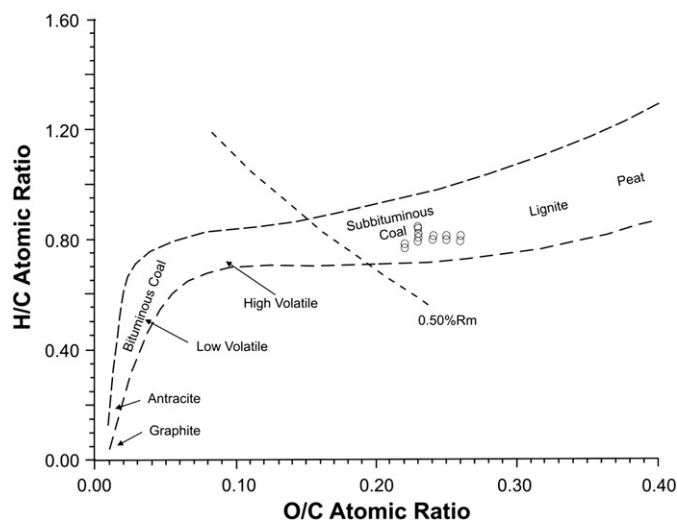


Fig. 8. van Krevelen diagram illustrating the coalification band and coal rank in relation to atomic H/C and O/C ratios (modified after Costa et al., 2010).

H/C–O/C atomic ratios of the studied coal plot within the van Krevelen coalification band indicated that this was not perhydrous coal. Moreover, the fact that the coal-forming peat of the studied coal was deposited in fresh-water depositional conditions (see also Section 5.1.3) rules out the vitrinite/huminite reflectance readings being compromised. Statistical analyses conducted also did not indicate the suppression of vitrinite/huminite reflectance being due to the increase in liptinite content ($r = 0.26$). As such, the lower coal rank determined using the vitrinite/huminite reflectance is believed to be due to the low-rank nature of the studied coal in the first instance, with suppression of the readings also due to early generated hydrocarbons present (see also following discussion). Thus, in this case, the vitrinite/huminite reflectance itself is not considered a reliable thermal maturity indicator for Balingian coal.

Though the measured vitrinite/huminite reflectance suggests that the studied coal is still thermally immature, the petrographical study shows, nonetheless, the expulsion of early generated hydrocarbons (Figs. 5d, 6a, b, c, d, e and f), suggesting its early maturation. The hydrocarbon is generated mainly from the disintegration of suberinite (Fig. 6a and b), and also from phlobaphinite (Fig. 5d) and cutinite (Fig. 6e and f). Although, according to Teichmüller (1974), maceral in coal starts to expel hydrocarbon at the sub-bituminous/bituminous coal rank boundary, Khorasani and Murchison (1988) found in related studies that suberinite of the Surat-Bowen basins (Australia) started to expel hydrocarbon at a rank equivalent to a vitrinite reflectance of 0.35%. In an investigation on brown coals from different countries, Shibaoka (1978) noted that hydrocarbon could be generated from resinite, alginite, and sporinite at brown coal stage. Also Hadiyanto (1992) noted the generation of hydrocarbon at a rank equivalent to a vitrinite reflectance of 0.25% in West Aceh Basin. Similar features of early hydrocarbon generation have also been previously reported for the Tertiary coals of Merit-Pila (Fig. 1) (Abdullah, 1997).

The maturity of coal has long been known to increase with depth, a phenomenon referred to as Hilt's Law, which can be measured by vitrinite/huminite reflectance. Nevertheless, there is no tendency of an increase of vitrinite/huminite reflectance with depth in the Balingian coalfield (Fig. 3). This is probably because no significant depth difference exists between the coal seams.

Statistical analyses showed that there was a significant positive correlation of vitrinite/huminite reflectance in the studied coal with funginite ($r = +0.42$), explaining the elevated vitrinite/huminite reflectance in association with funginite (also known as sclerotinite) in coal. This phenomenon has also been reported by Belkin et al. (2010), Hower et al. (2009, 2011), as well as O'Keefe and Hower (2011). Hower et al. (2009) attributed this phenomenon to enzymes secreted by fungi as they decompose woody remains; alternatively, it might be due to fluid migration along a weak horizon during coalification, or other causes entirely.

5.2.2. Peat-forming condition

Maceral composition in coals reflects the organic source materials which contribute to (a) the accumulation of peat and (b) the conditions during accumulation, viz. height of the water table, pH, decay by aerobic and anaerobic bacteria and mechanical breakdown of the organic matter related to transportation prior to final sedimentation (Kalkreuth et al., 1991). Maceral analysis measures the relative proportions and interrelationships of various macerals. The diagnostic macerals and petrographic facies indices derived from this analysis are widely used as an indicator for the paleodepositional conditions of the coal-forming peat.

5.2.2.1. Diagnostic macerals. The predominance of huminite group macerals (see also Section 4.2) in the studied coal indicates an anaerobic deposition condition in the peat-forming mires, whilst the low content of inertinite indicates the occurrence of low levels of peat (forest) fire and/or oxidation, and the coal having been

deposited in waterlogged conditions (Diessel, 1992; Erik, 2011; Flores, 2002; Stach et al., 1982; Sýkorová et al., 2005; Teichmüller et al., 1998). The presence of large amounts of liptinite group macerals like suberinite (e.g., sample B03/4, B03/2, ML46B/2, B01/5, B02/5 and B02/4) and resinite (e.g., sample ML46B/1) in the studied

coal (see also Section 4.2) suggests an accumulation within forested wet raised bogs (Erik, 2011; Ratanasthien et al., 1999).

As suggested by the Pearson's correlation coefficients and/or scatter plots, the depletion of huminite in the studied coal is always accompanied by the enrichment of liptinite ($r = -0.98$) (Fig. 9a), particularly

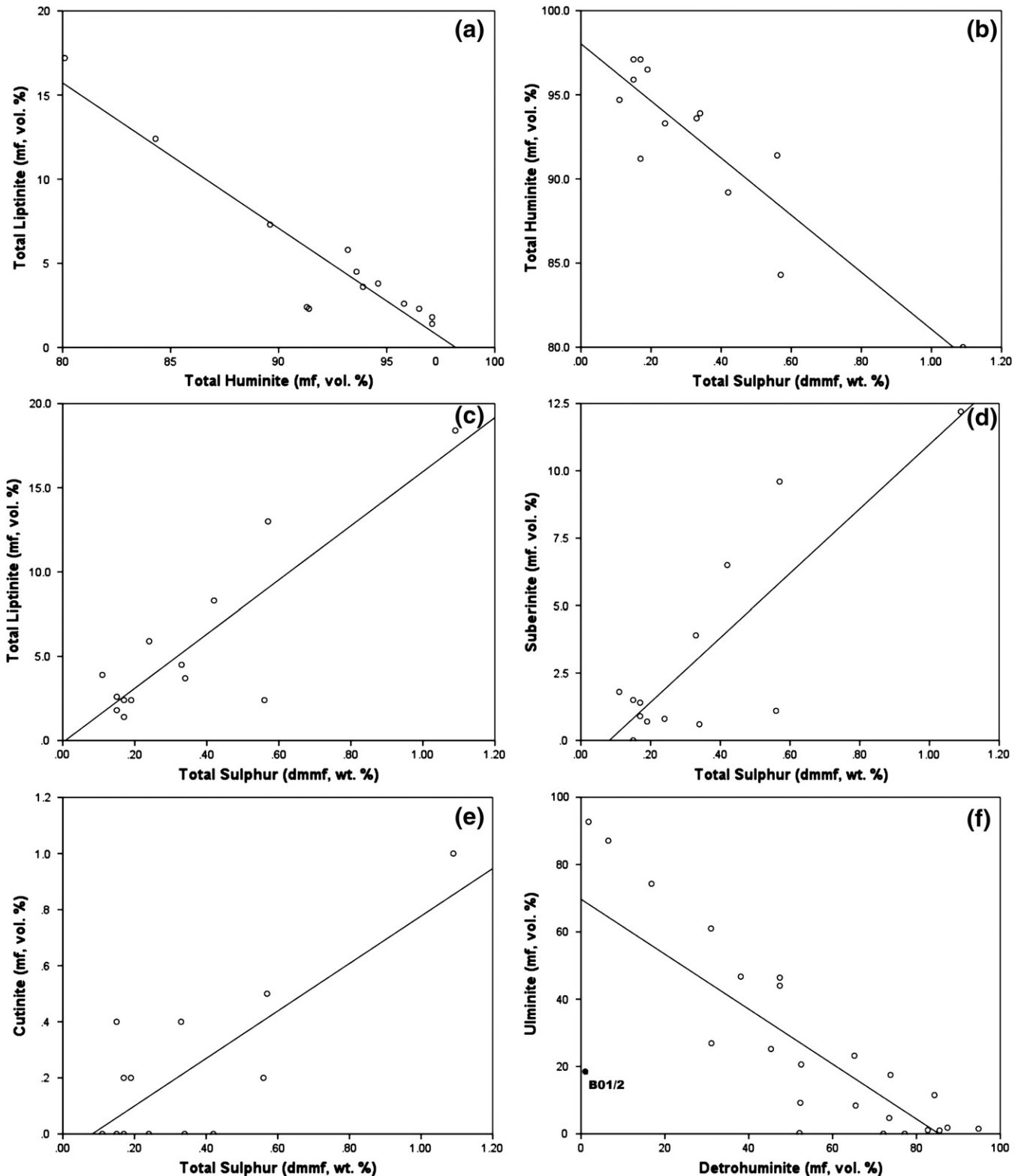


Fig. 9. Scatter plots showing the relationship between (a) total huminite and total liptinite ($r = -0.98$) (b) total sulphur and total huminite ($r = -0.90$) (c) total sulphur and total liptinite ($r = 0.87$) (d) total sulphur and suberinite ($r = 0.84$) (e) total sulphur and cutinite ($r = 0.78$) (f) detrohuminite and ulminite ($r = -0.80$). Solid circle is sample with low ulminite/detrohuminite ratio.

the suberinite ($r = -0.91$) and cutinite ($r = -0.72$), and *vice versa*, whilst inertinite contributes little to this ($r = -0.21$). This implies that bacterial activities played a more important role in the destruction of lignocelluloses material as compared with forest fire or oxidation. In the process, the more resistant liptinite was enriched. The proposition is further supported by the scatter plots based on 13 geochemically analyzed samples which demonstrate that whilst content of huminite decreases (Fig. 9b), content of liptinite (Fig. 9c), particularly the cutinite (Fig. 9d) and suberinite (Fig. 9e), increases with the rise of total sulphur content.

In the present case, large amounts of detrohuminite in the studied coal could be related to both the dominance of herbaceous plants in the paleomires and the poor preservation of woody substance due to prolonged humification in slowly subsiding paleomires (Diessel, 1992; Suárez-Ruiz et al., 2012) (see also discussion earlier), which are discussed in detail in Section 5.3. The decrease of detrohuminite in the studied coal was always accompanied by the increase of ulminite, except for sample B01/2 (Fig. 9f), indicating either increasing forest-type mires or a lower decomposition rate. For sample B01/2, the decrease of detrohuminite was accompanied by an increase of textinite and corpohuminite, indicating a lower degree of gelification under relatively dry conditions (see also Section 5.3.4).

5.2.2. Petrographic facies

Diessel (1986) developed a scheme to reconstruct the peat-forming conditions with the help of two petrographic facies indices derived from maceral analyses, namely the Tissue Preservation Index (TPI) and the Gelification Index (GI), both of which have been extensively used to interpret peat-forming conditions of coal deposits. TPI is a measure of tissue preservation versus destructive tissue breakdown and the proportion of woody plants in the original peat forming assemblages, whereas GI measures the relative dryness or wetness of autochthonous peat forming conditions (Alkande et al., 1992; Diessel, 1992; Kalkreuth et al., 2000; Lamberson et al., 1991; Silva and Kalkreuth, 2005).

Most of the studied samples are characterised by low TPI and high GI values, and are plotted on the marsh field of the Diessel's diagram (Fig. 10). Coals with low TPI values could also suggest large scale destruction of wood in forested swamps (Amijaya and Littke, 2005; Diessel, 1992). Nevertheless, marsh and forested swamp are considered

as a kind of minerotrophic mires (Amijaya and Littke, 2005), coals originating from both of these sources usually generate high ash yield (Amijaya and Littke, 2005; Diessel, 1992), which is not the case for the studied coal (see also Section 5.1.2). This shows that the interpretation as suggested by the Diessel's diagram is not valid for the studied coal. Crosdale (1993), as well as Amijaya and Littke (2005), had also drawn the same conclusion in their studies carried out on the Miocene coals of Maryville, New Zealand and Tanjung Enim, Indonesia, respectively. Crosdale (1993) and Suárez-Ruiz et al. (2012), however, pointed out that the interpretation of mire types is based largely on studies of minerotrophic mires. For ombrotrophic mires, the distribution of diagnostic macerals is still poorly defined and the relationships between sedimentary environments, mire types and maceral composition are not yet established. Hence there is no good basis for paleoenvironmental interpretation (Crosdale, 1993; Dehmer, 1995; Moore and Shearer, 2003; Suárez-Ruiz et al., 2012; Wüst et al., 2001). Interpretations based on maceral ratios as proposed by Diessel (1986) are also not well supported by the analyses of modern peat deposits. A study carried out on modern tropical peat deposits of Tasek Bera, Malaysia (Wüst et al., 2001), as well as on temperate peat deposits at Ontario, Canada (Hawke et al., 1999) and New Zealand (Moore and Shearer, 2003) showed poor or no correlation between maceral indexes and the depositional environments.

Therefore, the Diessel's diagram was not used for paleoenvironmental interpretation, but to indicate the degree of humification and gelification of plant materials (Moore and Shearer, 2003). In the present case, the low TPI ($TPI < 1$) which is accompanied by low ash yield of the studied coal, could be related to poorer vegetation, especially in the central parts of the domed peats, or prolonged humification in slowly subsiding raised bogs (Amijaya and Littke, 2005; Anderson, 1983; Cohen and Stack, 1996; Davis et al., 2007; Diessel, 1992; Gruber and Sachsenhofer, 2001; Obaje et al., 1994; Taylor et al., 1998) (see also Sections 5.1.2 and 5.1.3). The low TPI and low ash yield of Tanjung Enim coal of the South Sumatra Basin (Amijaya and Littke, 2005), Maryville coal of the New Zealand (Crosdale, 1993) and Foord seam of the Stellarton Basin of Nova Scotia (Kalkreuth et al., 1991) have also been attributed to the development of raised bogs (see also Section 5.1.2). High TPI value ($TPI > 1$) was shown in samples B03/9, B03/3, B01/3, B01/2, B01/1, and B02/2,

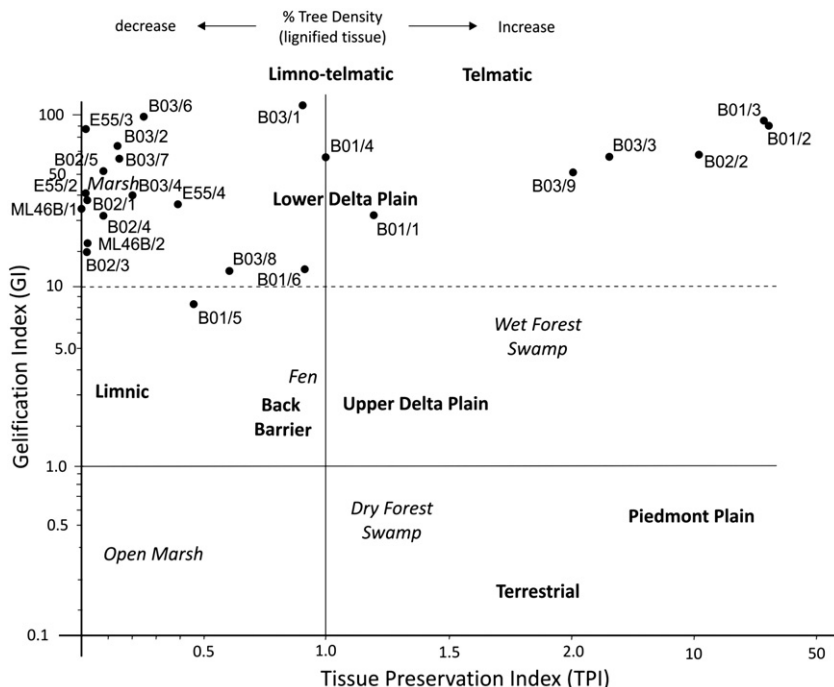


Fig. 10. Diagram of TPI versus GI showing the paleodepositional environment of the Balingian coal facies.

suggesting mild humification in rapidly subsiding forested raised bogs (Diessel, 1992).

All the studied samples possessed high GI value ($GI > 1$). The values suggest strong gelification of plant tissues in continuous wet raised bogs (Diessel, 1992).

5.3. Changes in the peat-forming environment

Vertical changes in the peat-forming conditions for the five coal seams were explored using their petrographic characteristics, along with ash yield and total sulphur content. The coal graphic logs are illustrated and discussed in a down-sequence order that is from E55 (Fig. 11), B03 (Fig. 12), ML46B (Fig. 13), B01 (Fig. 14) to B02 (Fig. 15). All the coal seams are made up entirely of coal, except for a tonstein parting at sampling site B03. The lack of non-coal epiclastic partings is also an important indicator for the ombrotrophic origin of coal seams (Cecil et al., 1985; Clymo, 1987; Greb et al., 2002; McCabe, 1987; Staub, 1991; Staub and Esterle, 1992).

5.3.1. E55

This coal seam, 3.30 m thick, and was intersected by a drill hole (Fig. 11). Three bench samples collected from this drill core were petrographically examined, but only two selected samples were geochemically analysed.

Ash yield and total sulphur content were low for the two geochemically analysed samples, indicating that the coal was deposited in ombrotrophic raised bogs (see also Sections 5.1.2 and 5.1.3). The ash yield increased from 2.5 to 3.3 wt.% from the middle to the upper part of the seam, whilst content of total sulphur increased from 0.13 to 0.27 wt.% (Table 1). The highest values of ash yield and sulphur contents were at the upper part of the coal seam (Fig. 11), indicating the non fresh-water origin of the overlying clastic sediments. This agrees well with the brackish-water deposition environment of the host rocks.

Huminite content in the seam was high, ranging from 89.2 to 96.5 vol.% (Table 3; Fig. 11), and was dominated by detrohuminite (65.2–94.8 vol.%). Liptinite content was low in the seam (2.4 to 8.3 vol.%). Higher liptinite was counted at the top (8.3 vol.%) and bottom (5.8 vol.%) parts of the seam, in correspondence with high suberin content (6.5 and 5.2 vol.% respectively) (Table 3; Fig. 11), indicating the presence of forested plants. Inertinite content was low in the seam, ranging from 1.1 to 2.4 vol.%, suggesting limited thermal and oxidative tissues destruction. Most of the recorded inertinite was actually funginite derived from fungal sclerotia.

The presence of large amounts of detrohuminite in the studied samples is believed to be due mainly to the predominance of herbaceous plants, as no significant enrichment of liptinite group macerals

were counted in the samples (Table 3; Fig. 11). The content of ulminite, however, increased from non-existent at the bottom to 23.2 vol.% at the upper part of the seam, suggesting an increase of forested plants in rapidly subsiding paleomires (Diessel, 1992; Šýkorová et al., 2005). This appears to contrast with the doming process, where, as a result of doming, vegetation in the central parts of the domed peat became poorer due to lack of nutrients. The sparse vegetation was mostly stunted *Shorea* trees, besides shrubs, pitcher plants, herbs and mosses (Amijaya and Littke, 2005; Anderson, 1983; Esterle, 1990; Staub, 2002; Taylor et al., 1998), resulting in an upward increase of the ratio of unstructured/structured huminite (Grady et al., 1993). The contrast could be the result of increased supply of nutrients by the inflowing fluvial-water in the rapidly subsiding paleomires (see also discussion earlier); though in a fully raised bog the water table was fed by rainfall alone. Also, as pointed out by McCabe (1984), though raised mires formed in temperate countries are dominated by low herbaceous flora, raised mires in the tropics are densely forested.

The coal seam is characterised by very low TPI and high GI values. The TPI increases from 0.01 and 0.02 at the lower and middle parts of the seam to 0.37 at the top (Table 3, Fig. 11). An extraordinarily low TPI at the lower and middle parts of the seam is related to the predominance of herbaceous plants, and probably also due to prolonged humification in the slowly subsiding raised bogs. The relatively higher TPI value at the top could be the result of increase in forested plants in the paleomires and also the increased rate of subsidence. The high GI value, ranging from 73.17 to 88.80, indicates waterlogged paleomires.

5.3.2. B03

The coal seam is 7.38 m thick with the presence of a tonstein parting (Fig. 12). Nine samples, inclusive of the tonstein parting sample, were collected. Except for the tonstein parting sample, all other samples were petrographically examined, but only four selected samples were geochemically analysed.

Ash yield (1.3 to 2.2 wt.%) and total sulphur content (0.11 to 0.24 wt.%) were also low for the four geochemically analysed samples (Table 1; Fig. 12) (see also Sections 5.1.2 and 5.1.3). Ash yield did not correlate well with the total sulphur variability, suggesting that fluvial-water had only a minor influence on the pH conditions. This is in agreement with the criteria used to classify raised bogs, where it is fed by rainwater only. No enrichment of sulphur and ash were noted at the upper parts of the coal seam, suggesting that the overlying clastic sediments were fresh-water origin.

The seam is characterised by moderate to high content of huminite (65.7 to 95.9 vol.%), and is represented mainly by detrohuminite (16.8 to 84.3 vol.%) and ulminite (8.4 to 74.3 vol.%) in varying proportions and display opposite trend (Table 3; Fig. 12). The contents of

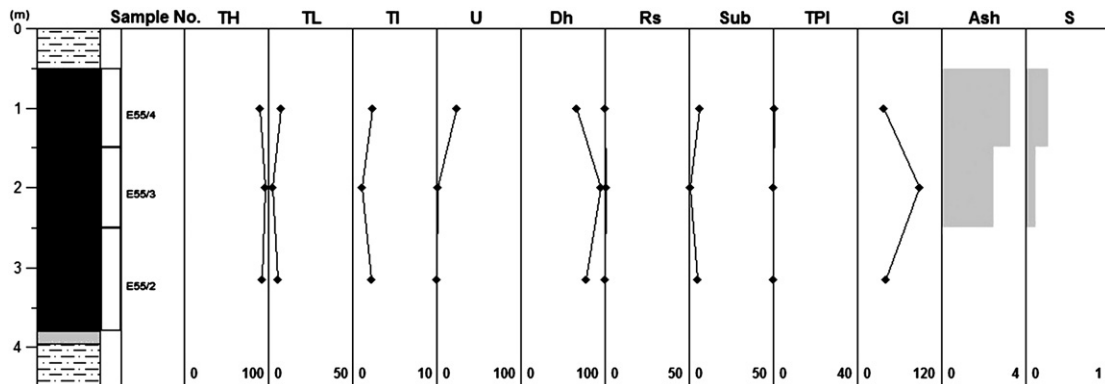


Fig. 11. Vertical in-seam variations of maceral composition, petrographic facies indices, ash yield and total sulphur content for coal seam at E55. TH – total huminite, TL – total liptinite, TI – total inertinite, U – ulminite, Dh – detrohuminite, Rs – resinite, Sub – suberinite, TPI – Tissue Preservation Index, GI – Gelification Index, S – sulphur. (The legend of symbols used is shown in Appendix A).

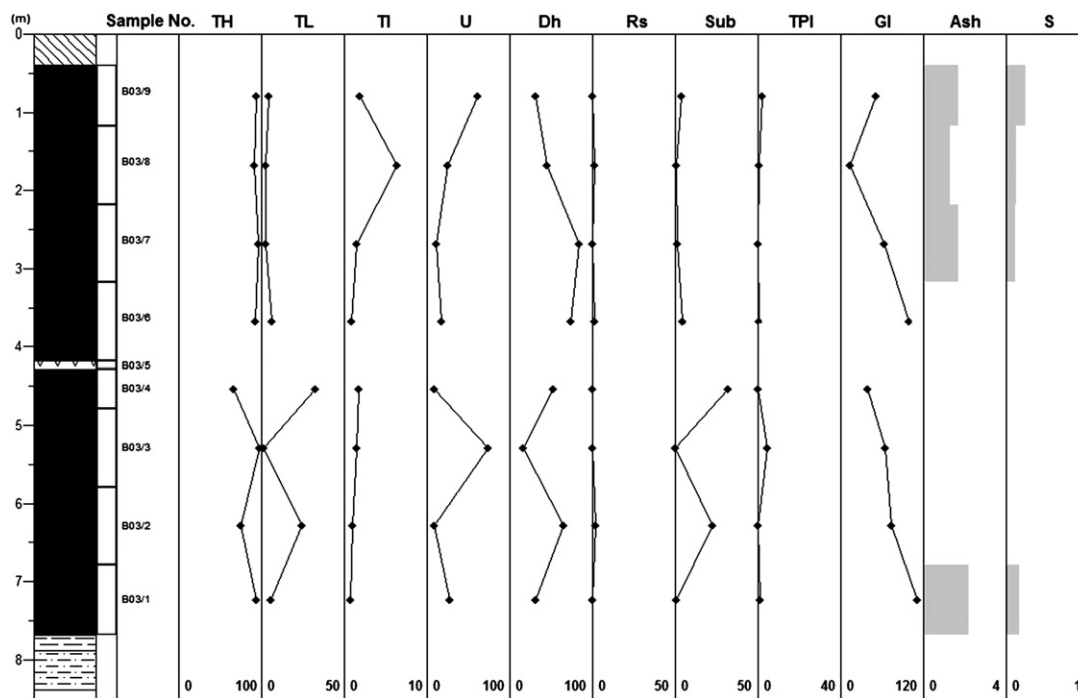


Fig. 12. Vertical inseam variations of maceral composition, petrographic facies indices, ash yield and total sulphur content for coal seam at B03. TH – total huminite, TL – total liptinite, TI – total inertinite, U – ulminite, Dh – detrohuminite, Rs – resinite, Sub – suberinite, TPI – Tissue Preservation Index, GI – Gelification Index, S – SULPHUR. (The legend of symbols used is shown in Appendix A).

detrohuminite and ulminite vary greatly below the tonstein parting. Samples with large amount of liptinite group macerals (up to 32.6 vol.%), particularly suberinite (up to 31.8 vol.%) (Table 3; Fig. 12). This suggests that coal seam below the tonstein parting was deposited within forested raised bogs that had experienced different stages of humification, probably caused by varying rates of subsidence. Nonetheless, above the tonstein parting, the content of detrohuminite fell, from 84.3 to 31.0 vol.%, without enrichment of liptinite group macerals (not more than 6.6 vol.%). This probably suggests changes of vegetation type in the peat-forming mires, from predominance of herbaceous plants to forested plants. The coal seam also contains low amounts of inertinite, ranging from 0.8 to 6.4 vol.%. Higher inertinite content was encountered in sample B03/8 (6.4 vol.%), as a result of high inertodetrinite content (3.0 vol.%), which could be due to aerobic decay at the top of domed peat (ICCP, 2001; Moore et al., 1996).

The coal seam is characterised by low to moderate TPI (0.13 to 4.42) and high GI values (14.23 to 111.00) (Table 3; Fig. 12). Wide variations of TPI are due to the change of vegetation types and also the different rates of subsidence (see also discussion earlier). There are two phases of water table fluctuation, separated by the tonstein parting. The drastic change in water table could be attributed to the rapid subsidence of the paleomires caused by volcanic activities nearby. Below the tonstein parting, the GI value decreases from 111.00 to

39.25. The value of GI decreases from 98.00 to 50.33 above the tonstein parting, with sample B03/8 containing the lowest GI value (14.23). These may indicate that the peat-forming paleomires became drier as a result of more ombrogenous (Jasper et al., 2010). It can be extrapolated, from the difference in vegetation types and also the two gelification stages separated by the tonstein parting, that the coal seam might represent the accumulation of two markedly different mires.

5.3.3. ML46B

The coal seam at ML46B, which was intersected by a drill hole, measures 1.40 meters. Two samples were collected from this coal seam (Fig. 13). Both samples were petrographically examined, but they were not geochemically analysed.

Huminite (56.7–72.9 vol.%) was the main maceral group present. A substantial amount of liptinite (25.0–40.8 vol.%), particularly suberinite (up to 39.6 vol.%) and resinite (up to 20.4 vol.%) were also found (Table 3; Fig. 13). Inertinite content was low (less than 2.5 vol.%), and was represented mainly by funginite (<1.4 vol.%).

Detrohuminite (52.1–72.1 vol.%) was the main huminite group maceral that was present in both samples, and was accompanied by the enrichment of liptinite group macerals (Table 3; Fig. 13). This shows the presence of forested plants, and plant tissues that had

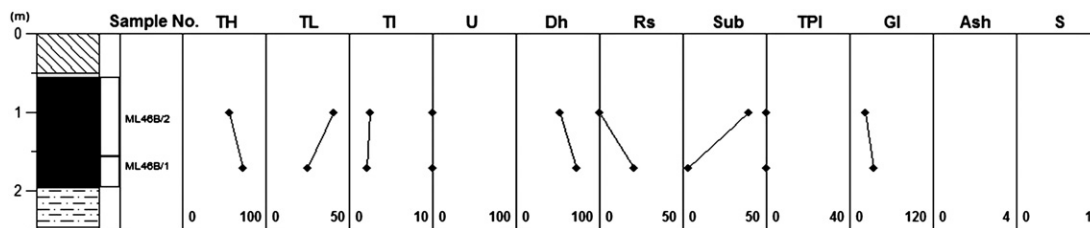


Fig. 13. Vertical inseam variations of maceral composition and petrographic facies indices for coal seam at ML46B. TH – total huminite, TL – total liptinite, TI – total inertinite, U – ulminite, Dh – detrohuminite, Rs – resinite, Sub – suberinite, TPI – Tissue Preservation Index, GI – Gelification Index, S – sulphur. (The legend of symbols used is shown in Appendix A).

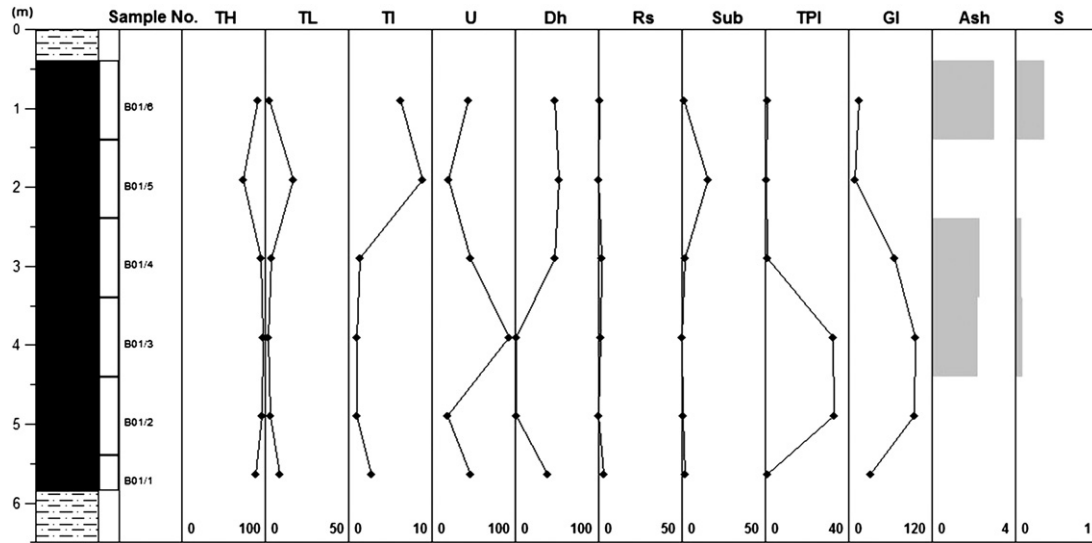


Fig. 14. Vertical in-seam variations of maceral composition, petrographic facies indices, ash yield and total sulphur content for coal seam at B01. TH – total huminite, TL – total liptinite, TI – total inertinite, U – ulminite, Dh – detrohuminate, Rs – resinite, Sub – suberinite, TPI – Tissue Preservation Index, GI – Gelification Index, S – sulphur. (The legend of symbols used is shown in [Appendix A](#)).

undergone large scale destruction, leading to the enrichment of the more resistant liptinite group macerals.

The coal seam is characterised by very low TPI value (less than 0.01) and high GI value (more than 22.36). The very low TPI value argues for an environment which favoured a severe humification of the plant tissues prior to their being buried, probably in slowly subsiding paleomires, whilst the high GI value indicates that the water table was high enough to ensure the enhanced gelification of the tissues.

5.3.4. B01

The coal seam is 5.45 meters thick. Six bench samples were collected from this coal seam ([Fig. 14](#)). All the samples were petrographically examined, but only three selected samples were geochemically analysed.

Ash yield (2.2 to 3.0 wt.%) and total sulphur content (0.07 to 0.35 wt.%) were low for the three geochemically analysed samples ([Table 1](#); [Fig. 14](#)). The results of the analyses showed an enrichment of ash yield and sulphur content at the upper part of the seam, with a value of 3.0 wt.% and 0.35 wt.% respectively. This suggests the

overlying rock was deposited in a brackish-water environment, which is consistent with the depositional environment of the host rocks.

Petrographically, the coal seam is characterised by high huminite (74.0–97.1 vol.%), indicating an oxygen-deficient deposition condition in the peat-forming mires. The studied coal contained large amounts of well-preserved telohuminate (either textinite or ulminite), except for sample B01/5 ([Table 3](#)). Large amounts of telohuminate indicate an origin from forested raised bogs ([Diessel, 1992](#); [Erik, 2011](#); [Flores, 2002](#); [Sýkorová et al., 2005](#); [Teichmüller et al., 1998](#)), with relatively little humification probably as a result of rapid burial of the peat. Sample B01/5, as evidenced by the enrichment of liptinite (17.1 vol.%), particularly suberinite (15.5 vol.%), was however believed to have originated from forested raised bogs, which had undergone more extensive degradation, probably in a slowly subsiding paleomire. The greater abundance of textinite (48.3 vol.%) over ulminite (18.5 vol.%) for sample B01/2 is an indication of decreased biochemical gelification related to bacterial activities under relatively dry conditions within forested raised bogs

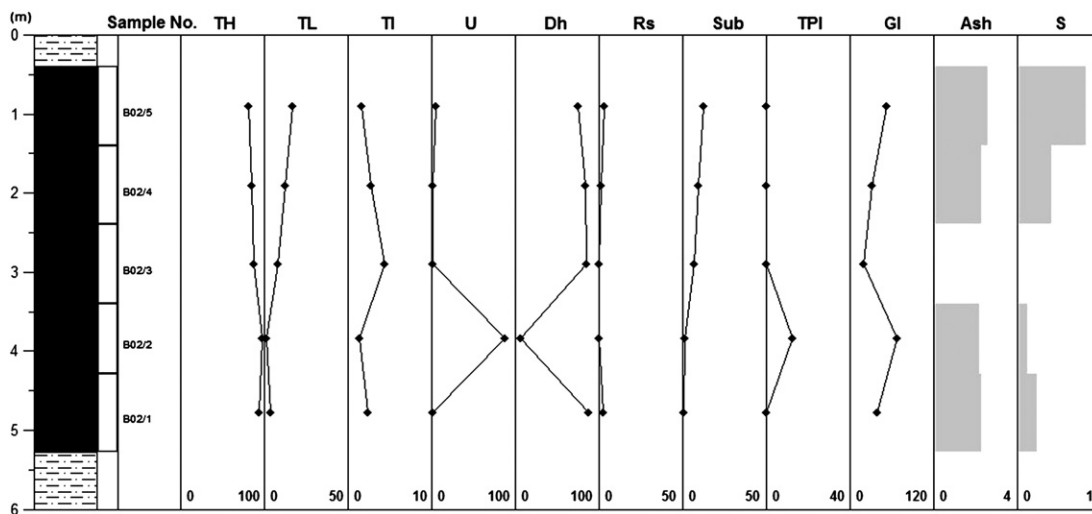


Fig. 15. Vertical in-seam variations of maceral composition, petrographic facies indices, ash yield and total sulphur content for coal seam at B02. TH – total huminite, TL – total liptinite, TI – total inertinite, U – ulminite, Dh – detrohuminate, Rs – resinite, Sub – suberinite, TPI – Tissue Preservation Index, GI – Gelification Index, S – sulphur. (The legend of symbols used is shown in [Appendix A](#)).

(Diessel, 1992; Sýkorová et al., 2005). Large amounts of corpohuminite (28.0 vol.%) were also counted in sample B01/2, indicating the presence of tannins within the sample (Mavridou et al., 2003). Inertinite content in this seam ranged from 1.0 to 8.9 vol.%. No consistent vertical variations in inertinite group macerals were seen for the seam. Maximum inertinite contents were determined in two samples from the top of the coal seam, indicating higher levels of peat (forest) fire and/or oxidation in the paleomires before the termination of peat formation.

TPI for this seam ranged from 0.46 to 33.2, whilst GI was from 8.32 to 95.40 (Table 3; Fig. 14). Higher TPI was calculated for most of the samples, except for sample B01/5, indicating a mild humification, probably in rapidly subsiding forested raised bogs. Lower TPI for sample B01/5 was accompanied by enrichment of liptinite group macerals, also indicating the presence of forested raised bogs, where the plant tissues had undergone more severe degradation. The higher GI, except for the upper part of the seam, reflects higher proportions of vitrinite over inertinite macerals; this indicates a relatively higher degree of gelification in continuously wet conditions.

5.3.5. B02

The coal seam is 4.88 m thick. Five samples were collected from this coal seam (Fig. 15). All the samples were petrographically examined, but only four selected samples were geochemically analysed.

Chemically, the studied coal was also characterised by low ash yield (2.2–2.6 wt.%) and low total sulphur content (0.13–0.82 wt.%). Maximum ash yield and total sulphur content were determined in samples at the top of the seam. The similar vertical variation patterns between ash yield and sulphur content suggests that pH of the paleomire was raised due to the influx of neutralizing waters into the mire, although in a fully raised bog the water table would have been fed by rainfall alone. The low sulphur content however points to fluvial-waters, but not marine-waters, in diluting the humic acids.

The studied coal was dominated by huminite group macerals (80.0–97.1 vol.%), particularly detrohuminite (6.5–87.4 vol.%) and ulminite (1.0–87.1 vol.%). Other huminite group macerals, namely textinite (0.0–0.8 vol.%), corpohuminite (0.2–4.7 vol.%) and porigelinite (0.0–2.5 vol.%), were present only in small amounts (Table 3). Detrohuminite dominated all the studied samples, except for sample B02/2. High detrohuminite for the sample collected from the bottommost of the seam, namely sample B02/1, was not accompanied by enrichment of liptinite group macerals (3.7 vol.%), indicating the dominance of herbaceous plants; nevertheless, the small amounts of resinite (2.4 vol.%) point to the presence of stunted trees in the paleomires. High detrohuminite at the middle and top parts of the seam were, however, accompanied by the enrichment of liptinite group macerals (7.9–18.4 vol.%), particularly suberinite (7.1–12.2 vol.%) and resinite (0.2–2.9 vol.%), with a rising trend (Table 3; Fig. 15). This indicates an increase of forested plants, but at a decreasing subsidence rate, so that the plant tissues would have sufficient time to be humified in usually acidic raised bogs. The high ulminite content for sample B02/2 (87.1 vol.%), however, suggests the presence of forested plants in continuous wet and rapidly subsiding raised bogs.

TPI value of the studied coal ranged from 0.03–12.34, whilst the GI value ranged from 19.83–67.86 (Table 3; Fig. 15). The wide variation of TPI value is due to a change of vegetation type as well as the subsidence rate of the paleomires (see also discussion earlier), whilst the high GI value indicates waterlogged depositional conditions.

6. Conclusions

Geochemical data indicate that the studied coal is characterised by high moisture, low ash and low sulphur contents. The low ash yield and low sulphur content, together with the lack of epiclastic partings clearly indicate that the coal was deposited in ombrotrophic raised

bogs. In agreement with the brackish-water depositional environment of Liang Formation, slight enrichment of ash yield and sulphur content was noted at the upper parts of the coal seams. Nevertheless, the low sulphur content at the upper parts of the coal seam indicates either a barely or mildly brackish-water depositional environment for the overlying clastic sediments.

The H/C and O/C atomic ratios of the studied coal were plotted in the Type III terrigenous kerogen zone, within the coalification band of the van Krevelen diagram, indicating a subbituminous coal rank. This suggests that the coal was derived from plant materials of terrigenous origin following a “normal” coalification path. The H/C values of the studied coal are all below the H/C value of 0.9 that is considered necessary for petroleum generation and expulsion from subbituminous coals. In spite of this, petrographical evidence shows the early hydrocarbon generation of Balingian coal.

The studied coal is dominated by huminite with low amounts of inertinite, suggesting a predominantly anaerobic deposition conditions in the paleomires with limited thermal and oxidative tissues destruction. Detrohuminite and ulminite are the two dominating huminite group macerals that are present in varying proportions in the studied coal. Samples with high proportions of detrohuminite are attributed to the predominance of herbaceous plants in the paleomires, and also to the degradation of woody substance in slowly subsiding paleomires. On the other hand, samples with high proportions of ulminite indicate the predominance of forested plants in rapidly subsiding paleomires.

Most of the samples in this study, characterised by low TPI and high GI values, are plotted on the marsh field of the Diessel's diagram. Alternatively, it could also originate from forested swamps as a result of large scale destruction of wood. Nevertheless, coals originating from marsh or forested swamp usually have high ash yields (Amijaya and Littke, 2005; Diessel, 1992), whereas this is not the case for the studied coal. Hence, the interpretation suggested by the Diessel's diagram may not be valid for the coal investigated in the present study.



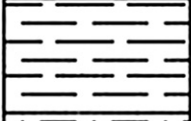




The geochemical classification of thermal maturity (coal rank) based on moisture and calorific value suggests a subbituminous C rank for the studied coal. However, the petrographical classification based on random vitrinite/huminite reflectance designates a lignite coal rank. This inference may be a result of the characteristics of low-rank Balingian coal for which vitrinite/huminite reflectance may not be a suitable rank parameter. Moreover, the presence of early generated hydrocarbons that were associated with these macerals could have lowered the reflectance values. Therefore, vitrinite/huminite reflectance is not a suitable rank parameter for Balingian coal, whereas moisture and calorific values are deemed more reliable rank indicators for these low-rank coals. There is also no tendency for vitrinite/huminite reflectance to increase with depth in the Balingian coalfield, contrary to what might be expected from Hilt's Law.

Acknowledgements

We would like to thank Dato' Haji Yunus Abd Razak, Director General of the Minerals and Geoscience Department Malaysia, for the use of the analytical facilities of the Accredited Coal Quality Testing Laboratory of the Mineral and Geoscience Department, Malaysia (Sarawak). We would also like to express our gratitude to Mr. Mohamad Aswandi Ariff and Ms Sidin Poren of the Minerals and Geoscience Department Malaysia (Sarawak) for assistance in the chemical analyses. The authors also sincerely thank Mr. Daulip Lakui and Mr. Nightingale Lian of the Minerals and Geoscience Department Malaysia (Sabah) who provided data on the Sabah coal resources. Thanks also go to Mr. Stamford and Mr. Ali of Sarawak Coal Resources Sdn. Bhd. who provided the coordinates of the drill hole. We also would like to thank Dr. Littke, R., and the two anonymous reviewers for their valuable comments. The study received financial support from the University of Malaya IPPP research grant No PS438-2010A.

Appendix A. Legend describing the meaning of the symbols used in coal graphic logs

Legend

	Coal
	Coaly Shale
	Shale
	Mudstone
	Clay
	Siltstone
	Tonstein

References

- Abdullah, W.H., 1997. Evidence of early Generation of Liquid Hydrocarbon from Suberinite as Visible under Microscope. *Organic Geochemistry* (ISSN: 01406701) 27, 591–596.
- Alkande, S.O., Hoffknecht, A., Erdtmann, B.D., 1992. Rank and petrographic composition of selected Upper Cretaceous and Tertiary coals of southern Nigeria. *International Journal of Coal Geology* 20, 209–224.
- Altschuler, Z.S., Schnepfe, M.M., Silber, C.C., Simon, F.O., 1983. Sulfur diagenesis in Everglades peat and the origin of pyrite in coal. *Science* 221 (4607), 221–227.
- Amijaya, H., Littke, R., 2005. Microfacies and depositional environment of Tertiary Tanjung Enim low rank coal, South Sumatra Basin, Indonesia. *International Journal of Coal Geology* 61, 197–221.
- Anderson, J.A.R., 1964. The structure and development of the peat swamp forests of Sarawak and Brunei. *Journal of Tropical Geography* 18, 7–16.
- Anderson, J.A.R., 1983. Tropical peat swamps of Western Malaysia. In: Gore, A.J.P. (Ed.), *Ecosystems of the World, 4B Mires: Swamp, Bog, Fen and Moor*. Regional Studies. Elsevier, Amsterdam, pp. 181–199.
- ASTM, 1987. Standard test method for ash in the analysis sample of coal and coke. *Annual Book of ASTM Standards*, 05. 05.
- ASTM, 1989. Standard practice for ultimate analysis of coal and coke. *Annual Book of ASTM Standards*, 05. 05.
- ASTM, 1990. Standard classification of coals by rank. *Annual Book of ASTM Standards*, 05. 05.
- Barker, C.E., 1991. An update on the suppression of vitrinite reflectance. *The Society for Organic Petrology Newsletter* 8, 8–11.
- Belkin, H.E., Tewalt, S.J., Hower, J.C., Stucker, J.D., O'Keefe, J.M.K., Tatu, C.A., Buta, G., 2010. Geochemistry and petrography of Oligocene bituminous coals from the Jiu Valley, Petrosani basin (southern Carpathian Mountains), Romania. *International Journal of Coal Geology* 82, 68–80.
- Bustin, R.M., Palsgrove, R., 1997. Lithofacies and depositional environments of the Telkwa coal measures central British Columbia, Canada. *International Journal of Coal Geology* 34, 21–51.
- Cameron, C.C., Esterle, J.S., Palmer, C.A., 1989. The geology, botany and chemistry of selected peat-forming environments from temperate and tropical latitudes. *International Journal of Coal Geology* 12, 105–156.
- Carpenter, A.M., Niksa, S., International, S.R.I., Scott, D.H., Wu, Z., 2007. *Fundamentals of coal combustion*. IEA Clean Coal Centre 120.
- Carr, A.D., 2000. Suppression and retardation of vitrinite reflectance: Part 1. Formation and significance for hydrocarbon generation. *Journal of Petroleum Geology* 23, 313–343.
- Casagrande, D.J., 1987. Sulfur in peat and coal. In: Scott, A.C. (Ed.), *Coal and coal-bearing strata: recent advances*. Geol. Soc. Spec. Publ., 32, pp. 87–105.
- Cecil, C.B., Stanton, R.V., Dulong, F.T., Renton, J.J., 1979. Some geologic factors that control mineral matter in coal. *West Virginia Geological and Economic Survey Bulletin* 37 (1), 43–56.
- Cecil, C.B., Stanton, R.W., Neuzil, S.G., Dulong, F.T., Ruppert, C.F., Pierce, B.S., 1985. Paleoclimate controls on Late Paleozoic sedimentation and peat formation in the central Appalachian basin (U.S.A.). *International Journal of Coal Geology* 5, 195–230.
- Chou, C.L., 1984. Relationship between geochemistry of coal and the nature of strata overlying the Herrin Coal in the Illinois Basin, USA. *Memoir of the Geological Society of China* 6, 269–280.
- Chou, C.L., 1997. Geological factors affecting the abundance, distribution and speciation of sulphur in coals. Part B. VSP In: Yang, Q. (Ed.), *Geology of fossil fuels-coal*. Proceedings 30th International Geological Congress, 18. The Netherlands, Utrecht, pp. 47–57.
- Clymo, R.S., 1987. In: Scott, A.C. (Ed.), *Rainwater-fed peat as a precursor of coal*. Coal and Coal-bearing Strata — Recent Advances, 32. Geological Society Special Publication, London, pp. 17–23.
- Cohen, A.D., Stack, E.M., 1996. Some observations regarding the potential effects of doming of tropical peat deposits on the composition of coal beds. *International Journal of Coal Geology* 29, 39–65.
- Cohen, A.D., Spackman, W., Dolson, P., 1984. Occurrence and distribution of sulfur in peat-forming environments of southern Florida. *International Journal of Coal Geology* 4, 74–96.
- Costa, A., Flores, D., Suárez-Ruiz, I., Pevida, C., Rubiera, F., Iglesias, M.J., 2010. The importance of thermal behaviour and petrographic composition for understanding the characteristics of a Portuguese perhydrous Jurassic coal. *International Journal of Coal Geology* 84, 237–247.
- Crosdale, P.J., 1993. Coal maceral ratios as indicators of environment of deposition: do they work for ombrogenous mires? An example from the Miocene of New Zealand. *Organic Geochemistry* 20, 797–809.
- Davis, A., Russell, S.J., Rimmer, S.M., Yeakel, J.D., 1984. Some genetic implications of silica and aluminosilicates in peat and coal. *International Journal of Coal Geology* 3, 293–314.
- Davis, R.C., Noon, S.W., Harrington, J., 2007. The petroleum potential of Tertiary coals from Western Indonesia: relationship to mire type and sequence stratigraphic setting. *International Journal of Coal Geology* 70, 35–52.
- Dehmer, J., 1995. Petrological and organic geochemical investigation of recent peats with known environments of deposition. *International Journal of Coal Geology* 28, 111–138.
- Diessel, C.F.K., 1986. On the correlation between coal facies and depositional environments. *Advances in the Study of the Sydney Basin*, Proc. 20th Symposium. University of Newcastle, Australia, pp. 19–22.
- Diessel, C.F.K., 1992. *Coal-bearing Depositional Systems*. Springer-Verlag, New York, Berlin 3 540 52516 5. 721 pp.
- Diessel, C.F.K., 1998. Sequence stratigraphy applied to coal seams: two case histories. In: Shanley, K.W., McCabe, P.J. (Eds.), *Relative Role of Eustasy, Climate and Tectonism in Continental Rocks*. Special Publication, 59. Society of Economic Paleontologists and Mineralogists, Tulsa, OK, pp. 151–173.
- Diessel, C.F.K., Gammidge, L., 1998. Isometamorphic variations in the reflectance and fluorescence of vitrinite — a key to depositional environment. *International Journal of Coal Geology* 36, 167–222.
- EIA, 2012. *International Energy Outlook 2010*. Energy Information Administration, USA, Washington DC <http://204.14.135.140/cfapps/ipdbproject/iedindex3.cfm?tid=1&pid=7&aid=1&cid=MY&syid=2010&eyid=2010&unit=TST>.
- Erik, N.Y., 2011. Hydrocarbon generation potential and Miocene–Pliocene paleoenvironments of the Kargal Basin (Central Anatolia, Turkey). *Journal of Asian Earth Sciences* 42, 1146–1162.
- Esterle, J.S., 1990. Trends in petrographic and chemical characteristics of tropical domed peats in Indonesia and Malaysia as analogues for coal formation. University of Kentucky, USA, PhD Thesis. 270pp.
- Esterle, J.S., Ferm, J.C., 1994. Spatial variability in modern tropical peat deposits from Sarawak, Malaysia and Sumatra, Indonesia: analogues for coal. *International Journal of Coal Geology* 26, 1–41.
- Ferm, J.C., Horne, J.C., Weisenfuh, G.A., Staub, J.R., 1979. Carboniferous Depositional Environments in the Appalachian Region. Department of Geology, University of South Carolina, South Carolina. 760 pp.
- Flores, D., 2002. Organic facies and depositional palaeoenvironment of lignites from Rio Maior Basin (Portugal). *International Journal of Coal Geology* 48, 181–195.
- Grady, W.C., Eble, C.F., Neuzil, S.G., 1993. Brown coal maceral distributions in a modern domed tropical Indonesian peat and a comparison with maceral distribution in Middle Pennsylvanian Appalachian bituminous coal beds. In: Cobb, J.C., Cecil, C.B. (Eds.), *Modern and ancient coal-forming environment: Special Paper-Geological Society of America*, 286, pp. 63–82.
- Gray, V.R., 1983. A formula for the mineral matter to ash ratio for low rank coals. *Fuel* 63, 94–97.
- Greb, S.F., Eble, C.F., Hower, J.C., Andrews, W.M., 2002. Multiple-bench architecture and interpretations of original mire phases — examples from the Middle Pennsylvanian of the Central Appalachian Basin, USA. *International Journal of Coal Geology* 49, 147–175.
- Gruber, W., Sachsenhofer, R.F., 2001. Coal deposition in the Noric Depression (Eastern Alps): raised and low-lying mires in Miocene pull-apart basins. *International Journal of Coal Geology* 48, 89–114.

- Gurba, L.W., Ward, C.R., 1998. Vitrinite reflectance anomalies in the high-volatile bituminous coals of the Gunedah Basin, New South Wales, Australia. *International Journal of Coal Geology* 36, 111–140.
- Gurba, L.W., Ward, C.R., 2000. Elemental composition of coal macerals in relation to vitrinite reflectance, Gunedah basin, Australia, as determined by electron microprobe analysis. *International Journal of Coal Geology* 44, 127–147.
- Hadiyanto, 1992. Organic petrology and geochemistry of the tertiary formations at Meulaboh area, west Aceh Basin, Sumatra, Indonesia. PhD Thesis. 458 pp.
- Hawke, M.I., Martini, I.P., Stasiuk, L.D., 1999. A comparison of temperate and boreal peats from Ontario, Canada: possible modern analogues for Permian coals. *International Journal of Coal Geology* 41, 213–238.
- Hower, J.C., O'Keefe, J.M.K., Watt, M.A., Pratt, T.J., Eble, C.F., Stucker, J.D., Richardson, A.R., Kostova, I.J., 2009. Notes on the origin of inertinite macerals in coals: observations on the importance of fungi in the origin of macrinite. *International Journal of Coal Geology* 80, 135–143.
- Hower, J.C., O'Keefe, J.M.K., Eble, C.F., Volk, T.J., Richardson, A.R., Satterwhite, A.B., Hatch, R.S., Kostova, I.J., 2011. Notes on the origin of inertinite macerals in coals: funginite associations with cutinite and suberinite. *International Journal of Coal Geology* 85, 186–190.
- Hunt, J.W., Hobday, D.K., 1984. Petrographic composition and sulphur content of coals associated with alluvial fans in the Permian Sydney and Gunedah Basins, eastern Australia. In: Rahmani, R.A., Flores, R.M. (Eds.), *Sedimentology of coal and coal-bearing sequences: Special Publication of the International Association of Sedimentologists*, 7, pp. 43–60.
- Hutchison, C.S., 2005. *Geology of North-west Borneo: Sarawak, Brunei and Sabah*, 1st ed. Elsevier, New York, USA. 13: 978-0444558909.
- ICCP, 2001. The new inertinite classification (ICCP System 1994). *Fuel* 80, 459–471.
- Iglesias, M.J., del Río, J.C., Laggoun-Dé farge, F., Cuesta, M.J., Suárez-Ruiz, I., 2002. Control of the chemical structure in perhydrous coals by FTIR and Py-GC/MS. *Journal of Analytical and Applied Pyrolysis* 62/1, 1–34.
- Jasper, K., Hartkopf-Fröder, C., Flajs, G., Littke, R., 2010. Review article — Evolution of Pennsylvanian (Late Carboniferous) peat swamps of the Ruhr Basin, Germany: comparison of palynological, coal petrographical and organic geochemical data. *International Journal of Coal Geology* 83, 346–365.
- Kalkreuth, W., Kotis, T., Papanicolaou, C., Kokkinakis, P., 1991. The geology and coal petrology of a Miocene lignite profile at Meliadi Mine, katerini, Greece. *International Journal of Coal Geology* 17, 51–67.
- Kalkreuth, W., Marchioni, D., Utting, J., 2000. Petrology, palynology coal facies, and depositional environments of an Upper Carboniferous coal seam, Minto Coalfield, New Brunswick, Canada. *Canadian Journal of Earth Science* 37, 1209–1228.
- Khorasani, G.K., Murchison, D.G., 1988. Order of generation of petroleum hydrocarbons from liptinitic macerals with increasing thermal maturity. *Fuel* 67, 1160–1162.
- Kosters, E.C., Bailey, A., 1983. Characteristics of peat deposits in the Mississippi River delta plain. *Gulf Coast Association of Geological Societies Transactions* 33, 311–325.
- Lamberson, M.N., Bustin, R.M., Kalkreuth, W., 1991. Lithotype (maceral) composition and variation as correlated with paleowetland environments. Gates Formation, Northeastern British Columbia, Canada. *International Journal of Coal Geology* 18, 87–124.
- Markic, M., Sachsenhofer, R.F., 1997. Petrographic composition and depositional environments of the Pliocene Velenje lignite seam (Slovenia). *International Journal of Coal Geology* 33, 229–254.
- Mastalerz, M., Stankiewicz, A.B., Salmon, G., Kvale, E.P., Millard, C.L., 1997. Organic geochemical study of sequences overlying coal seams; example from the Mansfield Formation (lower Pennsylvanian), Indiana. *International Journal of Coal Geology* 33, 275–299.
- Mavridou, E., Antoniadis, P., Khanaqa, P., Riegel, W., Gentzis, T., 2003. Paleoenvironmental interpretation of the Amynteon–Ptolemaida lignite deposit in northern Greece based on its petrographic composition. *International Journal of Coal Geology* 56, 253–268.
- McCabe, P.J., 1984. Depositional environments of coal and coalbearing strata. In: Rahmna, R.A., Flores, R.M. (Eds.), *Sedimentology of coal and coal-bearing sequences*. Int. Assoc. Sedimentol., Spec. Publ. 7. Blackwell, Oxford, pp. 13–43.
- McCabe, P.J., 1987. Facies studies of coal and coal-bearing strata. In: Scott, A.C. (Ed.), *Coal and coal-bearing strata: recent advances: Geological Society Special Publication*, 32, pp. 51–66.
- Moore, T.A., Shearer, J.C., 2003. Peat/coal type and depositional environment — are they related? *International Journal of Coal Geology* 56, 233–252.
- Moore, T.A., Shearer, J.C., Miller, S.L., 1996. Fungal origin of oxidised plant material in the Palangkaraya peat deposit, Kalimantan Tengah, Indonesia: Implications for 'inertinite' formation in coal. *International Journal of Coal Geology* 30, 1–23.
- Mukhopadhyay, P.K., 1992. Maturation of organic matter as revealed by microscopic methods: applications and limitations of vitrinite reflectance, and continuous spectral and pulsed laser fluorescence microscopy. In: Wolf, K.H., Chilingarian, G.V. (Eds.), *Diagenesis III. Developments in Sedimentology*, 47. Elsevier Science, Pub, Amsterdam, pp. 435–510.
- Mukhopadhyay, P.K., 1994. Vitrinite reflectance as maturity parameter: petrographic and molecular characterization and its applications to basin modeling. In: Mukhopadhyay, P.K., Dow, W.G. (Eds.), *Vitrinite reflectance as a maturity parameter: ACS Symposium Series*, 570, pp. 1–25.
- Neuzil, S.G., Supardi, Cecil, C.B., Kane, J.S., Soedjono, K., 1993. Inorganic geochemistry of domed peat in Indonesia and its implication for the origin of mineral matter in coal. In: Cobb, J.C., Cecil, C.B. (Eds.), *Modern and ancient coal-forming environment: Special Paper-Geological Society of America*, 286, pp. 23–84.
- Obaje, N.G., Ligouis, B., Abaa, S.I., 1994. Petrographic composition and depositional environments of Cretaceous coals and coal measures in the Middle Benue Trough of Nigeria. *International Journal of Coal Geology* 26, 233–260.
- O'Keefe, J.M.K., Hower, J.C., 2011. Revisiting Coos Bay, Oregon: a re-examination of funginite–huminites relationships in Eocene subbituminous coals. *International Journal of Coal Geology* 85, 34–42.
- Phillips, S., Bustin, R.M., Lowe, L.E., 1994. Earthquake induced flooding of a tropical coastal peat swamp: a modern analogue for high sulphur coals? *Geology* 22, 929–932.
- Postma, D., 1982. Pyrite and siderite formation in brackish and freshwater swamp sediments. *American Journal of Science* 282, 1151–1183.
- Price, L.C., Barker, C.E., 1985. Suppression of vitrinite reflectance in amorphous rich kerosene — a major unrecognized problem. *Journal of Petroleum Geology* 8, 59–84.
- Ratanasthien, B., Kandharosa, W., Chompusri, S., Chartprasert, S., 1999. Liptinite in coal and oil source rocks in northern Thailand. *Journal of Asian Earth Sciences* 17, 301–306.
- Ruppert, L.F., Stanton, R.W., Cecil, C.B., Eble, C.F., Dulong, F.T., 1991. Effects of detrital influx in the Pennsylvanian Upper Freeport peat swamp. *International Journal of Coal Geology* 17, 95–116.
- Shibaoka, M., 1978. Micrinite and exsudatinite in some Australian coals, and their relation to the generation of petroleum. *Fuel* 57, 73–77.
- Silva, M.B., Kalkreuth, W., 2005. Petrological and geochemical characterization of Candiotia coal seams, Brazil — implication for coal facies interpretations and coal rank. *International Journal of Coal Geology* 64, 217–238.
- Singh, P.K., Singh, M.P., Singh, A.K., Arora, M., 2010. Petrographic characteristics of coal from the Lati Formation, Tarakan basin, East Kalimantan, Indonesia. *International Journal of Coal Geology* 81, 109–116.
- Sivek, M., Jirásek, J., Sedláčková, L., Čáslavský, M., 2010. Variation of moisture content of the bituminous coals with depth: a case study from the Czech part of the Upper Silesian Coal Basin. *International Journal of Coal Geology* 84, 16–24.
- Spears, D.A., Zheng, Y., 1999. Geochemistry and origin of elements in some UK coals. *International Journal of Coal Geology* 38, 161–179.
- Speight, J.G., 2005. *Handbook of Coal Analysis*. John Wiley & Sons, Inc., Publication. 222 pp.
- Stach, E., Mackowsky, M.Th., Teichmüller, M., Taylor, G.H., Chandar, D., Teichmüller, R., 1982. *Stach's Textbook of Coal Petrology*, 3rd edition. Gebrüder Borntraeger, Berlin. 535p.
- Staub, J.R., 1991. Comparisons of central Appalachian Carboniferous coal beds by benches and a raised Holocene peat deposit. *International Journal of Coal Geology* 18, 45–69.
- Staub, J.R., 2002. Marine flooding events and coal bed sequence architecture in southern West Virginia. *International Journal of Coal Geology* 49, 123–145.
- Staub, J.R., Esterle, J.S., 1992. Evidence for a tidally influenced upper Carboniferous omogenous mire system — Upper bench, Beckley bed (Westphalian A), southern West Virginia. *Journal of Sedimentary Petrology* 62, 411–428.
- Suárez-Ruiz, I., Jiménez, A., Iglesias, M.J., Laggoun-Defarge, F., Prado, J.G., 1994a. Influence of the resinite on huminite properties. *Energy & Fuels* 8, 1417–1424.
- Suárez-Ruiz, I., Iglesias, M.J., Jiménez Bautista, A., Laggoun-Defarge, F., Prado, J.G., 1994b. Petrographic and geochemical anomalies detected in the Spanish Jurassic jet. In: Mukhopadhyay, P.K., Dow, W.G. (Eds.), *Vitrinite reflectance as a maturity parameter: applications and limitations*. American Chemical Society Symposium Series, 570. ACS Books, pp. 76–92. Chapter 6.
- Suárez-Ruiz, I., Flores, D., Filho, J.G.M., Hackley, P.C., 2012. Review and update of the applications of organic petrology: Part 1, Geological applications. *International Journal of Coal Geology*. doi:10.1016/j.coal.2012.02.004.
- Sýkorová, I., Pickel, W., Christanis, K., Wolf, M., Taylor, G.H., Flores, D., 2005. Classification of huminite—ICCP System 1994. *International Journal of Coal Geology* 62, 85–106.
- Taylor, G.H., Teichmüller, M., Davis, A., Diessel, C.F.K., Littke, R., Robert, P., 1998. *Organic Petrology*. Gebrüder Borntraeger, Berlin-Stuttgart. 704 pp.
- Teichmüller, M., 1974. In: Tissot, B., Biener, F. (Eds.), *Generation of petroleum-like substances in coal seams as seen under the microscope: Adv. Org. Geochem.*, 1973, pp. 321–348.
- Teichmüller, M., Taylor, G.H., Littke, R., 1998. The nature of organic matter-macerals and associated minerals. In: Taylor, G.H., Teichmüller, M., Davis, A., Diessel, C.F.K., Littke, R., Robert, P. (Eds.), *Organic Petrology*. Gebrüder Borntraeger, Berlin. 704 pp.
- Triplehorn, D., 1990. Applications of tonsteins to coal geology: some examples from western United States. *International Journal of Coal Geology* 16, 157–160.
- Turner, B.R., Richardson, D., 2004. Geological controls on the sulphur content of coal seams in the Northumberland Coalfield, Northeast England. *International Journal of Coal Geology* 60, 169–196.
- Ward, C.R., 2002. Analysis and significance of mineral matter in coal seams. *International Journal of Coal Geology* 50, 135–168.
- Ward, C.R., Suárez-Ruiz, I., 2008. Chapter 1 Introduction to applied coal petrology. 388p. In: Suárez-Ruiz, I., Crelling, J.C. (Eds.), *Applied Coal Petrology — the Role of Petrology in Coal Utilization*. ISBN: 978-0-08-045051-3, pp. 1–18.
- Wilkins, R.W.T., George, S.C., 2002. Coal as a source rock for oil: a review. *International Journal of Coal Geology* 50, 317–361.
- Williams, E.G., Keith, M.L., 1963. Relationship between sulphur in coals and the occurrence of marine roof beds. *Economic Geology* 58, 720–729.
- Wüst, R.A.J., Hawke, M.I., Bustin, R.M., 2001. Comparing maceral ratios from tropical peatlands with assumptions from coal studies: do classic coal petrographic interpretation methods have to be discarded? *International Journal of Coal Geology* 48, 115–132.
- Wüst, R.A.J., Ward, C.R., Bustin, R.M., Hawke, M.I., 2002. Characterization and quantification of inorganic constituents of tropical peats and organic-rich deposits from Tasek Bera (Peninsular Malaysia): implications for coals. *International Journal of Coal Geology* 49, 215–249.
- Yin, E.H., 1991. *Annual Report Geological Survey of Malaysia 1991*. 134p. ISSN 0127-0559.