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Berau coal in East Kalimantan; Its petrographics characteristics and depositional environment

NANA SUWARNA and BAMBANG HERMANTO
Center for Geological Survey, Jalan Diponegoro No.57, Bandung

ABSTRACT

To asses the characteristics of the Early to Middle Miocene Berau coal in the Berau Basin, leading to interpretation of coal depositional environments, some fresh outcrop and subcrop samples and also drill cores of the coals have been analyzed microscopically. Coal petrographic analysis was performed on twenty four coal samples from the Middle Miocene Lati Formation. Vitrinite, present in a high value, and ranging between 66.2 - 96.2%, is dominated by vitrinite B. On the other hand, inertinite and exinite, showing a similar value, exist in a low to moderate amount. Vitrinite reflectance, present in a low value, varies from 0.40 - 0.58%. Low mineral matter content is dominated by clay minerals (0.4 - 6.6%) with minor pyrite.

Transitions from wet and very wet forested swamps to drier conditions with lower tree density are indicated by the higher content of vitrinite B, whilst a reverse trend is indicated by the lower content of vitrinite A. Petrographic indices obtained from facies diagnostic macerals show that an accumulation of the ancient peats under prevailing relatively wet limited influx clastic marsh to very wet forest swamps or moors is considered. The composition of the coal samples supports the interpretation of a system of fluvial to meandering streams in an upper delta plain environment. The original peat-forming vegetation was composed mainly of cellulose rich, shrub-like plants, tree ferns, herbaceous plant communities, with minor amount of trees. Thereby, the organic facies concept is thus applicable in basin studies context and has potential to become an additional tool for depositional environment interpretation.

Keywords: Berau Coal Measures, Miocene, East Kalimantan, petrography, depositional environment

SARI

Dua puluh empat percontoh batubara Formasi Lati berumur Miosen Tengah di Cekungan Berau, yang diambil dari singkapan ataupun inti bor, dianalisis secara petrografis untuk kemudian hasilnya digunakan dalam pendugaan lingkungan pengendapannya. Kelompok vitrinit yang menunjukkan kandungan tinggi dan berkisar dari 66,2 - 96,2%, didominasi oleh vitrinit B. Sementara itu, inertinit dan eksinit hadir dalam kandungan hampir sama, dengan kisaran rendah sampai menengah. Reflektan vitrinit umumnya termasuk kategori rendah, yakni dalam kisaran 0,40 - 0,58%. Selanjutnya, bahan mineral yang didominasi oleh mineral lempung memperlihatkan kandungan rendah, dengan kisaran 0,4 - 6,6%.

Peralihan dari kondisi basah dan sangat basah lingkungan rawa bertumbuhan tinggi ke arah kondisi lebih kering dengan tumbuhan rendah atau perdu ditunjukkan oleh kandungan vitrinit B tinggi, sedangkan vitrinit A kandungannya rendah. Indeks petrografi memperlihatkan bahwa bahan dasar batubara diduga terendapkan di zona rawa basah dengan influx klastika terbatas sampai rawa basah bertumbuhan tinggi. Berdasarkan komposisi batubara diduga lingkungan pengendapannya adalah fluviatil berkekelok sampai dataran delta bagian atas. Komposisi batubara memperlihatkan bahwa vegetasi pembentuk batubara terutama terdiri atas kumpulan tumbuhan herbaceous, paku-pakuan, dan tanaman perdu yang kaya akan selulosa, sementara pohon tinggi hadir dalam jumlah yang kecil. Oleh karena itu, konsep fasies organik ini dapat diterapkan dalam konteks kajian cekungan, dan berfungsi sebagai salah satu parameter penafsiran lingkungan pengendapan.

***Kata Kunci**: Batubara Berau, Miosen, Kalimantan Timur, petrografi, lingkungan pengendapan*

Introduction

Petrographic analysis of coal provides information about the numerous physical components that comprise coal. Besides determining the coal maceral and mineral matter, the analysis is also used to investigate coal depositional environment.

This paper will emphasize most of the coal petrographic data within the Berau Coal Measures, located in Lati, Sambarata, and Binungan regions (Figure 1), related to its palaeodepositional environment. The data presented here are discussed in terms of two geological problems, such as: (1) Are there any relationships between maceral composition of the coal and its depositional environments? and (2) Are changes in maceral composition due to the change in peat swamp vegetation?

A significant amount of new data from fresh outcrop, subcrop and drill core samples has been obtained during a cooperation project between LEMIGAS and GRDC for CBM inventory in 2004-program of the Research and Development Centre For Oil and Gas Technology – LEMIGAS, and a coal research conducted by Geological Research and Development Centre - GRDC (now Geological Survey Institute) in 2005. Thereby, a useful review of the patterns of maceral distribution in the Berau seams can now be made.

Methods

Sample Preparation and Microscopic Analysis

A channel or ply-and-ply coal sample was taken for petrographic analyses from each sub-seam. Microscopic results on twenty four coal samples collected from the Berau Basin were assembled. Majority of the samples had microscopically been analysed by the authors at the GSI (formerly GRDC) laboratory.

Petrographic analysis required for the study was focused on maceral and mineral matter analyses, determined by reflected light microscopy on polished specimens made from crushed samples mounted in epoxy resin. The polished briquettes were prepared from crushed 1 mm-size samples representing each sample, which were then mounted in epoxy resin. Ordinary white reflected light from a tungsten lamp and violet-blue light from a high-pressure mercury lamp to initiate fluorescence were used for illumination. Maceral observation was carried out on a Leitz MPV-2 photomicroscope.

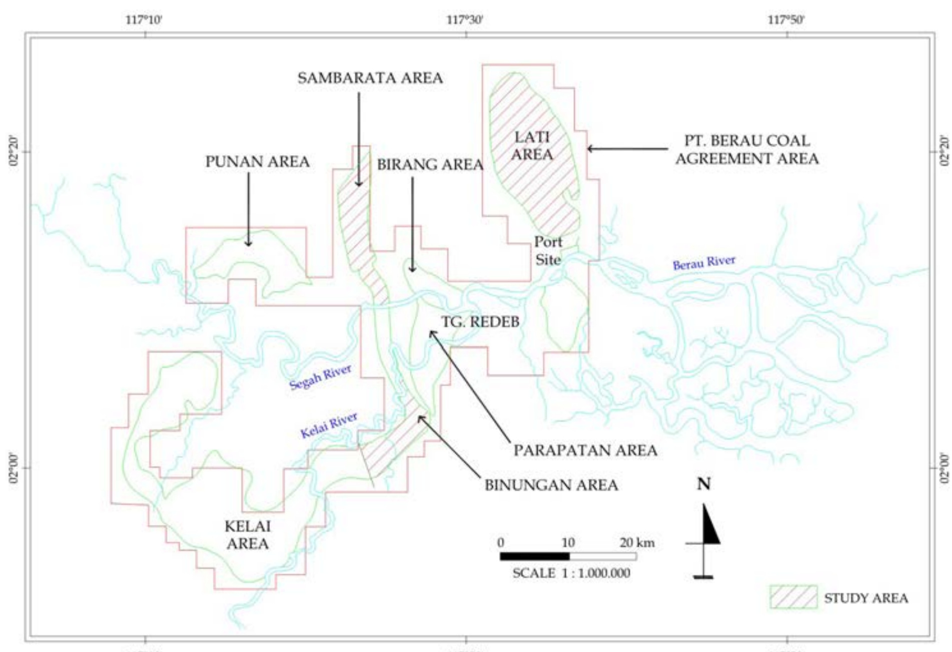

Figure 1. Locality map of the studied area (source map: PT Berau Coal, 1999).

In all essential aspects, the preparation and polishing of the specimens are done in accordance with Standard Association of Australia (1977). Furthermore, according to the Standard Association of Australia (1981, 1986), the analyses are based on point counting of 500 macerals on one specimen of each sample. The methods used for estimation of organic matter abundance and maceral composition are outlined in Cook & Kantsler (1982), Sappal (1986) and Struckmeyer & Felton (1990). The reported results are expressed as semiquantitative volumetric percentages of the various microscopically recognizable macerals including mineral matter of the coal, which are defined by their morphology and colour. Vitrinite, inertinite, and exinite data are reported in terms of sub-macerals.

Most macerals determined are defined by the International Committee for Coal Petrology (ICCP, 1963, 1971, 1975, and 1993). Brown *et al*. (1964) introduced vitrinite A and B terms used as convenient terms to separate the structured vitrinite macerals from the unstructured or degraded vitrinites. Macerals telinite, telocollinite, and *in-situ* corpocollinite are included into vitrinite A sub-group; whereas vitrinite B includes desmocollinite, gelocollinite and detrital corpocollinite. The nomenclature and classification of the macerals used for the study are given in Table 1.

Coal Facies and Palaeoenvironmental Analysis

According to McCabe (1987) and Moore (1987 and 1989), a ‘mire’ (moor) is a habitat in which organic material, especially peat is accumulated. ‘Low moors’ or ‘topogenic mires’ are environments of peat or coal deposition, generally slowly sinking depressions, where mineral input is nil or very small, in which the groundwater table can keep abreast of peat formation. However, ‘high moors’ or ‘ombrogeneous mires’ including ‘blanket bogs’ and ‘raised bogs’, which may form above the groundwater table, only occupy areas of very high rainfall.

The abundance of vitrinite in the coal is indicative of a wet forest swamp environment (Teichmüller and Teichmüller, 1982; Bustin *et al*., 1983), mainly from arborescent vegetation (Rimmer and Davis, 1988). Teichmüller and Teichmüller (1982), Stout and Spackman (1989), and Shearer and Moore (1994) stated that the type of vegetation, depth of water, pH, bacterial activity, and temperature of peat, or mixed environmental conditions across the peat swamp (Marchioni and Kalkreuth, 1991) might be resulted in the high content of degraded vitrinite.

Furthermore, coals deposited in wet forest swamp of upper delta plain and fluvial environments are rich in vitrinite (wet forest swamp), and also in clastic clay minerals. Generally, coals rich in vitrinite are thought to have been deposited in wet and more anoxic environments.

Predominantly, decomposition of fragile, cellulose-rich plant tissues tend to produce the finely divided detritus, which then suggest an indication of an open limnotelmatic to telmatic facies (Hacquebard and Donaldson, 1969; Teichmüller, 1982; Teichmüller and Teichmüller, 1982; Diessel, 1986 and 1992). Moreover, within this facies, herbaceous-like plants and small gymnosperms yield vitrodetrinite, whilst tissues of shrubs, trees and ferns form telinite. The gelified telinite is considered to be derived from both biochemical and geochemical gelifications of plant remains rich in cellulose and lignin (tissues from shrub-like plants, small trees, and probably, fern trees).

Table 1. Maceral Classification (modified from I.C.C.P., 1963 and 1971)

Maceral Group		Maceral	Sub-maceral
Vitrinite	Structured	Vitrinite A	Telinite
			Telocollinite
	Unstructured	Vitrinite B	Desmocollinite
			Corpocollinite
			Vitrodetrinite
Exinite		Sporinite	
		Cutinite	
		Resinite	
		Liptodetrinite	
		Alginite	Lamalginite
			Telalginite
		Suberinite	
Inertinite	Structured	Fusinite	
		Semifusinite	
	Unstructured	Sclerotinite	
		Macrinite	
		Inertodetrinite	

In cases, where a more alkaline environment is established, the growth of bacteria is favoured, which then promoted decomposition and lead to a higher amount of gelification (Cecil *et al.*, 1980; Teichmüller and Teichmüller, 1982; McCabe, 1984 and 1987). This condition is due to the increasing pH in the swamp water.

Peat fires, desiccation of the peat surface, or percolating oxygenated water lead to the formation of inertinite. The presence of inertodetrinite reflects a charring process of the thin-walled, herbaceous, in situ vegetation occurred. Furthermore, a redeposition of desiccated peat surface and fragmentation of the fusinite during transportation, or *in situ* formation and disintegration of fusinite during drier conditions formed inertodetrinite (Cohen, 1973; Diessel, 1982; Teichmüller, 1982; Hunt and Smyth, 1989; Marchioni and Kalkreuth, 1991). Predominantly, a woody tissue charring from shrubs and trees resulted in the fusinite formation. The cell structure in semifusinite is normally poorly preserved. Desiccation and oxidation at the peat surface or oxygenated water probably lead to an incomplete fusinisation showing by varying reflectance.

Diagnostic maceral ratios or petrographic indices are used as palaeo-environmental indicators. Structured vitrinite, and structured inertinite, alginite, and sporinite are facies diagnostic macerals. The structured vitrinite, formed in a relatively high moisture conditions, are derived from partially gelified woody tissues. On the other hand, the structured inertinite was derived from woody vegetation, but it formed under relatively dry oxidizing conditions. The ratio between vitrinite A and vitrinite B (A/B), structured vitrinite and structure inertinite (T/F), semifusinite and fusinite (SF/F), and also combination of telinite + telocollinite (T), alginite + sporinite + inertodetrinite + macrinite (D), and structure vitrinite + structured inertinite (W), are important diagnostic macerals in coal facies and depositional environmental interpretation.

Furthermore, plotting data on a coal facies diagram by means of the ratio of specific (diagnostic) maceral combinations or petrographic indices, comprising “Tissue Preservation Index” (**TPI**) and the “Gelification Index” (**GI**) is another way to determine the depositional environment of the coals (Diessel, 1965, 1982, 1992). These petrographic indices are formulated as follows:

$$\textbf{TPI} = \frac{\text{Structured (Vitrinite + Inertinite)}}{\text{Unstructured Vitrinite + Macrinite}}$$

$$\textbf{GI} = \frac{\text{(Vitrinite + Macrinite)}}{\text{(Inertinite - Macrinite)}}$$

The TPI is a measure of the relationship between tissue and groundmass in the coal, whilst the GI is a measure of the humidity in the swamp. A decrease in the GI indicates an increase in oxidation, whereas a decrease in TPI suggests a decrease in lignified tissue compensated by an increase in coal groundmass. The formulae used is in accordance with the Kalkreuth *et al.*'s formulae (1991), as a modification of Diessel's (1965, 1986) in order to suit the type of the coals. The indices can be affected by the different plant communities and the degree of degradation.

High TPI and GI values indicate a wet condition of peat formation; whilst a dry condition is shown by low TPI and GI. Thereby, TPI indicates the type of plant input, whilst GI plays an important role in representing influence of groundwater. The high TPI and GI values, in which the content of vitrinite > inertinite and structured vitrinite > degraded vitrinite, occur in wet forest swamp of telmatic zone with rapid burial (Lamberson *et al.*, 1991). However, microbial attacks present on coal precursor that was deposited in limited influx-clastic marsh tend to produce low-moderate TPI and the high GI values. The coal existing is characterized by vitrinite > inertinite, and degraded vitrinite > structured vitrinite.

A degradation level of woody tissue structure of plant remnants can be predicted from the TPI - GI combination. Low TPI and high GI values imply that the coals were deposited in a limited influx, clastic marsh environment. In this case, the inertinite content is very low, due to the limited aerobic degradation process of cell structure (Lamberson *et al.*, 1991).

Additional information of the depositional environment can be provided by the mineral matter content. Minerals may indicate a periodic inundation of the peat from a nearby, active, clastic depositional environment. McCabe (1984, 1987) explained that an infrequent flooding event, with accompanying transport of minerals, will have a relatively large influence on the overall peat composition, if accumulation rates of organic matter are low. The syngenetic pyrite is the most important mineral in facies analysis, because its precipitation was contemporary with peat accumulation. High pyrite contents, associated with marine-influenced coal facies was accepted by Mackowsky (1982), Teichmüller and Teichmüller (1982), Styan and Bustin (1983), and Casagrande, (1987).

Geologic Setting

The Berau Coalfield is located in the Berau Basin (formerly Berau Sub-basin of the Tarakan Basin; Figure 2), occupying an area around and along the Berau River, East Kalimantan (Figure 3). The Mangkalihat Highs/Peninsula separates the basin from the Kutai Basin situated to the south (Tossin and Kadir, 1996).

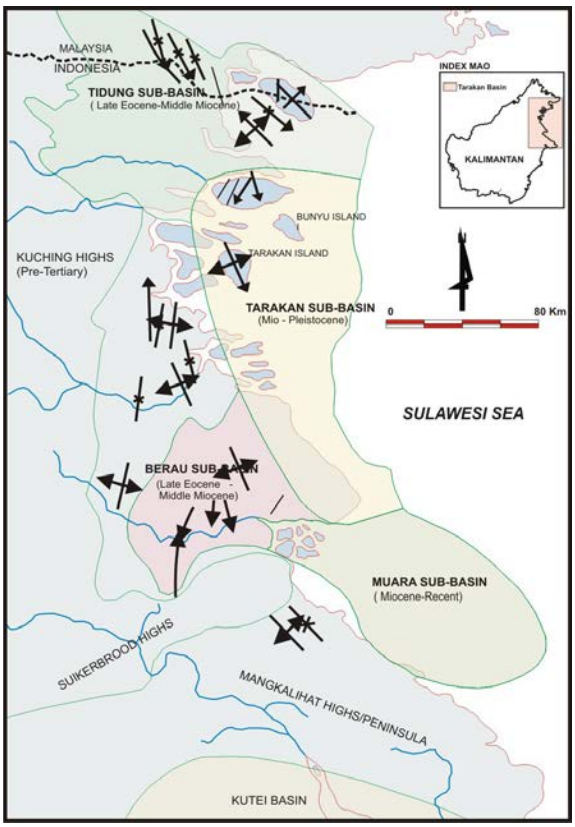

Figure 2. Locality map of the Tarakan Basin, divided into: Tidung, Tarakan, Berau, and Muara Sub-Basins (Tossin & Kadir, 1996).

Several published and unpublished reports, *e.g*. Situmorang and Burhan (1995 a,b) and PT Berau Coal (1999) have described the geologic setting of the Berau area. Geologically, the studied area includes the Lati Syncline and Rantaupanjang Anticline, showing NNW - SSE fold axis (Figure 3).

The basin is presumed to develop in a back-arc setting, during the Late Cretaceous - Early Tertiary. Predominantly, the depression was filled with Tertiary paralic to marine clastics. Sedimentation of the Tertiary sedimentary units was tectonically controlled, and each rock unit is separated along their lower and upper contacts by a well-defined conformity.

Stratigraphically, the Sembakung, Tabalar, Birang, Lati, Labanan, Domaring, and Sinjin Formations are recognized in the studied area, from older to younger units, respectively (Situmorang and Burhan, 1995 a,b). However, PT. Berau Coal (1999) stated that the Tertiary formations, occupying the region, comprised the Tabalar Marls (Tes), Lepidocyclina Limestone (Tol), Globigerina Marls (Tog), Sterile Formation (Tms), Berau Formation (Tmb), Labanan Formation (Tmp), and Bunyu-Sajau Formations (Tp) (Figure 3). Sediments containing coal seams are the Miocene Lati Formation or the Berau Formation (Berau Coal Measures). The coal measures are underlain by the Oligo-Miocene Birang Formation, and overlain by the Mio-Pliocene Labanan Formation.

The Oligo-Miocene Birang Formation, underlying conformably the Berau Formation, consists of two parts. Alternating marl, chert, conglomerate, quartz sandstone, and limestone form the lower portion; whilst the upper part comprises alternating marl, limestone, and tuff. The rock unit is more than 1000 m thick, and was deposited in a shallow to deep marine environment. The Birang Formation (Situmorang and Burhan, 1995 a,b) is equivalent to the Lepidocyclina Limestone, Globigerina Marl, and Sterile Formation of PT Berau Coal's (1999).

The Berau Coal Measures (Berau Formation) of late Early Miocene age, or the Lati Formation is a potential coal-bearing unit in the region. The lower part, deposited in a delta plain environment is barren in coal; whilst the upper part, containing coal seams, was deposited in a fluvial to upper delta plain zone. The coal measures, generally, comprising quartz

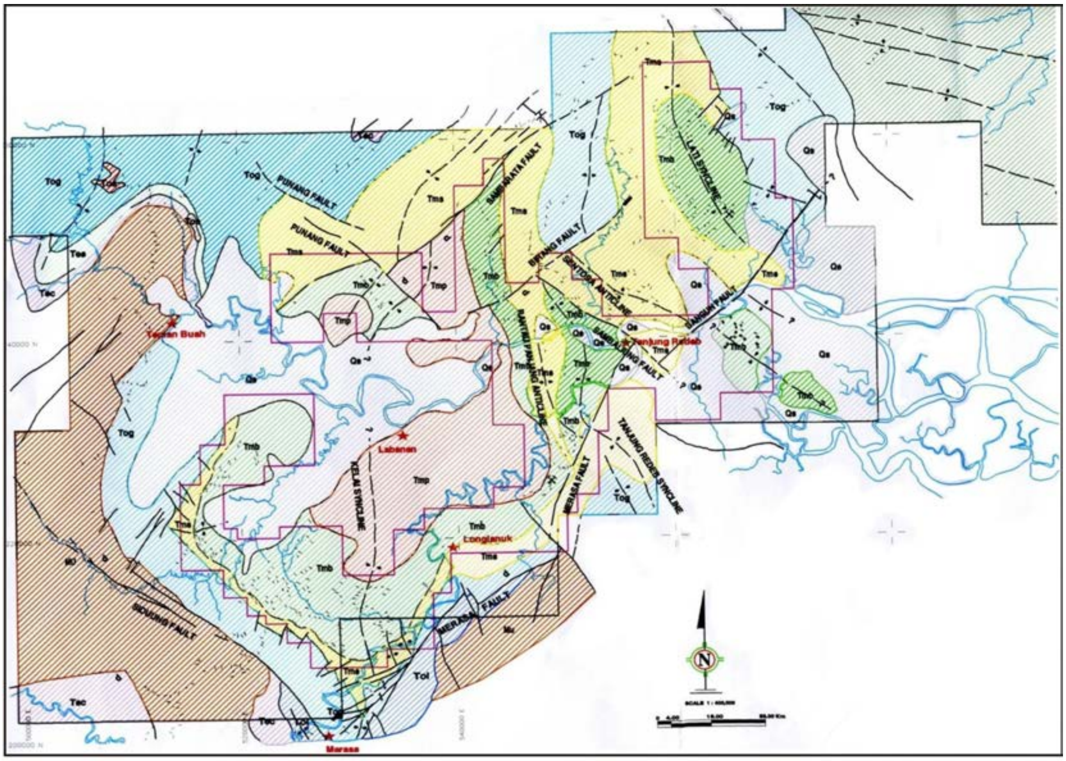

Figure 3. Geological map of the study area and its surroundings (after PT Berau Coal, 1999).

sandstone, claystone, siltstone, conglomerate, and coal, alternate with sand shale in the upper part. The formation, being up to 800 m in thickness, overlies conformably the Birang Formation.

The Mio-Pliocene Labanan Formation consisting of alternating polymict conglomerate, sandstone, siltstone, claystone, and thin coal intercalations, has a thickness of about 450 m. The formation deposited in a fluvial environment, overlies unconformably the Lati Formation.

The Late Miocene to Pliocene Domaring Formation interfingering with the Labanan Formation, is composed of reef limestone, chalky limestone, marl, and coal intercalations. The formation is 1000 m thick, and was deposited in a swampy area to littoral zone.

Petrography of Coal

Thirteen different macerals and three mineral matters were identified (Table 2). The terminology for middle rank coals was used because the coal seams, based on vitrinite reflectance values, are sub-bituminous in rank. The coal samples were primarily identified on the basis of the maceral composition, but the pyrite content, especially framboidal type, was also a significant parameter. Detailed discussion on the petrographic data, which then related to the interpretation of coal depositional environment is gained mainly from maceral analysis, presented as follows:

Maceral and Mineral Matter

Table 2 shows data of the maceral and mineral matter proportion in the individual Berau coals, whilst Table 3 presents their ratios of specific maceral combinations (measure of petrographic indices).

Table 2 indicates that the Berau coals, predominantly, have consistently high proportions of vitrinite (66.2 - 96.2%), that is dominated by vitrinite B. Inertinite content exists in a low to moderate level, varying from 0.6 - 14.4%; however one sample shows a high content, that is 26.6%. The presence of exinite, ranging between 0.8 - 6.8%, and mineral matter between 0.4 - 10.6% fall under low to medium

Table 2. Maceral and Mineral Matter Analysis Data of the Berau Coal

Sample No.	Maceral (%)																	%						Rv (%)		
	Tl	Dt	Gl	**V**	F	Sf	Ma	Sc	Idt	**I**	Re	Sp	Sb	Cu	Alg	Lpt	**E**	Cly	Crb	PFr	Py	**MM**	Min	Max	**Av**
1.	59.0	29.6	2.6	**91.2**	-	2.4	-	2.6	1.0	**6.0**	1.2	-	-	0.6	-	-	**1.8**	0.4	-	-	0.6	1.0	0.35	0.50	**0.42**
2.	54.8	30.0	2.4	**87.2**	1.8	2.2	-	1.0	0.4	**5.4**	1.2	-	-	0.8	-	0.8	**3.2**	1.2	-	1.6	1.4	4.2	0.42	0.60	**0.46**
3.	47.4	24.6	0.8	**72.8**	0.4	2.0	-	7.0	3.0	**12.4**	2.6	-	0.6	1.0	0.2	-	**4.2**	1.0	-	8.2	1.4	10.6	0.36	0.58	**0.46**
4.	47.6	30.4	0.6	**78.0**	0.6	5.0	-	6.6	1.0	**13.2**	2.4	-	-	-	-	-	**2.4**	2.4	-	1.6	2.4	6.4	0.38	0.62	**0.49**
5.	16.2	50.0	-	**66.2**	2.0	17.0	-	4.0	3.6	**26.6**	2.4	-	1.0	1.4	-	-	**4.8**	0.6	-	0.4	1.4	**2.4**	0.31	0.51	**0.41**
6.	22.0	60.0	10.4	**92.4**	-	0.6	-	1.6	0.4	**2.6**	1.8	-	0.6	0.2	-	-	**2.6**	2.0	-	-	0.4	**2.4**	0.35	0.55	**0.48**
7.	42.0	41.6	3.2	**86.6**	-	3.4	-	2.4	0.4	**6.2**	3.4	-	-	3.0	-	-	**6.4**	0.4	-	-	0.2	**0.6**	0.40	0.67	**0.50**
8.	35.6	41.4	3.0	**80.0**	-	12.0	-	1.4	1.0	**14.4**	0.4	-	1.0	1.6	-	-	**3.0**	1.8	-	0.4	0.4	**2.6**	0.43	0.67	**0.55**
9.	15.6	69.4	4.6	**89.6**	-	2.6	-	0.8	0.6	**4.0**	2.0	-	0.4	1.4	-	-	**3.8**	1.8	-	-	0.8	**2.6**	0.46	0.70	**0.61**
10.	39.6	43.4	-	**83.0**	-	4.6	-	3.4	0.6	**8.6**	4.0	0.4	1.0	1.0	-	-	**6.4**	1.8	-	-	0.2	**2.0**	0.53	0.74	**0.62**
11.	38.0	52.0	0.6	**90.6**	-	-	-	2.0	1.2	**3.2**	3.0	-	0.6	1.0	-	-	**4.6**	1.2	-	-	0.4	**1.6**	0.38	0.55	**0.47**
12.	42.0	41.6	3.2	**86.6**	0.2	3.2	-	2.4	0.4	**6.2**	3.4	-	-	3.0	-	-	**6.4**	0.4	-	-	0.2	**0.6**	0.40	0.67	**0.50**
13.	36.6	46.4	2.4	**85.4**	-	0.6	-	4.6	1.6	**6.8**	2.4	0.4	-	2.0	-	-	**4.0**	2.6	-	-	0.4	**3.0**	0.48	0.71	**0.58**
14.	44.4	45.2	0.4	**90.6**	-	0.4	-	2.6	1.4	**4.4**	3.4	0.4	-	0.6	-	-	**4.0**	1.0	-	-	0.6	**1.6**	0.47	0.72	**0.58**
15.	46.4	48.6	0.2	**95.2**	-	0.6	-	2.0	1.0	**3.6**	0.4	0.4	-	-	-		**0.8**	-	-	-	0.4	**0.4**	0.41	0.55	**0.48**
16.	24.6	55.6	3.0	**83.2**	-	3.6	-	5.4	0.6	**9.6**	3.6	-	0.6	1.0	-	0.4	**5.6**	1.4	-	-	0.4	**1.6**	0.40	0.61	**0.51**
17.	50.2	36.8	2.2	**89.2**	-	0.4	-	0.8	-	**1.2**	0.6	-	-	2.4	-	-	**3.0**	4.4	-	0.2	2.0	**6.6**	0.36	0.52	**0.43**
18.	29.4	59.4	1.0	**89.8**	-	0.6	0.4	2.6	0.2	**3.8**	0.6	-	-	1.0	-	-	**1.6**	3.8	-	-	2.0	**5.8**	0.39	0.62	**0.50**
19.	21.0	66.0	1.2	**88.2**	-	1.4	0.2	2.0	1.4	**5.0**	2.4	1.0	-	3.0	-	-	**6.4**	0.2	-	-	0.2	**0.4**	0.58	0.76	**0.66**
20.	32.4	48.6	0.6	**81.6**	-	2.0	0.4	2.4	1.4	**6.2**	1.6	-	1.6	3.4	-	-	**6.8**	3.6	-	-	1.8	**5.4**	0.45	0.67	**0.57**
21.	37.6	56.0	2.6	**96.2**	-	-	-	0.6	-	**0.6**	-	-	-	1.2	-	-	**1.2**	1.4	-	-	0.6	**2.0**	0.46	0.66	**0.58**
22.	28.4	60.4	0.4	**89.2**	0.2	3.4	-	3.0	0.6	**7.2**	0.4	-	0.6	1.0	-	-	**2.0**	1.0	-	-	0.6	**1.6**	0.59	0.77	**0.70**
23.	41.6	51.6	0.6	**93.8**	-	-	-	0.6	0.4	**1.0**	1.4	-	-	3.4	-	-	**4.8**	-	-	-	0.4	**0.4**	0.41	0.67	**0.57**
24.	19.6	70.0	-	**89.6**	-	1.6	-	1.0	0.6	**3.2**	2.6	-	0.4	1.4	-	6.4	**4.8**	0.6	0.2	-	1.6	**2.4**	0.33	0.56	**0.46**
25.	61.2	15.8	-	**77.0**	-	0.6	-	5.4	0.6	**6.6**	6.0	-	0.4	-	-	-	**6.4**	7.0	-	-	3.0	**10.0**	0.36	0.52	**0.42**
26.	63.6	21.6	-	**85.2**	-	-	-	7.0	0.8	**7.8**	3.4	-	-	-	0.2	-	**3.6**	2.0	-	0.2	1.2	**3.4**	0.35	0.52	**0.40**

Remarks:

Tl = telocollinite	**V** = vitrinite	Ma = macrinite	**I** = inertinite	Sb = suberinite	Lpt = liptodetrinite	Crb = carbonate	**MM**= mineral matter
Dt = detrovitrinite	F = fusinite	Sc = sclerotinite	Re = resinite	Cu = cutinite	**E** = exinite	PFr = framboidal pyrite	min = minimum **Av**= average
Gl = gelocollinite	Sf = semifusinite	Idet = inertodetrinite	Sp = sporinite	Alg = alginite	Cl = clay	Py = pyrite	max = maximum Rv=reflectance

Table 3. Maceral Petrographic Indices of the Berau Coal

Sample No.	T	F	T/F	SF/F	D	W	A/B	GI	TPI	Cluster
1.	59.0	2.4	24.58	-	3.6	61.4	1.8	15.2	1.73	C
2.	54.8	4.0	13.7	1.22	1.4	58.8	1.69	16.15	1.74	C
3.	47.4	2.4	19.75	5.0	10.0	49.8	1.87	5.87	1.41	C
4.	47.6	11.6	4.10	8.33	7.6	59.2	1.54	5.9	1.38	C
5.	16.2	19.0	0.85	-	7.6	35.2	0.32	2.49	0.61	A
6.	22.0	0.6	36.67	-	2.0	22.6	0.31	35.54	0.31	A
7.	42.0	3.4	12.35	-	2.8	45.4	0.94	13.97	0.96	B
8.	35.6	12.0	2.97	-	2.4	47.6	0.80	5.56	1.02	B
9.	15.6	2.6	6.0	-	1.4	18.2	0.21	22.4	0.24	A
10.	39.6	4.6	8.61	-	4.4	44.2	0.91	9.65	2.09	C
11.	38.0	-	-	-	3.2	38.0	0.72	28.31	0.68	A
12.	42.0	3.4	12.35	16.0	2.8	45.4	0.94	13.97	0.95	B
13.	36.6	0.6	61.0	-	6.6	37.2	0.75	12.56	0.67	A
14.	44.4	0.4	111.0	-	4.4	44.8	0.97	20.59	0.90	B
15.	46.4	0.6	77.33	-	3.4	47.0	0.94	26.44	0.91	B
16.	24.6	3.6	6.83	-	6.0	28.2	0.42	8.67	0.44	A
17.	50.2	0.4	125.5	-	0.8	50.6	1.29	74.33	1.27	C
18.	29.4	0.6	49.0	-	3.2	30.0	0.49	23.74	0.47	A
19.	21.0	1.4	15.0	-	3.7	22.4	0.31	17.68	0.32	A
20.	32.4	2.0	16.2	-	4.2	34.4	0.66	13.23	0.64	A
21.	37.6	-	-	-	0.6	37.6	0.64	160.3	0.64	A
22.	28.4	3.6	7.89	17.0	3.6	32.0	0.47	12.39	0.50	A
23.	41.6	-	-	-	1.0	41.6	0.79	29.3	0.78	B
24.	19.6	1.6	12.25	-	1.6	21.22	0.28	28.0	0.30	A
25.	61.2	0.6	10.2	-	0.6	61.2	3.87	11.67	2.75	C
26.	63.6	-	-	-	0.8	63.6	2.94	10.92	2.24	C

Remarks:

T(elinite) = telinite + telocollinite
D(ispersed) = alginite + sporinite + inertodetrinite + macrinite
T/F = structured (vitrinite/inertinite)
SF/F = semifusinite/fusinite
F(usinite) = fusinite + semifusinite
W(oody) = structured (vitrinite + inertinite)
A/B = vitrinite A/vitrinite B
TPI = structured (vitrinite + inertinite)/ unstructured (vitrinite+inertinite) + macrinite
GI = (Vitrinite + macrinite)/inertinite

degree. Furthermore, vitrinite reflectance values averaging mainly from 0.41 - 0.58%, tend to indicate that the coal falls under sub-bituminous rank.

A remarkable regular maceral and mineral matter contents of the coals studied is recognised, as presented in Table 2.

Vitrinite Group

The high vitrinite content varying from 66.2 to 96.2% (Table 2), is predominated by vitrinite B that is represented by nineteen samples (5 - 16, and 18 - 24); whereas the rest, five samples (1 - 4, and 17), are classified as vitrinite A. The vitrinite A is composed of telocollinite (Figures 4 a, b, d, i, j), whilst vitrinite B consists of desmocollinite and vitrodetrinite showing 24.6 - 70.0% in content and low amount of gelovitrinite (corpocollinite) of 0.2 -10.4 %.

Desmocollinite (Figures 4 c, d, e, g, j), together with gelovitrinite are present as structureless groundmass. Corpocollinite, constituting 0.4 - 10.4%, is included into gelovitrinite. It is usually present as a discrete or *in-situ* excretion, in subrounded to rounded shapes with various sizes (Figures 4 d, g). Detrovitrinite is a common constituent of carbagilite (Figure 4 f). This condition indicates that the coal has undergone a high degree of diagenesis.

A reasonable degree of preservation of decayed plant material present is indicated by the high vitrinite content in most of the coal samples. The vitrinite could be used as a measure of petrographic indices (Table 3) to interpret a peat depositional environment.

Table 2 shows that averaged vitrinite reflectance

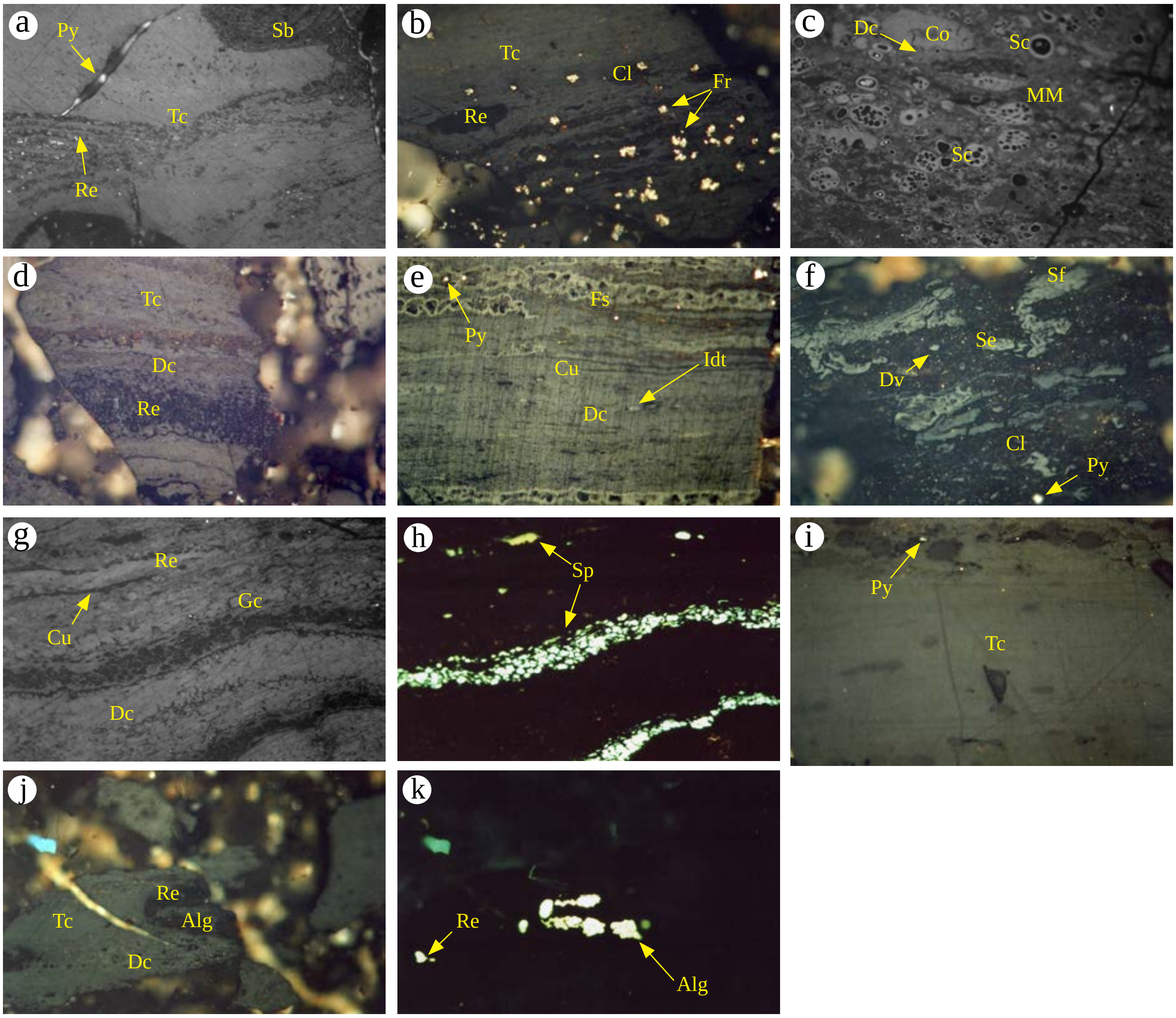

Figure 4. Photomicrographs of macerals and mineral matter of the Berau coals.

a. Photomicrograph of telocollinite (Tc) with resinite (Re), suberinite (Sb), and pyrite (Py); (RL).
b. Photomicrograph of framboidal pyrite (Fr) associated with telocollinite (Tc) and clay minerals (Cl); (RL).
c. Photomicrograph of plenty of sclerotinite (Sc) associated with desmocollinite (Dc) and a little mineral matter (MM); RL).
d. Photomicrograph of telocollinite (Tc), Re (resinite), Dc (desmocollinite), and Sf (semifusinite) (RL).
e. Photomicrograph of desmocollinite (Dc), fusinite (Fs), cutinite (Cu), and inertodetrinite (Idt); (RL).
f. Photomicrograph of semifusinite (Sf), sclerotinite (Sc), detrovitrinite (Dv), and pyrite (Py) embedded within clay minerals (Cl); (RL).
g. Photomicrograph of desmocollinite (Dc), gelocollinite/corpocollinite (Gc), cutinite (Cu), and resinite (Re) (RL).
h. Same as figure 4g, showing resinite assemblages (Re) FL).
i. Photomicrograph of telocollinite (Tc) and tiny specks of pyrite; (RL).
j. Photomicrograph of telocollinite (Tc), desmocollinite (Dc), and exinite (E); (FL).
k. Same as figure 4j. Alginite (telalginite/Alg), and resinite (Re) (Fl).

varies from 0.40 - 0.70%. However, the dominant values range between 0.40 - 0.58%. In this case, the dominant reflectance values of the Berau coal indicate a coalification stage at sub-bituminous level according to the Australian rank value, approximately corresponding to the sub-bituminous A and B rank of the ASTM classification, or Bright Brown Coal of Germany Din and into B3 – D rank of USSR. Furthermore, according to Pareek classification (1987) the Berau coal is assigned as a metalignitous type.

Inertinite Group

The majority of maceral group reaches up to 14.4%, except sample 5 having amount of 26.6% (Table 2). On the basis of their abundance order, the inertinite maceral group consists of sclerotinite, semifusinite, inertodetrinite, fusinite, and macrinite, respectively. Sclerotinite having content of 0.6 - 7.0%, is the predominant maceral of the inertinite group, and commonly associated with vitrinite B (Figures 4 c and f). Semifusinite, the second major inertinite maceral group, varies from 0.4 - 17.0% (Figure 4 h). Inertodetrinite associated with vitrinite and clay mineral (Figures 4 e and f), is 0.2 - 3.6% in content.

The presence of embedded tiny specks of inertodetrinite in the vitrinite (Figure 4 f), suggests that the inertodetrinite has undergone a high degree of degradation. Then, fusinite observed as an association with vitrinite (Figure 4 e), has a value of 0.2 - 2.0%. The lowest maceral content within inertinite group is macrinite, showing amount of 0.2 - 0.4%. Therefore, the inertinite maceral group, in interpreting the coal-precursor palaeoenvironment, could be used as a measure of petrographic indices (Table 3).

Exinite Group

The exinite maceral group is recognized as resinite, cutinite, suberinite, sporinite, liptinite, and alginite (Table 2). The content of the group varies from 1.2 - 6.8%, which falls under low to moderate class. Resinite, observed in almost all samples, except sample 21, is present between 0.4 - 4.0%. It is commonly recognized in an association with cutinite, telocollinite, desmocollinite, and corpocollinite (Figures 4 a, d, g, h, k).

Cutinite, the second major exinite group, present from 0.2 – 3.4%, is associated with desmocollinite, corpocollinite, and resinite (Figures 4 e and g). However, in samples 4 and 15, the cutinite is absence. Suberinite, recognized in samples 3, 5, 6, 8,9, 10, 11, 16, 20, 22, and 24, is associated with telocollinite and resinite (Figure 4 a); its content varies from 0.4 - 1.6%. Sporinite, determined rarely, ranges between 0.4 - 1.0%. It is only observed in samples 10, 13, 14, and 15. Liptodetrinite is present in samples 2, 16, and 24, with content of 0.8%, 0.4%, and 6.4%, respectively. Alginite, existing in the form of telalginite (Figure 4 k), is present as traces. The presence of this submaceral tends to indicate a marine environment.

Mineral Matter

The coal samples are characterized by very low to moderate amounts of mineral matter, comprising clays (Figures 4 b, c, f), pyrites (Figures a, b, f, i), and carbonates. Clay mineral content, predominating the mineral matter, varies from 0.4 - 10.6%. The minor mineral matter is pyrite, composed of syngenetic (framboidal form; Figure 4 b) and epigenetic types filling in cracks and cleats (Figures 4 a, f, i). The framboidal pyrite content is 1.6 - 8.2% in range; whilst the epigenetic type ranges between 0.2 - 2.4%. The presence of framboidal pyrite indicates a marine environment influencing the coal deposition. The rare mineral matter is carbonate that is only determined in sample 24 and shows a value of 0.2%.

Discussions

Palaeoenvironmental Analyses

Table 3 displays the calculated petrographic indices used in the palaeoenvironmental interpretation. The high values of woody substances (W > 49.8), coinciding with high vitrinite-A to vitrinite-B (A/B) ratio and TPI (> 0.5), as represented by samples 1, 2, 3, 4, 17, 25, and 26, indicate the occurrence of well-preserved plant tissues or high degree of woody tissue gelification in the coal. On the other hand, the rest having low values in W (< 47.6), A/B (< 1.0), and TPI (< 0.5) shows a decrease in lignified tissues or tree density. Moreover, high T/F (structured vitrinite/structured inertinite, of >> 1.0) and SF/F (semifusinite/fusinite, of > 1.22) values indicating a low degree of coal oxidation, is supported by high GI value of generally > 5.56. This condition also demonstrates a wetness of forest moor.

The TPI values, occupying a compositional zone around 0.24 - 2.75, can be divided into three clusters (Table 2; Figure 5). Cluster A, the low TPI values (0.24 - 0.68), is represented by samples 5, 6, 9, 11, 13, 16, 18, 19, 20, 21, 22, and 24. Then, cluster B comprising samples 7, 8, 12, 14, 15, and 23, shows a moderate TPI level (0.78 - 1.02). Finally, cluster C, represented by samples 1, 2, 3, 4, 10, 17, 25, and 26 indicates TPI value of 1.27 - 2.75. Cluster A tends to indicate the presence of poor- preserved plant tissues, Then, within cluster B, moderate - to relatively well-preserved plant tissues occur; while cluster C is occupied by well-preserved lignified plant tissues in the coal. The GI, representing by value of commonly more than 5.56, indicates that the coals have a low oxidation degree which is compensated by high gelification process (Lamberson *et al.*, 1991). It means that the coal depositional environment is used to be wet, except sample 5 is probably to be subaqueous, shown by GI value of 2.49.

Predominantly, the samples occur within high GI and TPI. This case indicates a development in a marsh or lake swamp environment under anoxic conditions. High GI with variated TPI values, occurring in the Berau coals (Table 3) show that the depositional environment of the coals was a limited clastic input marsh to fen with microbial attack condition to wet forest swamp of rapid burial characteristics, under limno-telmatic to telmatic zones (Figure 3). However, sample 5 was probably deposited in a transgressive area. The coal, having high GI, should contain plenty of vitrinite both structured and unstructured types, with minor content of structured and unstructured inertinite comprising fusinite, semifusinite, and inertodetrinite. Diessel (1986), Cohen *et al*. (1987), Teichmüller (1989), Lamberson *et al*. (1991) and Calder *et al.* (1991) explained that vitrinite formation well developed, if the peat (coal precursor) is always in a wet condition. All coals studied, dominated by vitrinite lead to the high GI value. Therefore, the coals are suggested to be deposited in a wet zone of a low moor or topogenic mire.

To asses the prevailing moor during deposition of coal precursor, the TPI and GI values are used, as illustrated in Figure 5. This TPI-GI diagram, where all coal samples are located within wet area show that an almost stable wet phase occurred. An evidence of a stable limno-telmatic marsh to fen phase is displayed by samples included into the clusters A and B. On the other hand, another eight coal samples of cluster C tend to suggest a stable telmatic wet forest swamp.

Cluster C falls within telmatic of forest swamp with a rapid burial condition. However, clusters A and B occupy a limnic environment with limited influx-clastic marsh setting under a microbial attack condition. These conditions represent that a relatively permanently flooded area was present during the Berau coal deposition.

According to Kalkreuth *et al*. (1991), somewhat more frequent clastic influx during the Berau peat accumulation and favoured preservation of vitrinite precursor is indicated by a relatively wide TPI plot varying within 0.24 to 2.75 intervals. Moreover, a substantial degree of transportation process, taking place in the coal precursor marsh prior to final deposition of peat, is indicated by the low value of TPI (cluster A: 0.24 - 0.68) that also reflects a predominant occurrence of shrubs and grass in coal precursor environment.

The low GI value of sample 5, still situated in a wet environment area, indicates that the coals developed in wet zone of transgressive depositional environments. The high GI values (samples 17 of 74.33 and 21 of 160.30), coinciding with the high vitrinite and low inertinite contents, imply that the wettest condition of the coal precursor environment occurred. This condition also represents a low level of aerobic decomposition with rapid organic matter accumulation and burial (Lamberson *et al*., 1991).

A combination of major desmocollinite (and gelovitrinite), with minor telocollinite content, shows that the coal is originated from soft tissues of shrubs within a limited clastic influx of marsh environment. Therefore, coals having TPI < 1 and GI >1, represented by coal samples of clusters A and some of cluster B, indicate a marsh zone with limited input of clastics (Figure 5). The coal existing is characterized by vitrinite > inertinite, and degraded vitrinite > structured vitrinite. Moreover, this condition is due to microbial attack conducted on coal precursor. These high GI and low TPI values, as well as high amounts of pyrite and another mineral matter, present in brackish coals, partly as marsh peats, are due to marine transgressions.

Based on GI and TPI value variation, the Berau coal samples of clusters A and some of B accumulated in marsh peatland from weakly to relatively strong decomposed shrub and grass tissues, under a condition of microbial attack within moderate subsidence in limnic- to limno-telmatic setting, with a relatively high detrital input. However, the rests, those are coal samples of cluster C were deposited in forested swamp (peatland) from weakly to relatively strong decomposed woody tissues, under a condition of moderate to rapid subsidence in telmatic zone. These conditions are also characterized by a rapid burial, and mild to strong humification with strong gelification of plant tissues, occurring in the coal mire. The facies analysis of the coal seams tends to indicate that the peats were deposited within a system of meandering channels in an upper delta plain/alluvial plain environment.

The abundance of gelocollinite and desmocollinite indicates a vegetation of shrub-like plants and tree ferns with much cellulose-rich wood. Corpocollinite and suberinite were probably mainly derived from gymnospermous plant (Teichmüller, 1982), in which vegetation was partially submerged.

A high amount of vitrinite, supported by low amount of inertinite, is indicative of the absence of severe oxidation/dehydration during accumulation of the peat. However, a severe oxidation during coal accumulation occurred in sample 5, shown by a high content of inertinite. The presence of inertinite in the form of mainly semifusinite (SF/F > 5) with low reflectance, suggests incomplete fusinization, due either to oxygenated water or re-deposition of inertinite from a periodically desiccated peat surface. The low content of inertinite indicates that reducting conditions prevailed in the swamp environment. Varying precipitation caused a fluctuating water table and a periodic desiccation and oxidation of the peat surface resulted in incomplete fusinization. This explains the grey to white (existence of much semifusinite) reflectivity of the inertinite (Figures 4 d, f).

The coal samples determined have a low to moderate content of exinite (Table 2), probably as a result of the vegetation type. Some of the exinite was probably derived from the fragile plants and the relatively low content of sporinite may directly reflect the floral composition.

The presence of resistant macerals, such as sporinite, liptodetrinite, inertodetrinite, corpocollinite, and humic detritus, together with a relatively high content of mineral matter as represented by samples 3, 4, 17, and 25, is suggested as the result of transportation (Teichmüller and Teichmüller, 1982). Stach *et al*. (1982) and Teichmüller (1982) emphasized that a subaquatic facies was characterized by the presence of inertodetrinite, liptodetrinite, and clay minerals.

The composition of the coal samples shows that the peats were mainly deposited in a fresh water environment, but the content of pyrite in some of the coal seams implies that the peats were occasionally influenced by marine water. The pyrite content may be formed by the presence of marine sediments above the coal seam (Stach *et al*., 1982). The existence of low to moderate amount of pyrite, especially the framboidal type, is suggestive of brackish or marine influence conditions. This necessitates relative proximity to the sea, making an upper delta plain plausible.

Based on the organic facies gained from maceral and mineral matter analyses, the depositional environment of the Berau coal is postulated to vary from wet limnic- to limno-telmatic, limited-clastic influx marsh, with microbial attack activity, to telmatic wet forest swamp under rapid burial condition. An occurrence of transgressive influence is suggested.

The vitrinite reflectance values of the Berau coal indicate a coalification stage or rank at subbituminous level according to the Australian rank value, approximately corresponding to the subbituminous A and B rank of the ASTM classification. Commonly, without heat influence generated from intrusions, rank generally increases with depth; the younger and older seams may be distinguished from each other based on the degree of coalification or rank. Due to the variable lateral extent within the vitrinite reflectance values of the Berau coals (Table 2), a more accurate stratigraphic subdivision can not be applicable. In this case, burial processes are the important factor related to coalification stage.

Therefore, in general, the coalification occurring is suggested to be ‘pre-deformational’, mainly due

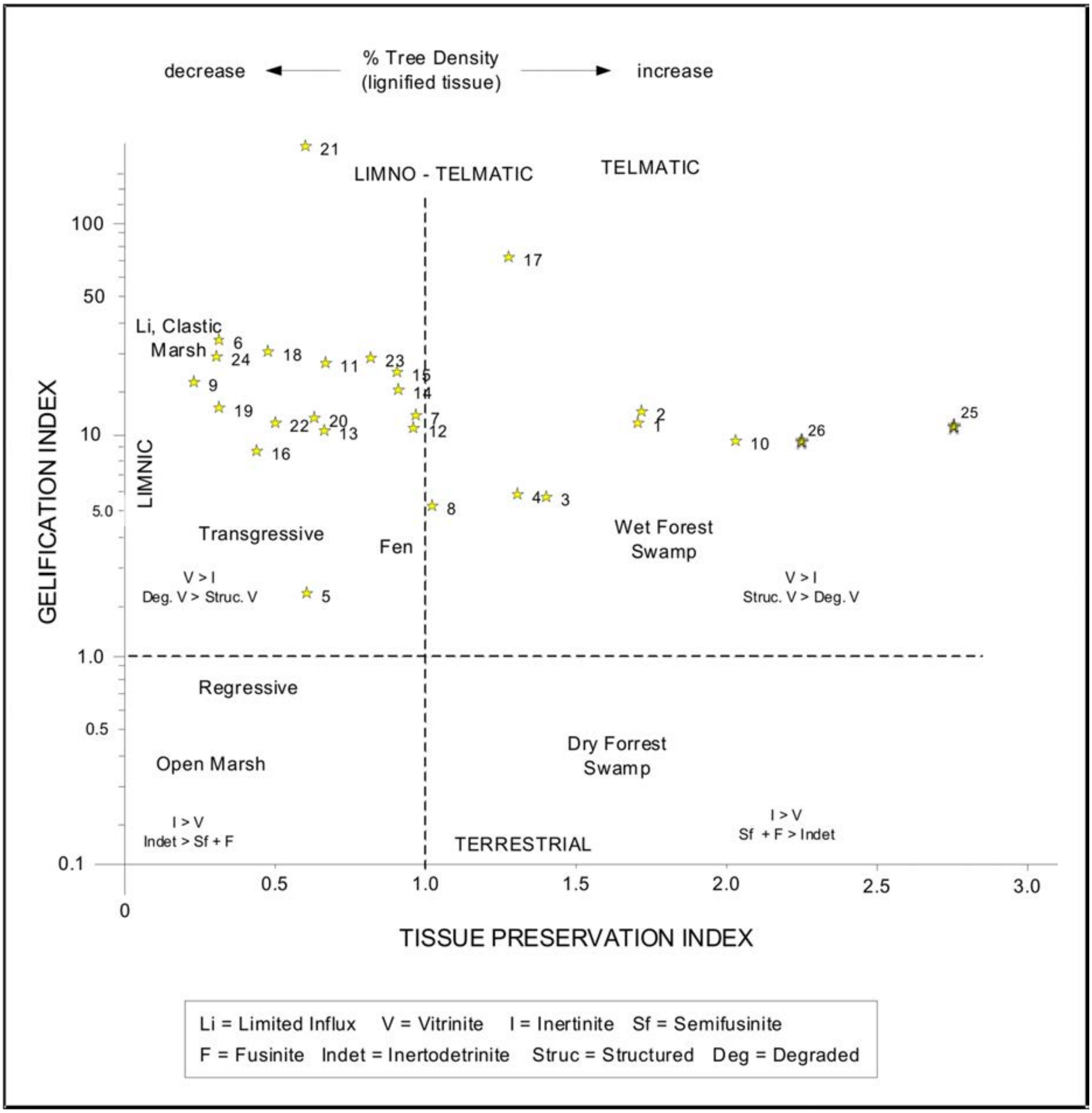

Figure 5. Diagram of TPI versus GI (Diessel, 1965, 1986; Kalkreuth *et al*., 1989) showing a paleodepositional environment of the Berau coal facies.

to former depths of burial processes. This case is evidenced by the presence of increasing vitrinite reflectance values regularly from the deeper to shallower seams (Seam 8: 0.57%; 9: 0.56% 10: 0.54%; 11: 0.50%, and the younger seam 12 of 0.49%). The same condition is present from Seam No. 13 (0.51%) to 14 (0.50%), and 15 (0.48%). However, although their stratigraphic position of seams 5, 6, and 7 is older to younger respectively, the vitrinite reflectance value of each seam is quite similar, around 0.48%. The almost similar source material and depositional environment (Figure 5), and similar diagenesis level due to burial processes lead to the quite same vitrinite reflectance value within the coal.

Conclusions

The coal seams of the Berau Coal Measures are mainly characterized by high contents of vitrinite, with low to moderate inertinite, exinite, and mineral matter content. High vitrinite content, supported by low amount of inertinite, is indicative of the absence of severe oxidation/dehydration during accumulation of the peat. The data show that a regular wet swampy zone occurred during the coal-precursor deposition.

Maceral analyses of the Berau coals indicate that vitrinite maceral group is dominated by unstructured vitrinite or vitrinite B, similar to inertinite where unstructured type dominates.

The presence of the course of the river that flowed through the extensive peat swamp that formed the coal is indicated by the relatively moderate content of exinite (sporinite, liptodetrinite), inertodetrinite, corpocollinite, and humic detritus, together with a relatively high content of mineral matter in coal samples.

High GI values or V/I ratios are thought to indicate that the peat swamps promoted humification of bark and woody tissues. The peat-forming vegetation is suggested mainly to comprise cellulose rich, shrub-like plants, tree ferns, herbaceous plant communities, with minor amount of trees.

Organic facies, gained from maceral analysis, tend to show that the depositional environment of the Berau coal ranges from wet limnic-telmatic zone, in limited-clastic influx marsh, with microbial attack activity, to telmatic wet forest swamp under rapid burial condition. This condition is consistent with the result of GI and TPI characteristics.

On the basis of coal petrographic data and facies interpretation, a conspicuous relationship occurs between maceral composition of the coal, its depositional environments, and the change in peat swamp vegetation.

The vitrinite reflectance values of the Berau coal indicate the coalification stage or rank of the Berau coals is situated at sub-bituminous level (Australian Standard) or sub-bituminous A and B rank (ASTM).

The coalification is ‘pre-deformational’, and is related to former depths of burial processes, which is evidenced by the presence of increasing vitrinite reflectance values regularly from the deeper to shallower seams. However, a similar value of some coal seams is suggested to be due to similar source material and depositional environment, and also same diagenesis level due to burial processes.

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