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Macroscopic, Microscopic, and Paleo-depositional Features of selected Coals in Arahan, Banjarsari, Subanjeriji, and South Banko Regions, South Sumatra

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Abstract

The Arahan, Banjarsari, Subanjeriji, and Banko Regions, parts of the Bukit Asam coalfield, is situated in the Lematang Depression of South Palembang Sub-basin, South Sumatera Basin. Twenty two fresh outcrop and subcrop samples of Seam B, A, Benuang, Enim, and Jelawatan of the Mio-Pliocene Muaraenim coals have been analyzed macroscopically and microscopically, to assess the characteristics and depositional environment of the coal present. On the basis of lithotype analysis, accompanied by organic-petrological and SEM analyses, the coal seams of the Muaraenim Formation show variations in the predominance of some macerals, indicating successions of environmental changes. Petrographically, the dominant maceral group is vitrinite, present in high to very high values (69.4 – 97.4 %); whilst the minor one is inertinite showing a low to moderate amount (0.4 – 22.0 %), followed by low to moderate value of exinite (0.4 – 18.2 %). Vitrinite reflectance values are present in a low to moderate level, varying from 0.34 to 0.55 %, with one sample showing value of 0.59 %. Mineral matter dominated by clay minerals, with minor pyrite and carbonate, displays a low degree (0.4 – 5.4 %), with one sample of 12.0 %. Organic facies study tends to indicate that the coals were deposited in a wet forest swamp to limnic zone, within lower delta plain to transgressive area. This condition has supported the depositional setting interpreted from sedimentary facies associations that shows a shallow-water continental margin sequence, varying from a fluvial to deltaic environment. The organic facies concept is thus applicable in basin studies context and has potential to become an additional tool for interpretation of depositional environment.

Keywords: coal, features, paleo-depositional, Bukit Asam coalfield, South Sumatra

Sari

Kawasan Arahan, Banjarsari, Subanjeriji, dan Banko Selatan, yang merupakan bagian tambang batubara Bukit Asam (PTBA), terletak di wilayah Depresi Lematang, Subcekungan Palembang Selatan, Cekungan Sumatra Selatan. Analisis megaskopis dan mikroskopis terhadap dua puluh dua percontoh batubara Seam B, A, Benuang, Enim, dan Jelawatan Formasi Muaraenim berumur Mio-Pliosen dilaksanakan untuk penafsiran karakteristik dan lingkungan pengendapannya. Analisis litotipe yang diikuti dengan petrologi organik dan SEM menunjukkan bahwa batubara tersebut terendapkan dalam lingkungan yang berbeda. Secara petrografi, kelompok maseral batubara tersebut didominasi oleh vitrinit yang kandungannya berkisar antara 69,4 – 97,4 % dan termasuk kategori tinggi – sangat tinggi. Sementara itu, kelompok inertinit hadir dalam jumlah rendah – menengah, antara 0,4 – 22,0 %. Begitu pula kelompok eksinit termasuk kategori rendah – menengah, dengan kisaran 0,4 – 18,2 %). Selanjutnya nilai reflektan vitrinit sekitar kategori rendah hingga menengah, dengan kisaran 0,34 – 0,55 %; namun satu percontoh nilainya 0,59 %. Bahan mineral yang didominasi oleh mineral lempung, dengan sedikit pirit dan karbonat termasuk tingkat rendah (0,4 – 5,4 %) dengan satu percontoh bernilai 12,0 %. Kajian fasies bahan organik cenderung menunjukkan bahwa batubara terendapkan di zona rawa berhutan basah sampai limnik, dalam lingkungan pengendapan lower delta plain – transgresi. Penafsiran ini bersesuaian dengan kajian asosiasi fasies sedimen yang menunjukkan lingkungan fluviatil – zona delta.

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Konsep fasies organik ini dapat diterapkan dalam konteks kajian cekungan dan berpotensi menjadi alat penafsiran lingkungan pengendapan.

Kata kunci: *batubara, fitur, lingkungan pengendapan, kawasan batubara Bukit Asam, Sumatra Selatan*

Introduction

Macroscopic, microscopic, and paleo-depositional features or characteristics of coals have been studied intensely by many authors, *e.g*. Stopes (1919, 1935), Schopf (1960), Cohen and Spackman (1972), Hagemann (1978), Stach *et al*. (1982), Teichmüller and Teichmüller (1982), Bustin *et al*. (1983), Hunt and Hobday (1984), Ward (1984), McCabe (1984, 1987), Daulay and Cook (1988), Rimmer and Davis (1988), Kalkreuth and Leckie (1989), Mishra *et al*. (1990), Marchioni and Kalkreuth (1991), Diessel (1992), Taylor *et al*. (1998), Scott (2002), Thomas (2002), Moore and Shearer (2003), Davies *et al*. (2005), Hackley *et al*. (2005), Hackley and Martinez (2007), Jelonek *et al*. (2007), Belkin *et al*. (2009), Toprak (2009), Singh *et al*. (2010), and Widodo (2010).

Thomas (2002) described that coal having been defined by numerous authors, essentially is combustible organoclastic sediments comprising lithified plant remains. An accumulation of vegetable debris in a special environment leads to the formation of coal of different rank and degrees of structural complexity, passing through a diagenesis or coalification process. Therefore, the composition and character of each coal are firstly determined by its organic compound or maceral and mineral matter or inorganic fraction contents. The understanding of macroscopic and microscopic properties of the coal is a fundamental significance for the coal genesis and depositional environment models.

A research, both macroscopic and microscopic analyses, on selected coals collected from Arahan, Banjarsari, and Subanjeriji regions (Figure 1) was performed, in order to gain a better understanding

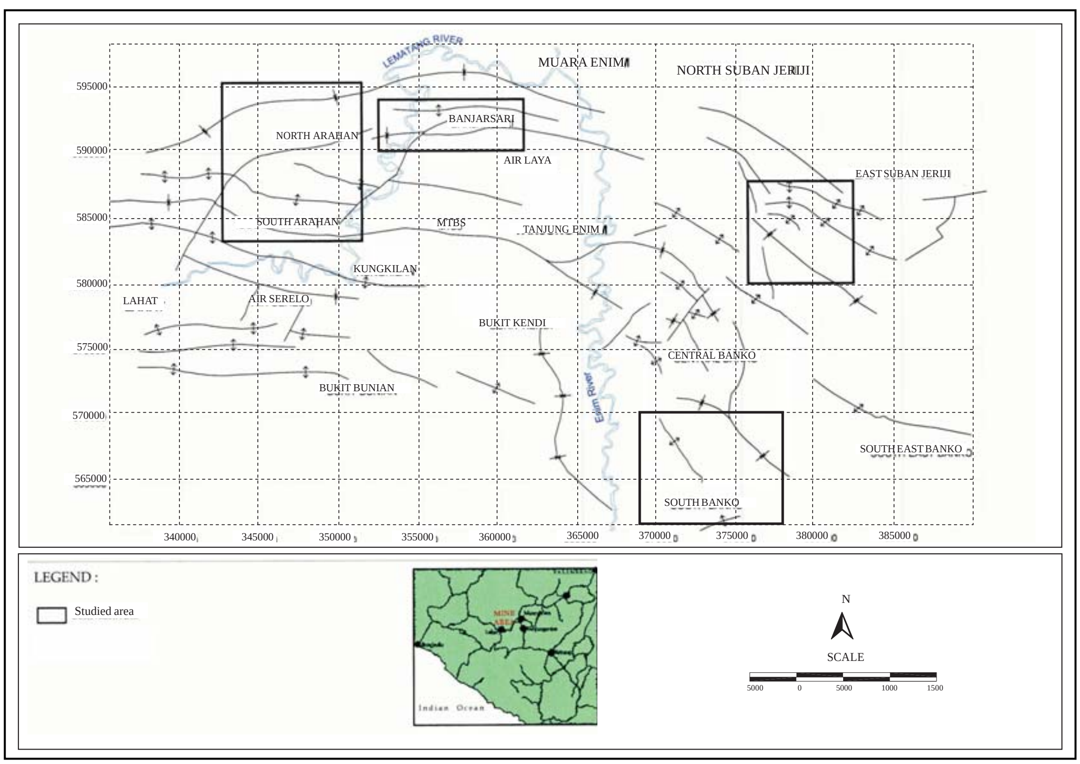

Figure 1. Locality map of the studied areas situated in the PTBA coal field, South Sumatra.

on their features and paleo-depositional environments. The studied area covering the northern and eastern parts of the Bukit Asam Coalfield. Surficial and subcrop coal studies, related to coal investigation in the area, is easy to perform, because the coal seams to be observed are almost well-outcropped. Predominantly, during the fieldwork, the study localities have to be reached on foot.

The aims of the research are to establish macroscopic and microscopic features or information obtained from selected Mio-Pliocene Muaraenim coals in part of the Bukit Asam coalfield. Moreover, the study adresses paleo-depositional environments of those selected coal seams based on the coal petrography conducted.

Specific objectives are to: (a). evaluate, determine, and analyze those coal lithotype and maceral features, and (b). describe the implications of lithotype and maceral variation on the interpretation of coal facies and depositional environments. Overall objectives are to advance our understanding of geological processes in the formation and origin of the Mio-Pliocene Muaraenim coals, by means of macro- and micro- petrographic techniques.

Methods And Techniques

In order to achieve the aims of the study, geologic field investigations and laboratory techniques were used. Primary fieldwork activity is focused on coal lithotype analysis, supported by stratigraphic observations. Then, collection of field data and samples for coal petrographic and SEM analysis purposes were conducted.

Sampling and Macropetrographic/Lithotype Analysis

During the fieldwork, the coals were determined in macroscopic appearance or lithotype characteristics, in terms of brightness *vs.* dullness or vitrinite contents, using lithotype classification proposed by Diessel (1965). In describing lithotype sequences, 1 cm was chosen as the minimum thickness for the delineation of individual lithotypes. On the basis of this character, basically the main coal lithotype can be divided into bright (vitrinite-rich) and dull (vitrinite-poor) components. Usually, the macroscopic features can predict the microscopic constituents of coals once a correlation between the two has been established. From each subseam, a channel sample was taken for petrographic analyses.

Seyler in 1954 (I.C.C.P., 1963) proposed the term lithotype to designate the macroscopically distinguishable bands of humic coals which Stopes (1919) had previously described and named. In order to avoid confusion with maceral and microlithotype terminology and to avoid implied correlation between lithotypes and their petrographic compositions, nomenclature changes have also been suggested (Schopf, 1960; Diessel, 1965; Cameron, 1978).

Variation in petrography of lithotypes is a function of their origins (vegetation and depositional setting) and contributes to variations in their properties due to the different characters of the maceral components. A systematic variation in typical petrographic compositions of lithotypes is shown by studying bituminous coals carried out by several authors (Diessel, 1965; Cameron, 1978; Marchioni, 1980; and Hower and Wild, 1982). Generally, vitrinite content increases whilst inertinite, exinite, and mineral matter contents decrease with increasing bright components.

A lithotype log forms a very useful basis for sampling and describing vertical variations in a seam relative both to macroscopic and broad microscopic properties. Lithotype logs can also serve as a basis for an interpretation of the succession of mire conditions during the seam formation.

Micropetrographic Analysis

The laboratory techniques deal with organic petrology of the coal. This analysis is important for having a better understanding of the maceral and mineral matter contents, vitrinite reflectance, and also characteristics of the coal.

Detailed petrographic studies of the individual samples have been carried out following ICCP procedures (ICCP, 1963, 1971, 1975, 1998, and 2001). 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. Similarly, inertinite maceral group is divided into structured and unstructured types. Structured inertinite comprises semifusinite and fusinite, whilst the unstructured one consists of sclerotinite, macrinite, and degraded inertinite.

Petrographic analysis was performed in two modes; those are maceral and mineral matter analysis, and reflectance measurement. By using standard procedures, the samples were present as polished briquettes, prepared from crushed 1 mm-size coal samples representing each seam, and then mounted in epoxy resin. The preparation and polishing techniques are conducted according to Standard Association of Australia (1977).

The maceral analysis determines the petrographic composition of the coals. The analysis based on 500 counts on each sample (including mineral matter) under reflected white light, was performed microscopically on polished briquette sections, based on the Standard Association of Australia (1981, 1986). 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 and reflectance measurements were carried out on a Leitz MPV-2 photomicroscope. 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 maceral and mineral matter are determined based on their morphology and colour. The analysis result reported is expressed in semiquantitative volumetric percentages.

The measurement, performed on the vitrinite macerals of each coal polished briquette that follows the ICCP 1971' procedure, is a standard and accurate procedure to determine the rank of the coals. Moreover, the vitrinite reflectance measurements were conducted according to the Australian Standard AS 2486 – 1981 and American Society for Testing and Materials (ASTM- 2009). Additional measurements of vitrinite reflectance were perfomed in 2010, in accordance with the American Society for Testing and Materials (ASTM- 2009).

Moreover, SEM analysis conducted on selected coal polished sections were focused on qualitative and semi-quantitative maceral and mineral observations, which can be used as supporting data to petrographic analysis results.

Geological Setting

The Bukit Asam coalfield occupies the Lematang Depression of South Palembang Sub-basin, South Sumatera Basin, trending parallel to the Sumatera axis. Several previous unpublished reports and publications, *e.g* de Coster (1975) have described the geologic setting and history of the Bukit Asam region. The subduction of the Indian-Australian Plate beneath the Southeast Asian Plate, during the Late Cretaceous - Early Tertiary, led to the basin formation developping in a back-arc setting. Tertiary terrestrial to marine clastics with minor limestone predominantly fill the depression. Tectonics controlled the sedimentation of the Tertiary sedimentary units, and in general a well-defined conformity separates along their lower and upper contacts of each rock unit.

Geologically, the study area is situated in the Muaraenim Anticlinorium. The anticlinorium shows two trends of fold axis, those are the 'Gumai Trend' with E-W fold axis and the 'Garba Trend' having NW - SE fold axis direction. Both structural trends are displayed in Figure 2 (Gafoer *et al*., 1986) presented as the Geological Map of the Bukit Asam (PTBA) coalfield.

Stratigraphy

The oldest formation in the studied area is the Airbenakat Formation, overlain conformably by the Muaraenim Coal Measures or Formation, which in turns is unconformably overlain by the Kasai Formation and other Quaternary deposits (Figures 1 and 2).

The uppermost part of the Airbenakat Formation, underlying conformably the Muaraenim Formation, comprises mainly light to dark gray siltstone and sandy siltstone, commonly calcareous and glauconitic, suggested the sediment unit was deposited in a shallow marine environment. Both types of sediments contain laminae or thin beds of light gray very fine- to fine-grained sandstone and striation of coal matter occasionally. The Muaraenim Formation is gently folded, and was formed in a back-arc basin, of a fluvial to deltaic condition occurring during a

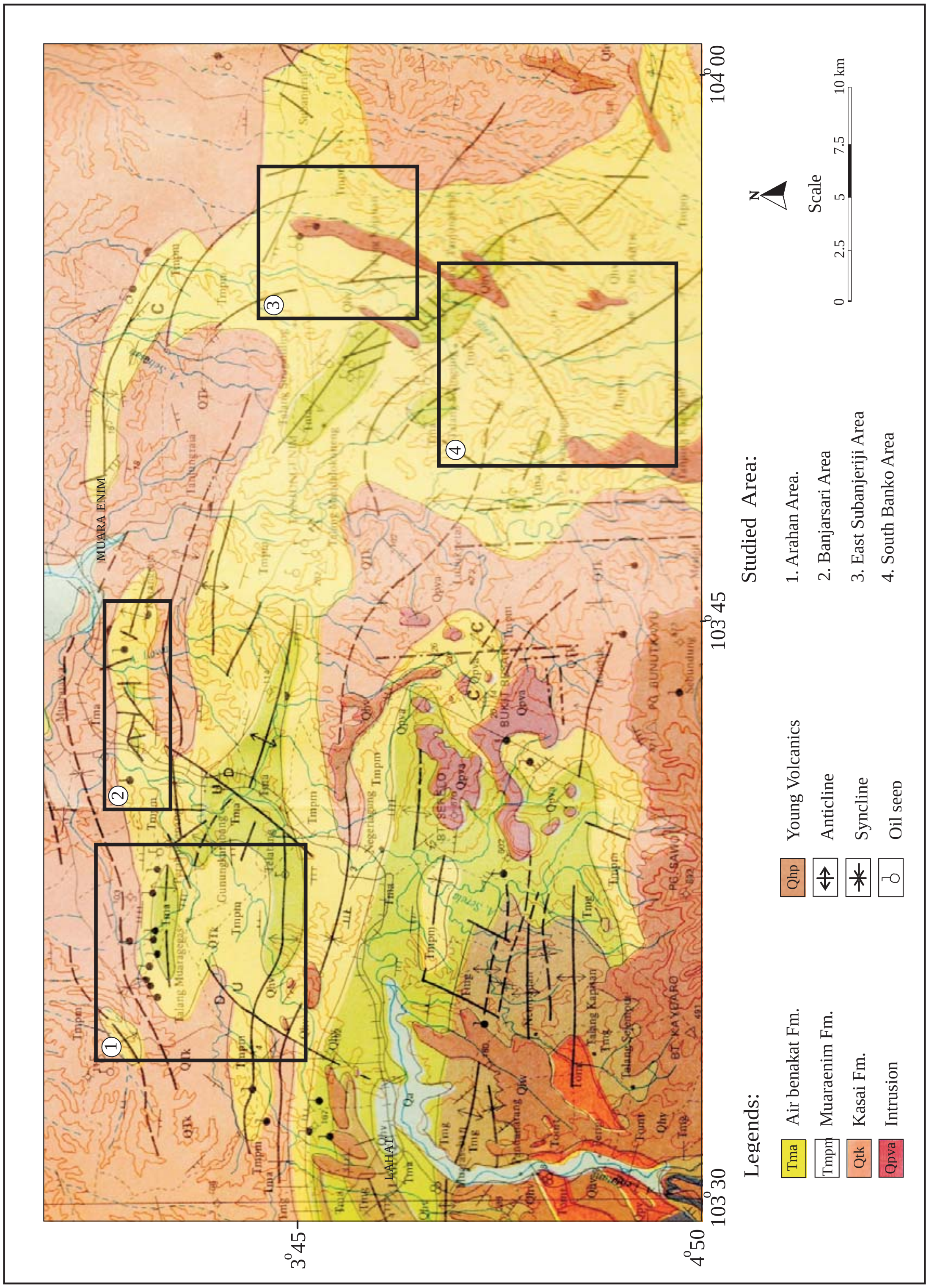

Figure 2. Geological map of the studied areas. part of the Lahat Quadrangles (after Gafoer *et al*., 1986).

depositional regression, as the Barisan Mountains were being uplifted. The Muaraenim Formation is subdivided into four units, from the oldest to youngest are M1, M2, M3 and M4 Sub-divisions (Figure 3).

The youngest unit is the Plio-Pleistocene Kasai Formation consisting of gravel, tuffaceous sands and clays, volcanic concretion, pumice, and tuff. The formation unconformably overlies the Muaraenim Formation.

Result of Investigations

Facies changes, occurring during accumulation of the coal precursor, are defined from the lithotype variations within the seams, together with the data of maceral and mineral matter variations or their petrographic composition. A general trend to increasing vitrinite, with decreasing inertinite and mineral matter contents from the dull to bright to types is shown by the mean petrographic compositions of the lithotypes. The banded lithotypes were formed under somewhat much drier conditions influenced by open moor conditions with lower tree density, whilst the brighter ones are considered to have been formed in a more wet and densely forested swamp and fens (Lamberson *et al*., 1991; Marchioni and Kalkreuth, 1991). These two distinct types were recognised within the dull lithotype, on the basis of the differences in petrographic composition and the occurrence or absence of facies diagnostic macerals. Furthermore, it is suggested that these differences are due to formation in distinct mire facies, under the influence of open moor or raised mire conditions.

Field Investigation

In the North and South Arahan coalfields, four coal seams of the M2 Subdivision, from top to bottom can be recognized, *i..e.* Benuang, Mangus (A), Suban (B), and Petai (C) Seams (Figure 4). Then, the M3 Subdivision, in which the Benuang Seam is situated, is a sequence which bounded by the top of A1 (Mangus) Seam in the bottom and the bottom of Enim Seam in the top (Figure 3).

The M4 Subdivision is a sequence between the bottom of the Enim Seam and the base of the Kasai Formation (Figure 3). This subdivision dominantly crops out in the Banjarsari, Subanjeriji, and South Banko regions (Figures 5, 6, and 7, respectively). The deposit of Enim Seam characteristically containing resin fragments, indicates that the depositional environment was a swampy condition within a high moor.

The general tendencies of coal features projected in aspects of coal lithotype, together with vitrinite reflectance, macerals, and mineral matter, were gained from macroscopic and microscopic analyses, carried out on the outcrop samples of A_1, A_2, B, Benuang, Enim, and Jelawatan Seams.

The fieldwork investigation comprises detailed determination, observations, and measurements on lithotype, position, and type of coal seam. Selected coal sample numbers collected, location, seam type, lithotype, maceral, and mineral matter analyses results both of the field and laboratory investigation are displayed in Table 1.

By determining megascopically, in general coals collected from the four studied areas comprise lithotypes ranging from dull (D) to banded (BD) type (Table 1). However, the main lithotype varies from dull banded to banded types. In these coal, tiny specks of pyrite are frequent recognized macroscopically.

In Arahan region, the uppermost seam (Benuang Seam) occurs as a dull coal, dominantly characterized by dark brownish black streak, lack woody structure, uneven fracture, some are finely to moderate laminated, predominantly massive, a little to plenty resin content. The dull banded lithotype recognized within the A1 sub-seam and C Seam, shows brownish black streak, uneven fracture (Figures 8a and 8b), and plenty of resin. Furthermore, the banded type of B Seam and B1 Sub-seam displays subvitreous luster, and moderately banding (Figures 8c and 8d).

From the Banjarsari region, five coal samples, those are 03HS.01, 03HS.02, 03YK.03, 03YK.04, and 03YK.05 (Figure 5), were collected for analysis purposes (Table 1). Lithotype of the coal samples varies from dull to banded types, characterized by brownish black streak, massive, uneven fractured, with some resin substances. The A Seam samples, 03 YK 04 and 03 YK 05, collected from Gegas River show dull and banded lithotypes, respectively. The rests, 03 YK 05, 03 HS 01, and 03 HS 02, belonging to the E Seam, are included into dull banded to banded lithotypes.

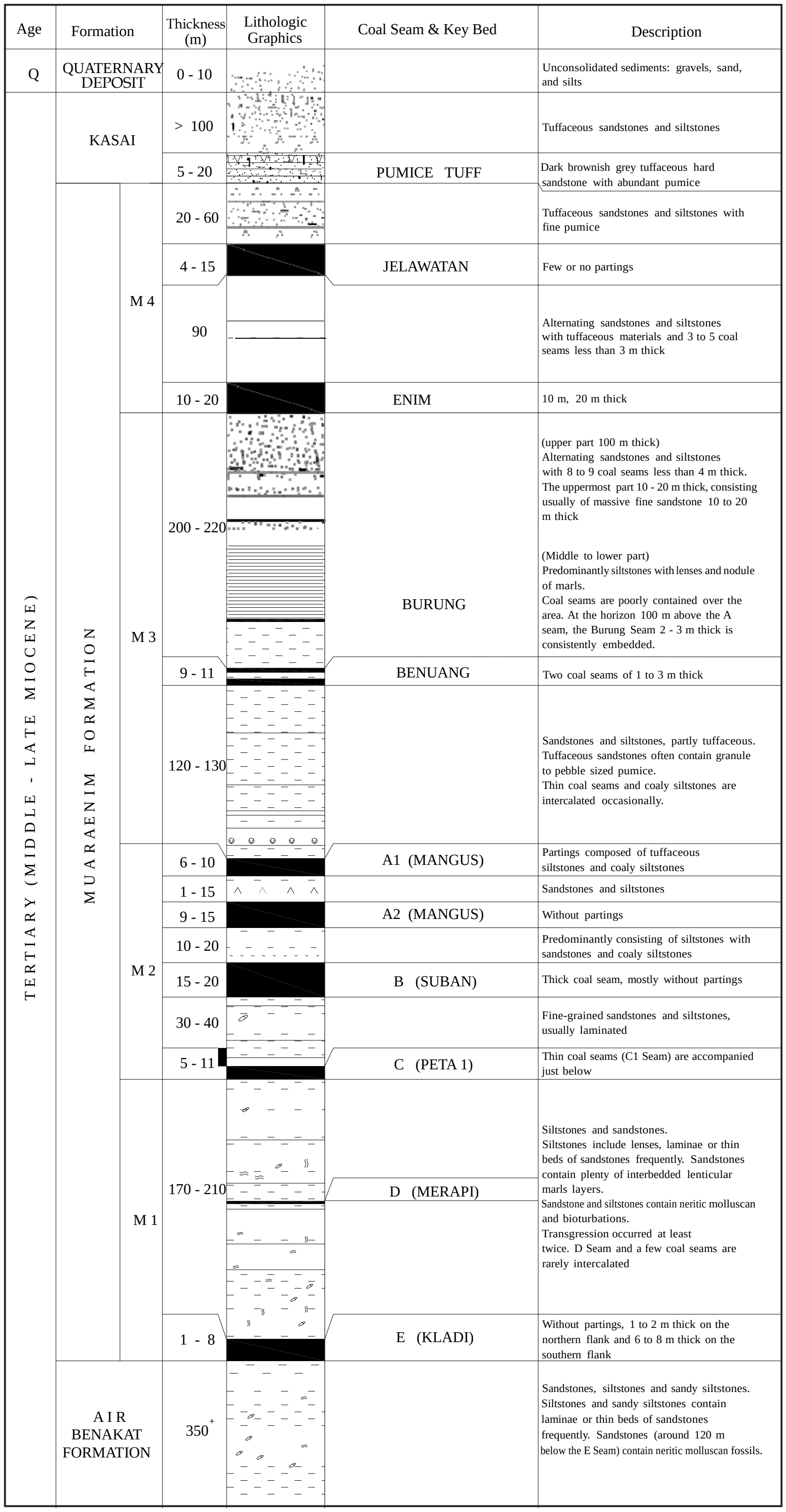

Figure 3. Generalized stratigraphic column of Bukit Asam Coalfield (Modified from PT. MKI, 1998).

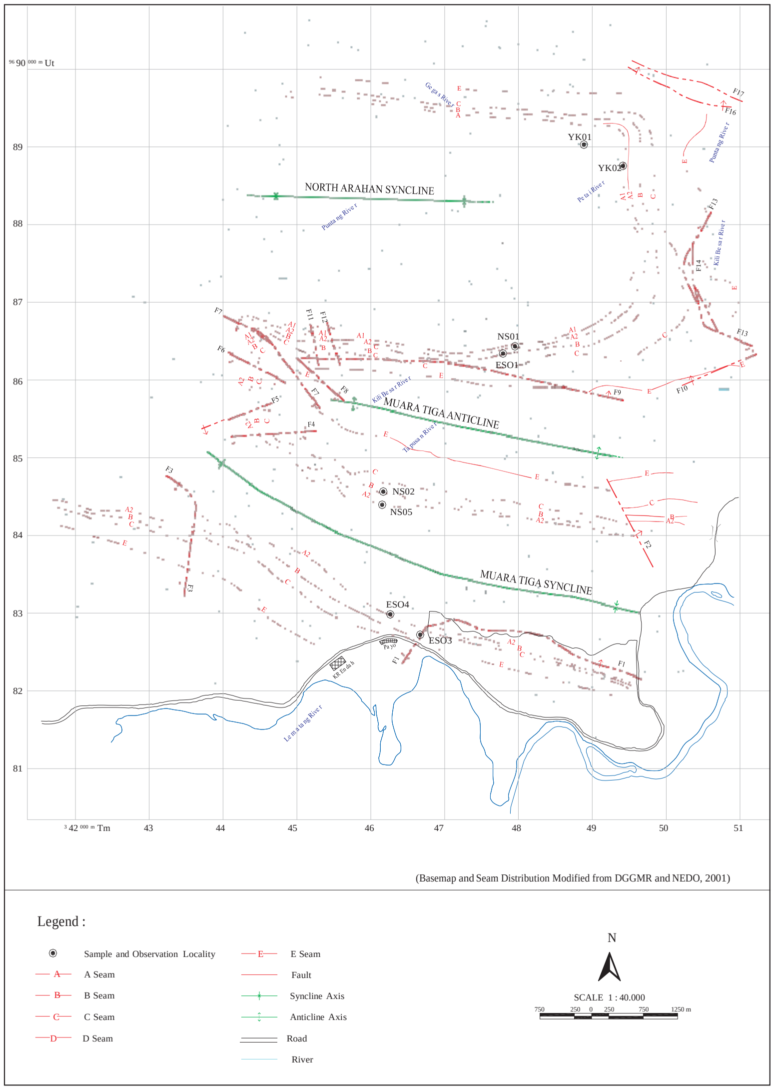

Figure 4. Outcrop sample and observation locality map of North and South Arahan areas.

The Enim (E) and Jelawatan (J) Seams as the youngest coal seams are recognized in the Banjarsari (Figure 5), Subanjeriji (Figure 6), and South Banko (Figure 7) regions. Some irregular sub-seams are also present between those Jelawatan and Enim Seams, which are almost low grade. Those two main seams occur as hard brown coals, on the borderline of class 3 and 4 (ISO, 1994), which is equivalent to lignite A (ASTM, 2009).

The seams were formed under intermediate conditions of stability in respect to flooding events. Predominance of banded lithotypes, dull lithotypes near parting and brightening and dulling up sequences characterizes the seams. Transitions from dry forest swamps to wet and very wet forest swamps are represented by the brightening up sequences, whilst a reverse trend is indicated for the dulling up sequences.

Two types of seam development occurring: (1) seams occupied by a high proportion of clastic beds indicate frequent floodings of the swamps, and (2) seams containing only minor thin clastic beds indicative of a relative stability of water levels during formation of the coal precursors. Transitions from wet and very wet forested swamps to slightly drier conditions with lower tree density are indicated by the dulling up sequences.

Laboratory Analyses

Ten selected coal samples (03ES.01-04, 03NS.01, 03NS.02, 03NS.05, 03YK.01, 03YK.02, and 03YK.02A) representing Seam B, A, and Benuang of the Arahan area (Figure 4); five samples (O3YK.03, 04, and 05; and 03HS.01 and 02) representing A and Enim Seams from Banjarsari area (Figure 5); two samples of Enim and Jelawatan Seams from Subanjeriji (03NS.03 and 03YK.06) (Figure 6); and five samples (03NS.04, 03ES 05 and 06, and 03RH.01 and 02) representing Enim Seam from South Banko (Figure 7) are collected for megascopic and laboratory analyses.

Analysis results as presented in Table 1, show that vitrinite comprising telocollinite (Figures 9a and 9b) and desmocollinite (Figure 9c) is the predominant maceral group. However, vitrodetrinite and corpocollinite are also identified. The vitrinite maceral group recognized in the B Seam varies from 78.0 % to 96.0 %, A Seam between71.2 % and 95.4 %, Benuang Seam is 69.4 %, Enim Seam from 71.2 % to 97.2 %, whilst Jelawatan Seam is 90.6 %.

Then, exinite maceral group is composed of resinite, suberinite, liptodetrinite; with rare sporinite, cutinite (Figure 9d), and exsudatinite macerals. Resinite (Figures 9d and 9e) is often obscured by clay minerals; however it is more discernable when determined under fluorescence mode. Sporinite is present with its typical elongated shape. Exinite in the B Seam ranges from 1.6 % to 4.8 %, A Seam of 0.8 – 18.2 %, Benuang Seam of 4.6 %, Enim Seam between 0.4 % and 6.8 %, whereas Jelawatan Seam is 3.0 %.

Furthermore, inertinite content of B Seam is from 2.0 % to 18.8 %; A Seam of 0.6 % – 12.6 %; Benuang Seam of 22.0 %, Enim Seam ranges from 0.4 % to 13.2 %, whilst Jelawatan Seam is 2.8 %. The inertinite group consists of semifusinite (Figures 9f and 9g), sclerotinite or funginite, macrinite, inertodetrinite (Figure 9g), and traces of fusinite (Table 2). Funginite as fungal bodies show their characteristics having single to numerous cells/chambers, either empty or filled with clay minerals (Figures 9b and 9g).

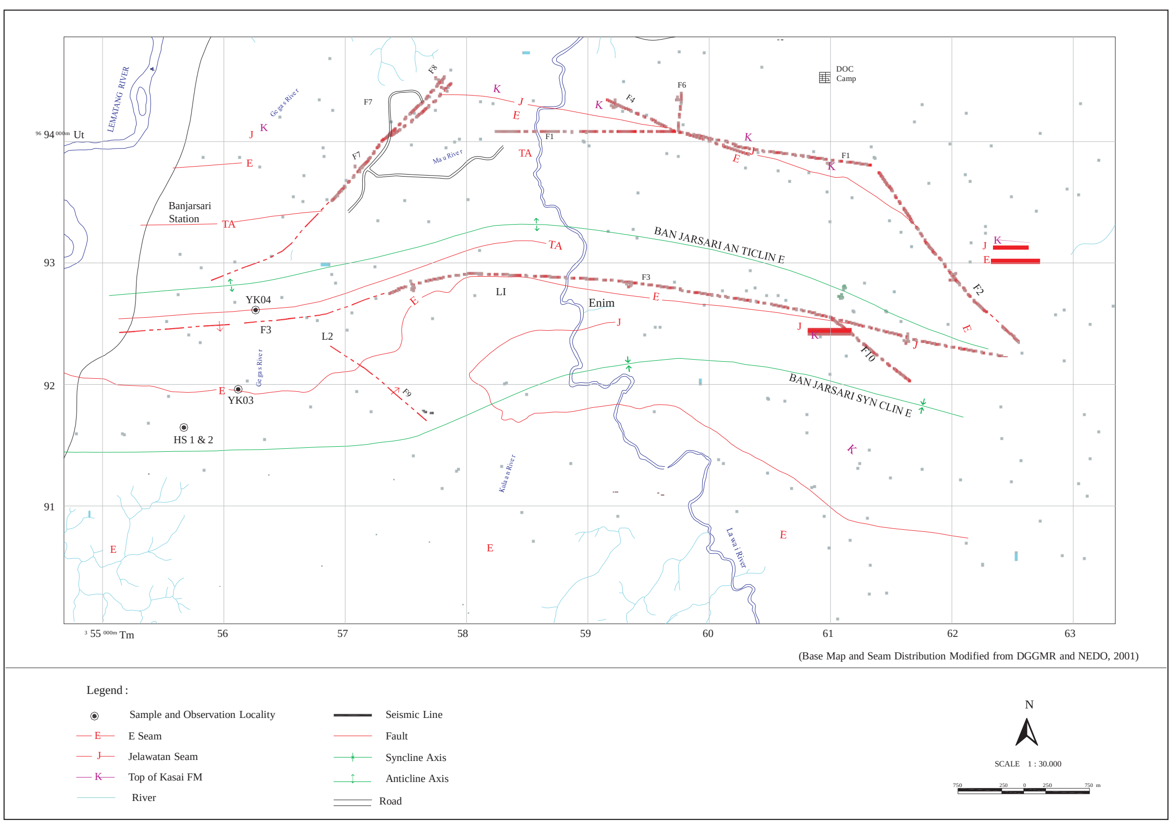

Figure 5. Outcrop sample and observation locality map of the Banjarsari area.

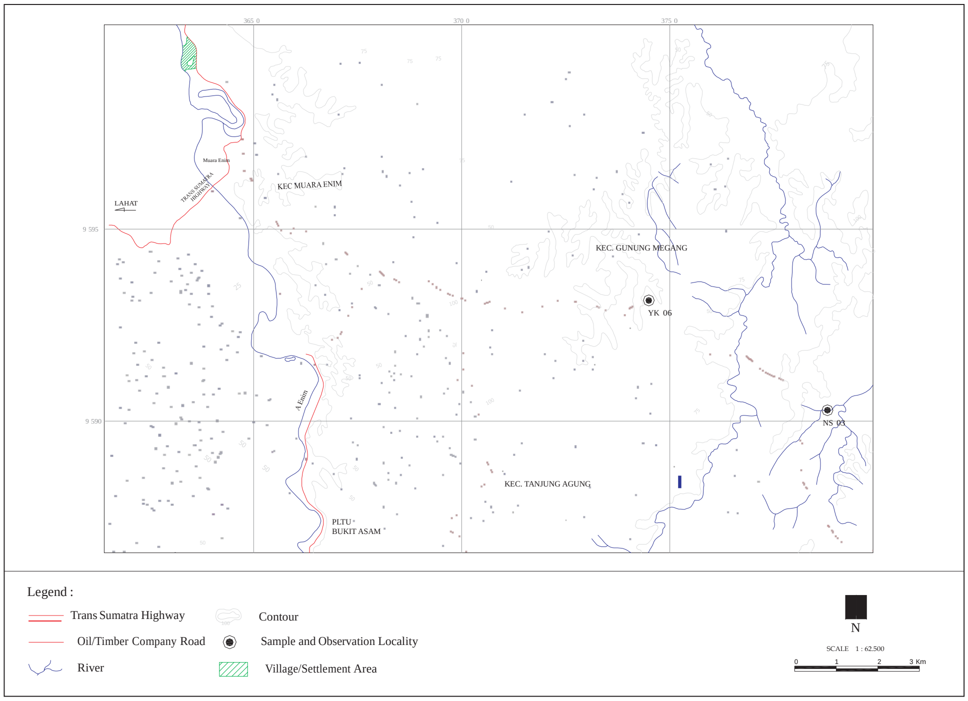

Figure 6. Outcrop sample and observation locality map of the Subanjeriji area.

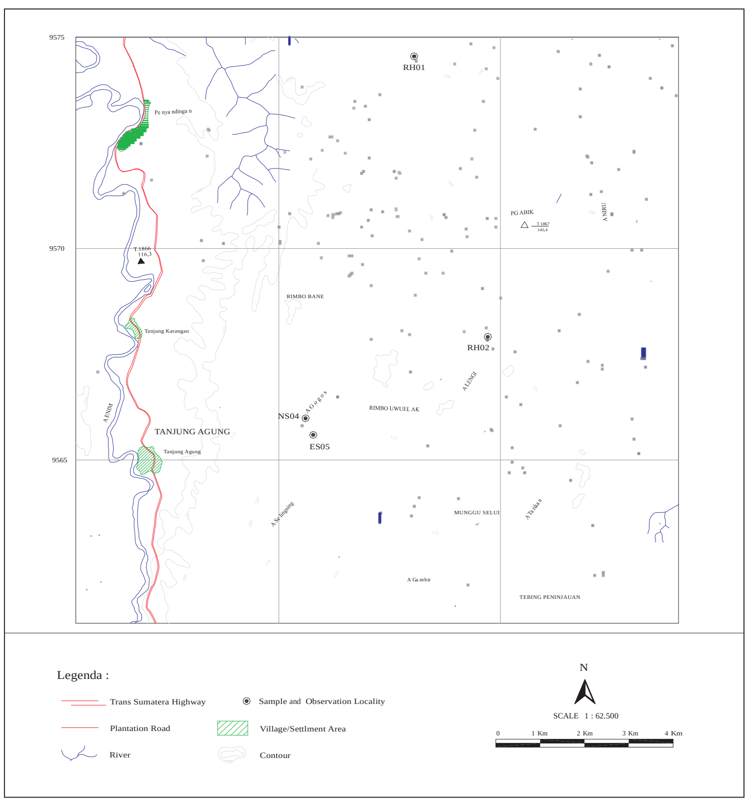

Figure 7. Outcrop sample and observation locality map of South Banko area.

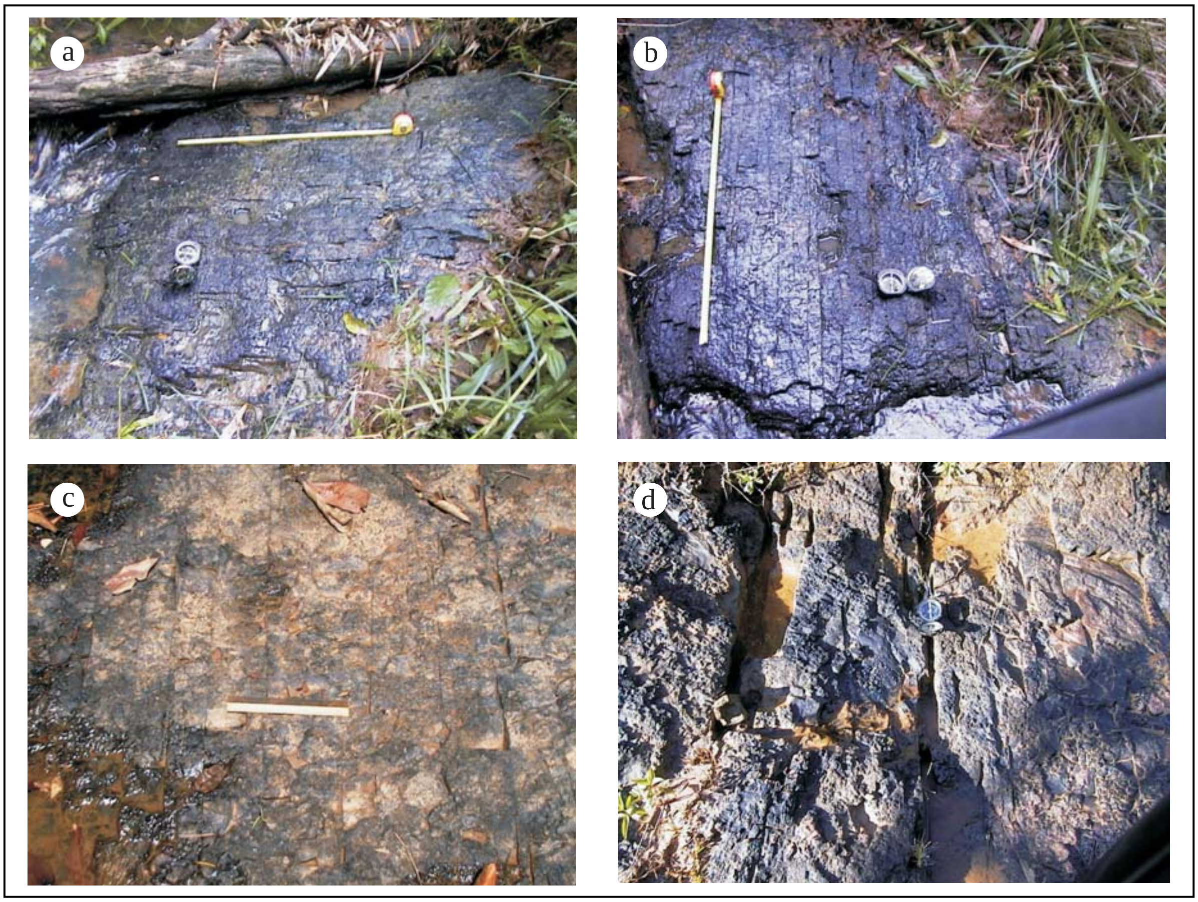

Figure 8. Photographs of coal outcrops in studied area:
a. cleated dull banded (DB) coal outcrop of A1 Seam at Arahan.
b. weathered dull banded (DB) coal outcrop of the C Seam, at Petai River, Arahan Area showing intensive face cleats.
c. sheared banded (BD) coal of B 1 Seam at Arahan showing irregular *fractures* due to a compressive stress.
d. banded (BD) coal outcrop of B Seam at a small river, situated in northeast of Arahan area showing good development of face and butt cleats.

Mineral matter content of all coal seam samples recorded is included into low to medium grade. It is dominated by clay minerals (Figures 9c and 9g) mainly recognized as kaolinite flakes (Table 2). A minor amount of pyrite (Figures 9h and 9i) and carbonates (Figure 9j) are also determined. Pyrite is present as framboids, granules, fine disseminated grains and rounded concretionary bodies (Figures 9h and 9i), and specks associated with vitrinite and inertinite. Sparse pyrite replaces inertinite macerals.

Clay minerals of B Seam ranges from 0.4 % to 2.2 %, with pyrite of 0.2 %. The A Seam contains clays of 0.4 % – 3.8 %, and pyrite of 0.2. Then, clays in Benuang Seam of 3.8 % with pryrite of 0.2 %. Moreover, in the Enim Seam, the amount of clays varies from 0.6 % to 11.4 %, pyrite between 0.2 % and 0.6 %, and carbonates from 0.2 % to 0.6 %. The Jelawatan Seam, is characterized by the clays content of 3.0 %, whilst pyrite and carbonates have a similar value (0.2 %). The presence of epigenetic pyrite tends to indicate that a marine incursion took place in the coal mire during coalification process.

The vitrinite reflectance is one of indicators of the coalification degree or coal rank. The vitrinite reflectance of the B Seam ranges from 0.43 % to 0.59 %, A Seam between 0.41 % and 0.51 %, whilst the Benuang Seam is 0.43 %. Moreover, the Enim Seam shows vitrinite reflectance values of 0.34 % – 0.55 %, and Jelawatan Seam of 0.40 %. Those ranges of vitrinite reflectance values tend to indicate that in

Table 1. Results of Macro - and Micro - petrographic Analyses of the selected Muaraenim Coals

No.	Sample No. (03)	Area	Lith.	Tl. %	Dv %	Gv %	V %	Sf %	Mac. %	Scl. %	Int. %	I %	Rs. %	Sp. %	Sub. %	Cu. %	Lpt. %	Exu. %	E %	Py %	Carb %	Clay %	MM %	Rv %	Seam
1.	ES.01		BD	67.4	27.6	1.0	96.0	0.6	-	1.0	0.4	2.0	0.8	0.2	-	0.6	-	-	1.6	-	-	0.4	0.4	0.49	B1
2.	ES.02		BD	40.6	36.6	0.8	78.0	8.6	-	4.6	2.6	15.8	3.4	0.2	0.6	0.6	-	-	4.8	0.2	-	1.2	1.4	0.49	B1
3.	ES.03		BD	66.6	21.6	0.4	88.6	4.6	-	0.6	1.4	6.6	1.4	0.2	0.4	0.4	-	-	2.4	0.2	-	2.2	2.4	0.59	B
4.	ES.04		BD	57.4	34.0	1.0	92.4	0.2	-	0.8	0.4	1.4	2.6	-	0.4	1.4	1.3	-	5.6	0.2	-	0.4	0.6	0.51	A2
5.	NS.01	Arahan	DB	31.0	45.4	4.6	81.0	5.0	-	4.0	3.6	12.6	2.0	-	-	-	-	-	2.0	0.6	-	3.8	4.4	0.44	A2
6.	NS.02		DB	15.4	56.6	1.6	73.6	4.0	0.4	10.0	4.4	18.8	3.8	0.2	-	-	-	-	4.0	0.2	-	3.4	3.6	0.43	B
7.	NS.05		BD	55.4	37.6	2.4	95.4	0.2	-	0.4	-	0.6	0.4	0.2	-	0.2	-	-	0.8	0.2	-	3.0	3.2	0.41	A2
8.	YK.01		D	19.4	50.0	-	69.4	6.4	-	11.6	4.0	22.0	4.6	-	-	-	-	-	4.6	0.2	-	3.8	4.0	0.43	Benuang
9.	YK.02		DB	30.0	54.0	1.4	85.4	0.4	-	3.0	1.0	4.4	5.8	0.2	-	-	-	-	6.0	0.2	-	4.0	4.2	0.44	A1
10.	YK.02 A		DB	28.6	48.6	0.4	77.6	0.4	-	1.0	0.4	1.8	17.0	0.8	-	0.4	-	-	18.2	0.2	-	2.2	2.4	0.46	A1
11.	YK.03		DB	34.4	54.2	1.4	90.0	0.4	-	1.0	0.6	2.0	2.4	0.2	1.4	1.4	-	-	5.4	0.2	-	2.4	2.6	0.47	A
12.	YK.04		D	3.6	64.6	3.0	71.2	1.4	-	7.6	1.0	10.0	6.2	0.4	-	-	-	0.2	6.8	0.4	0.2	11.4	12.0	0.50	Enim
13.	YK.05	B.Sari	BD	37.6	54.6	2.0	94.2	1.0	-	0.6	1.4	3.0	0.6	-	0.4	-	-	-	1.0	0.2	-	1.6	1.8	0.52	A
14.	HS.01		DB	49.2	30.6	3.4	83.2	3.2	2.6	1.0	7.4	13.2	0.8	-	0.4	-	0.4	0.2	1.8	0.2	-	0.6	0.8	0.38	Enim
15.	HS.02		BD	72.4	13.4	4.8	90.6	0.8	0.2	1.0	0.4	2.4	1.0	0.2	1.2	1.4	0.4	-	4.2	0.4	0.2	2.2	2.8	0.45	Enim
16.	NS.03		BD	18.0	70.0	2.6	90.6	0.4	0.2	1.6	0.8	2.8	2.6	-	-	0.4	-	-	3.0	0.2	0.2	3.0	3.4	0.40	Jelawatan
17.	YK.06	S.Jeriji	DB	73.0	21.6	2.8	97.4	0.2	-	-	0.2	0.4	0.2	0.2	-	0.2	-	-	0.6	0.4	-	1.2	1.6	0.51	Enim
18.	NS.04		BD	32.4	49.0	1.4	82.8	5.0	0.4	1.6	1.2	8.2	2.0	-	1.0	0.6	-	-	3.6	0.6	0.6	4.2	5.4	0.40	Enim
19.	ES.05		D	24.6	72.0	0.6	97.2	0.4	-	-	-	0.4	0.4	-	-	-	-	-	0.4	0.2	-	1.8	2.0	0.43	Enim
20.	ES.06	S.Banko	D	15.4	66.6	2.2	84.2	7.4	-	1.6	0.4	9.4	1.0	-	-	1.0	-	-	2.0	0.6	0.2	3.6	4.4	0.55	Enim
21.	RH.01		BD	52.0	41.6	-	93.6	0.4	-	1.0	0.6	2.0	0.3	-	-	2.6	-	-	3.0	0.4	-	1.0	1.4	0.39	Enim
22.	RH.02		BB	55.6	36.0	-	91.6	3.0	-	2.0	0.4	5.4	1.6	-	-	-	0.4	-	2.0	0.2	-	0.8	1.0	0.34	Enim

Legends:
Tl: telocollinite **Dv**: detrovitrinite **Gv**: gelovitrinite **V**: vitrinite **Sf**: semifusinite **Mac**: macrinite **Scl**: sclerotinite **Int**: inertodetrinite **I**: inertinite **Rs**: resinite
Sp: sporinite **Sub**: suberinite **Cu**: cutinite **Lpt**: liptodetrinite **Exu**: exsudatinite **E**: exinite **Py**: pyrite, including framboidal type **Carb**: carbonate
Clay: clay minerals **MM**: mineral matter, including clays **Rv**: mean vitrinite reflectance **N**: unstructured **Str**: structured

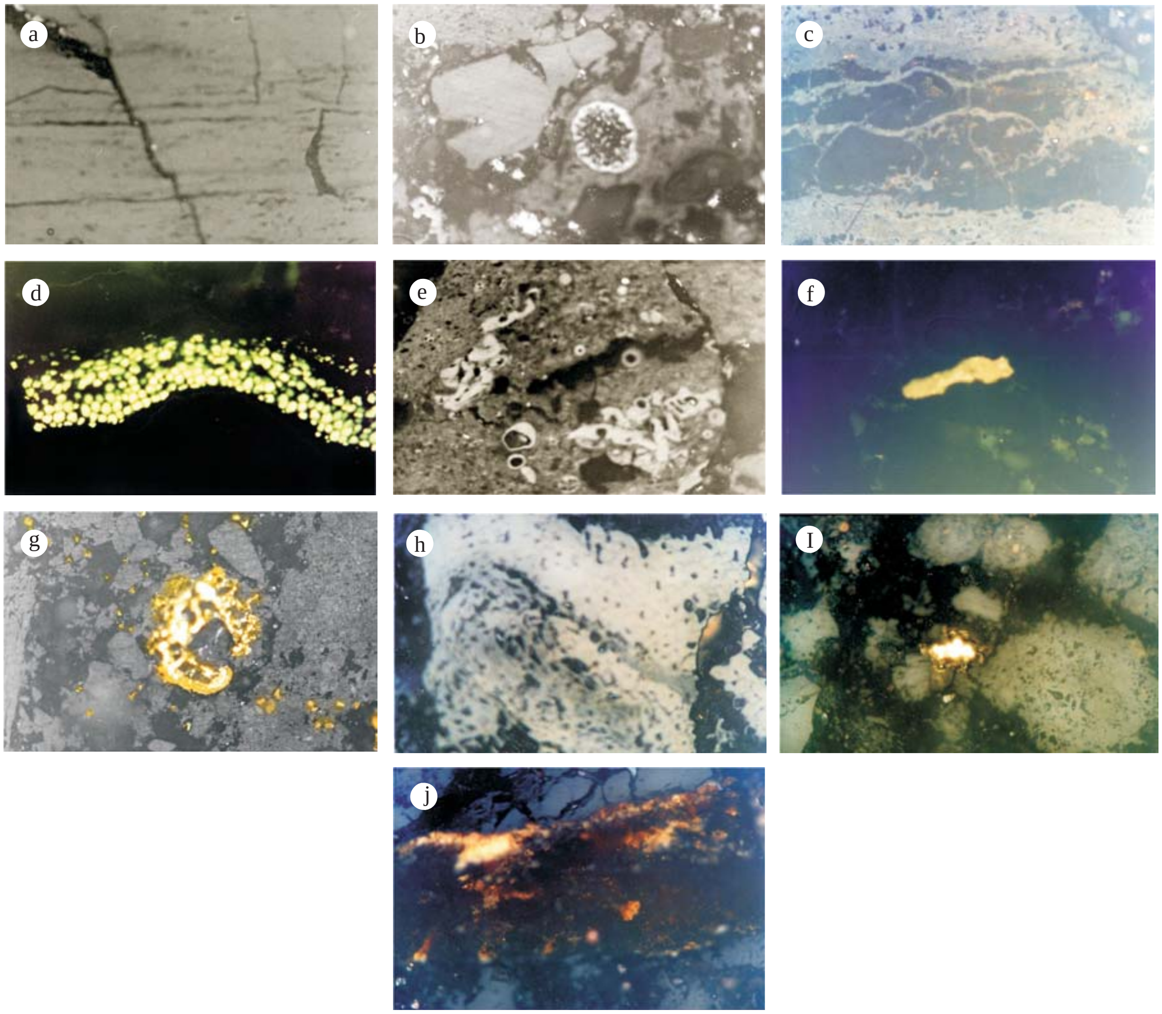

Figure 9. Photomicrographs of macerals and mineral matter:

a. Telocollinite maceral of Jelawatan Seam. Sample 03 NS 03 (Reflected light).
Location: Subanjeriji.

b. Telocollinite associated with furginite of A Seam (A_2 Subseam). Sample 03 NS 01 (Reflected light).
Location: Arahan.

c. Association of desmocollinite, semifusinite, and clay minerals of B1 Seams. Sample 03 ES 01 (Reflected light).
Location: Arahan.

d. An assemblage of resinite filling in cairities in-between cutinite (upper part of figure) Sample 03 NS. 04 (Fluorescence light).
Location: South Banko.

e. Semi-elongated resinite of A Seam (A2 Subseam). Sample 03 NS. 05 (Fluorescence light).
Location: Arahan.

f. Semifusinite of Enim Seam Sample 03 ES. 06 (Reflected light) .
Location: South Banko.

g. Sclerotinite, semifusinite, clays, and inertodetrinite of B Seam. Sample 03 NS. 02. (Reflected light).
Location: Arahan.

h. Pyrite (including framboidal type) associated with vitrinite and clay minerals of A Seam. Sample 03 YK. 05.
(Reflected light). Location: Banjarsari.

i. Framboidal pyrite, telocollinite, and semifusinite of Enim Seam. Sample 03 YK.06. (Reflected light).
Location: Subanjeriji.

j. Carbonates associated with vitrinite, Enim Seam. Sample 03 NS. 04. (Reflected light). Location: South Banko.

Table 2. Characters of the Coals studied under SEM Mode

No.	Sample No.	Location	Seam	Lithotype	Maceral & Mineral Matter
1.	03NS 01	Arahan	A2	DB	Predominantly desmocollinite; minor telocollinite; rare resinite; rare fusinite and sclerotinite. Some kaolinite flakes and pyrites.
2.	03NS 02		B	DB	Telocollinite, few desmocollinite; resinite, sporinite; semifusinite, sclerotinite. Sparse kaolinite and rare pyrite
3.	03NS 05		A2	BD	Telocollinite and some desmocollinite; resinite, few sporinite and cutinite; rare sclerotinite. Sparse kaolinite flakes and rare pyrite.
4.	03YK 01		Benuang	D	Telocollinite and some detrovitrinite; rare cutinite and sporinite; sclerotinite. Sparse clays and pyrites.
5.	03YK 02		A1	DB	Telocollinite and desmocollinite; resinite with some sporinite; sclerotinite and inertinite. Clays and pyrite (sparse)
6.	03YK02A		A1	DB	Telocollinite, detrovitrinite; sparse sporinite, few resinite and cutinite; sclerotinite. Sparse clays and pyrite.
7.	03ES 01		B1	BD	Desmocollinite and telocollinite; cutinite & sporinite; sclerotinite and rare semifusinite. Kaolinite with rare pyrite.
8.	03ES 02		B1	BD	Telocollinite with some desmocollinite; sporinite & resinite; sclerotinite with subordinate semifusinite. Kaolinite, few pyrites.
9.	03ES 03		B	BD	Predominantly telocollinite; sparse sporinite, resinite, and cutinite; semifusinite, micrinite and few sclerotinite. Clays and few pyrites.
10.	03ES 04		A2	DB-BD	Desmocollinite, subordinate detrovitrinite and telocollinite; cutinite and resinite; semifusinite and sclerotinite. Clays are common and pyrite is rare to sparse.
11.	03 YK 03	Banjarsari	Enim	DB	Desmocollinite and telocollinite; sporinite; sclerotinite. Rare pyrite and clays.
12.	03 YK 04		A	D	Attrinite, some desmocollinite; resinite, sporinite, and exsudatinite; sclerotinite and micrinite. Sparse clays and pyrite.
13.	03 YK 05		A	BD	Attrinite and few telocollinite; resinite and rare sporinite; few inertinite. Clays and rare pyrite.
14.	03 HS 01		Enim	DB	Desmocollinite, detrovitrinite and few telocollinite; exsudatinite, sporinite and resinite; sclerotinite and few semifusinite. Common clays, probably kaolinite, some pyrite.
15.	03 HS 02		Enim	BD	Desmocollinite, phlobaphinite, and few telocollinite; resinite, few sporinite and cutinite; sclerotinite. Sparse clays and pyrite.
16.	03 YK 06	East Subanjeriji	Enim	DB	Desmocollinite, rare - sparse telocollinite; sparse - common cutinite, rare - sparse sporinite and resinite; rare inertinite. Common kaolinite flakes and rare - sparse pyrites.
17.	03 NS 03		Jelawatan	D	Telocollinite and desmocollinite; few cutinite; rare inertinite. Sparse pyrite replacing inertinite macerals; rare clays.
18.	03 RH 01	South Banko	Enim	D	Desmocollinite and some telocollinite; cutinite and sporinite; sclerotinite and micrinite. Sparse clays and pyrite.
19.	03 RH 02		Enim	D	Telocollinite and corpocollinite (phlobaphinite); rare cutinite and resinite; rare inertinite. Rare clays and pyrite.
20.	03 NS 04		Enim	D	Prominently telocollinite, subordinate desmocollinite; cutinite and sporinite; rare inertinite. Rare pyrite and clays.
21.	03 ES 05		Enim	D	Telocollinite and desmocollinite; sporinite and resinite; sclerotinite and inertinite. Common pyrite, rare to sparse clays.

accordance with ASTM classification, the coal rank falls under subbituminous C - A level.

Discussion

Many parameters of coal seams such as thickness, continuity, roof and floor sediments, sulfur, and ash, are atributed to the depositional environment in which the coal-precursor formed (Horne *et al.*, 1978). Moreover, coal lithotype and composition are also the important parameter in interpreting coal depositional environment (Diessel, 1982, 1986, and 1992; Harvey and Dillon, 1986; Cohen *et al.*, 1987; Teichmüller and Teichmüller, 1982; Marchioni and Kalkreuth, 1991; Kalkreuth *et al.*, 1991; Moore and Shearer, 2003; Jelonek *et al.*, 2007; Toprak, 2009; and Singh *et al.*, 2010). By understanding its depositional setting, the characteristics of coal seam can be predicted.

Coal composition studied is dominated by maceral group of vitrinite. The dominated macerals are telocollinite (Figures 9a and 9b), desmocollinite (Figure 9c), and vitrodetrinite. This condition shows that the intensive gelification level in the early stage of coalification occurred. The process led to the majority of textinite change to ulminite and attrinite to densinite. The next process is vitrinization, where the ulminite and densinite macerals change to be telocollinite and desmocollinite.

Abundance of structured vitrinite is suggested that coal was deposited in a wet forest swamp of telmatic zone, mildly oxix to more anoxic environment with good tissue preservation (Teichmüller and Teichmüller, 1982; Bustin *et al*, 1983; Singh *et al*, 2010, Figure 10), within a rapid burial condition (Diessel, 1992) (Figure 11); mainly from arborescent vegetation (Rimmer and Davis, 1988). High content of degraded vitrinite was derived from a greater degree of degradation of woody tissue, mainly influenced by the type of vegetation, depth of water, pH, bacterial activity, and temperature of peat (Teichmüller and Teichmüller, 1982; Stout and Spackman, 1989; Shearer and Moore, 1994) or by mixed environmental conditions across the peat swamp (Marchioni and Kalkreuth, 1991).

The dominance of desmocollinite or unstructured vitrinite reflects that the majority of coal-precursor was derived from shrubs (herbaceous) or plants that are high in soft cellulose content (angiosperm). The maceral was deposited within a reed marsh condition or limited influx clastic marsh, with increasing maceration and microbial attack or bacterial activity and increasing anoxic condition (Figures 10 and 11). However, besides rich in cellulose, the angiosperm contains high lignin content. This condition leads to coal formation that is dominated by maceral huminite (ulminite, attrinite, or densinite) or vitrinite (telocollinite and desmocollinite). Coals rich in vitrinites (wet forest swamp), but also in clastic clay minerals indicate that the coals were deposited in wet forest swamp of upper delta plain and fluvial environments.

Semifusinite and fusinite are due to the existence of weak oxidation in the peat surface or fire. Sclerotinite or funginite is originated from fungus fossil. Thereby, the existence of funginite is related to the humid aerial environment. Structured inertinite (semifusinite and fusinite) derived from woody vegetation, under relatively dry oxidizing conditions. Inertodetrinite was originated from the disintegration of structured inertinites.

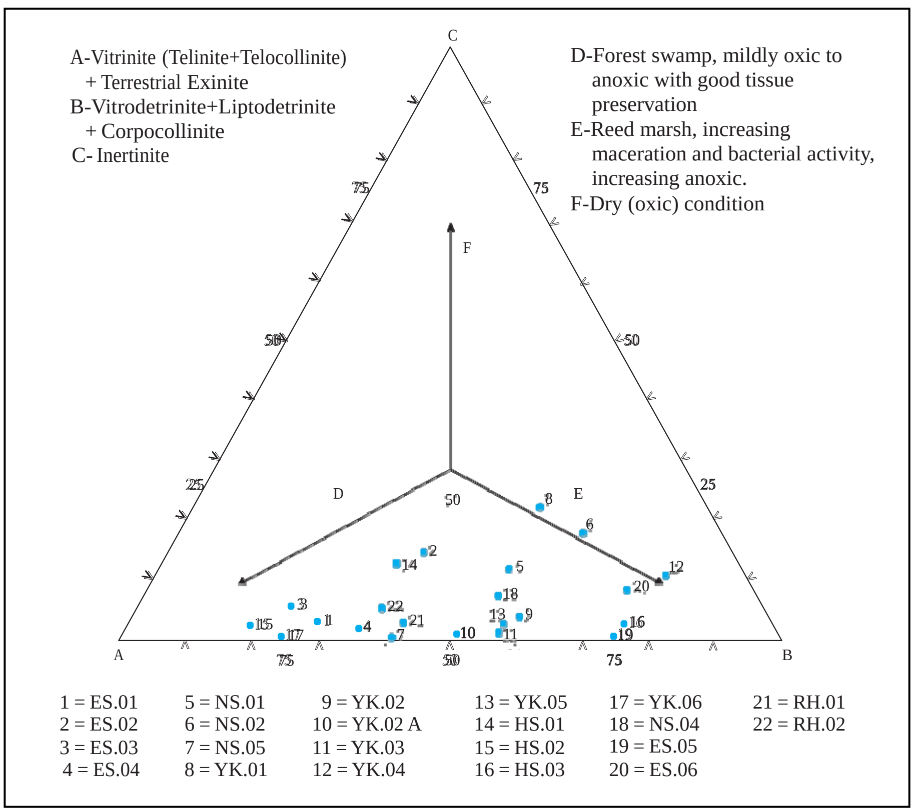

Figure 10. Ternary facies diagram of coals studied showing their paleodepositional facies (based on Singh *et al*'s. diagram, 2010).

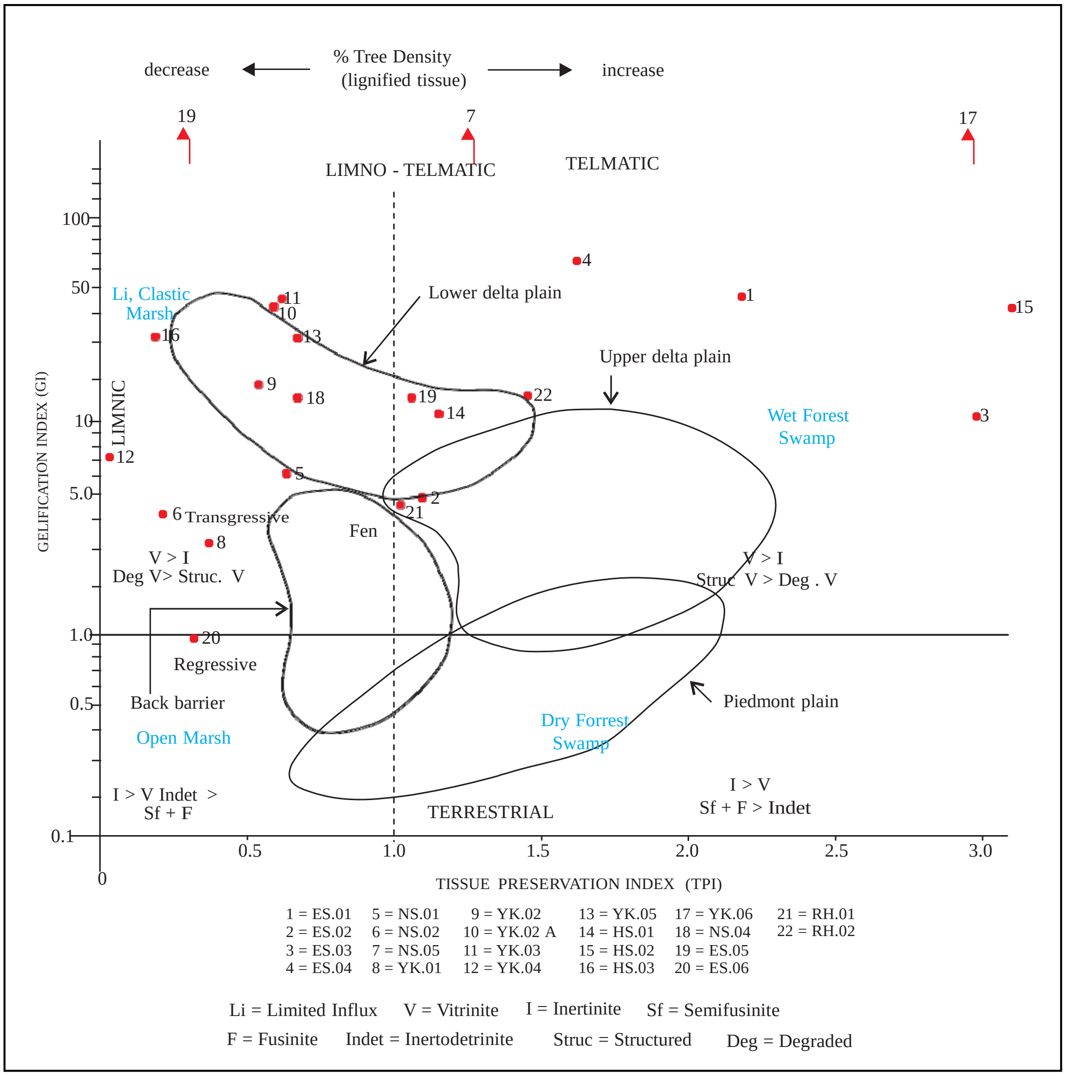

Figure 11. Coal facies diagram of TPI versus GI (Diesel 1965, 1986 ; Kalkreuth et al., 1989) of coals studied that displays their paleodepositional environment.

The dullness in coals studied, as recognized in samples 03YK.01, 03YK.04, 03ES05, and 03ES.06, are suggested to be due to their significant contents of dry and wet macerals, mineral matter, and also predominant vitrinite B, although their whole vitrinite contents can be categorized as a high level (Table 1). This case is in accordance with Diessel (1982) who stated that the "dullnes" of coal may be due to the content of dry and wet macerals, and mineral matter. The dry maceral comprises structured inertinites and macrinite, whilst the wet ones are inertodetrinite, discrete macrinite, sporinite, and alginite. Additionally, it is also concommittant with Sappal's statement (1986), who recognized in several Western Australian coals, that the presence of finely disseminated and laminated mineral matter leads to the dullness of coals rich-in vitrinite.

Depositional Facies

Coal composition and diagnostic macerals are the primary important parameters in studying facies analysis. The seams, in general, that are relatively high in vitrinite macerals are indicated by the overall petrographic characteristics of seam sections. Inertinite content is slightly higher than exinite and mineral matter that are present in a nearly similar content. Petrographic indices obtained from facies diagnostic macerals (Table 3) display that the accumulation of the coal precursor under a vicinity of open to closed conditions occurred characterized by the nearly similar input of degraded and structured vitrinite macerals.

Based on a triangular facies diagram (Figure 10) of Singh *et al*.'s (2010), ten coal samples (03ES.01, 02, 03, and 04; 03NS. 05; 03HS.01 and 02; 03YK.06; 03RH.01 and 02) fall under forest swamp, mildly oxic to anoxic with good tissue preservation; whilst twelve samples (03NS.01, 02, 03, and 04; 03YK.01, 02, 02A, 03, 04, and 05; 03ES.05 and 06) occupy reed marsh with increasing maceration and bacterial activity, and also increasing anoxic facies (Figure 23). The figure shows that the B Seam predominantly was deposited in a forest swamp zone; A Seam is more dominant in a reed marsh; Benuang Seam indicates a reed marsh origin; Jelawatan Seam in a reed marsh; whereas the Enim Seam varies from reed marsh to forest swamp characters.

Table 3. Maceral Petrographic Indices (TPI and GI) of the selected Muaraenim Coals

No.	TPI	GI
1.	2.27	48.00
2.	1.10	4.94
3.	2.97	13.42
4.	1.58	66.00
5.	0.63	6.43
6.	0.27	4.02
7.	1.38	159.00
8.	0.39	3.15
9.	0.54	19.41
10.	0.58	43.11
11.	0.61	45.00
12.	0.07	7.12
13.	0.66	31.40
14.	1.24	10.21
15.	3.69	41.27
16.	0.24	34.92
17.	2.97	243.50
18.	0.70	10.67
19.	0.34	243.00
20.	0.33	0.96
21.	1.19	46.80
22.	1.46	16.96

Furthermore, a diagram created by Diessel (1965 and 1986) which then modified by Lamberson *et al*. (1991), Kalkreuth *et al*. (1991), and Diessel (1992) (Figure 11) tends to show that delta development and groundwater fluctuation lead to changes in TPI (Tissue Preservation Index) and GI (Gelification Index). From upper delta to lower delta, marine water influence increases, and it was followed by the decreased development in plant variation. Then, the influence of groundwater represented by GI play an important role. On the other hand, TPI is related to the type of plant input, whether its tree (lignified tissue) density increases or decreases. The GI is low to very high, whilst the TPI is low to moderate (Table 3). This character tends to suggest mixed facies conditions (Figure 11).

TPI>1 or structured vitrinite > unstructured vitrinite (samples 03ES.01, 02, 03, and 04; 03NS.05; 03YK.06; 03HS.01 and 02; 03RH.01 and 02) tends to show that the coal is derived from woody plant. In the case of TPI < 1 or unstructured vitrinite > structured vitrinite (represented by samples 03ES.05 and 06; 03NS.01, 02, 03, and 04; 03YK.01, 02, 02A, 03, 04, and 05), vitrinite will be associated with cutinite (desmocollinite). However, the cutinite is very easy to be destroyed by marine water. Therefore, the reconstruction of depositional environment cannot be performed on the basis of these macerals. A combination of desmocollinite, plenty of cutinite, and also a little of telinite and telocollinite, shows that the coal is originated from soft tissues of shrubs within a marsh environment.

High GI with variated or low TPI (samples 03ES.05; 03NS.01, 02, 03, and 04; 03YK.01, 02, 02A, 03, 04, and 05) shows that the depositional environment is marsh to fen under limno-telmatic to telmatic condition. If the GI is very high (samples 03ES.05, 03NS.05, and 03YK.06), it should contain plenty of vitrinite and micrinite, with minor content of semifusinite, and inertodetrinite. However, these three coal samples are dominated by telocollinite and desmocollinite; the desmocollinite is well-known to be derived from shrubs (*Angiosperm*) growing in a marsh area, whereas telocollinite from woody plant (Teichmuller, 1989) which cannot grow in a marsh condition.

For coal seam low in GI and TPI values (sample 03ES.06), it is suggested that its depositional environment was an open-marsh where a dessication activity, under a falling water table condition commonly coupled with increasing inherent ash content.

Lamberson *et al*. (1991) stated that variation in coal composition is based upon its depositional environment, and is related to vegetation type, groundwater level, decomposition level, and accumulation rate. On the basis of the presence of pseudovitrinite and vitrodetrinite, he then modified the formula of GI and TPI of Diessel's 1986.

Vitrinite formation is well developed if the peat (coal precursor) is always in wet condition (Diessel, 1986; Cohen *et al*., 1987; Teichmuller, 1989; Lamberson *et al*., 1991; Calder *et al.*, 1991). Increasing in oxidation process leads to a decreasing gelification process (Lamberson *et al*., 1991)

TPI < 1 and GI > 1 (Figure 11) tends to show that the depositional environment of the coal is generally marsh zone with limited clastic input (samples 03ES.05; 03NS.01, 02, 03, and 04; 03YK.01, 02, 02A, 03, 04, and 05). Plenty of desmocollinite or unstructured vitrinite, with a little minerals is concomitant with the marsh environment condition, but the presence of high vitrinite B or unstructured vitrinite content is impossible for the marsh condition. The concept assumes that the process of gelification took place below groundwater level. Another theory says that vitrinite-derived material (huminite) may be formed subaerially within an always wet-condition. Vitrodetrinite sometimes present as structured vitrinites, is formed due to intensive degradation process within early stage of peat deposition (McCabe, 1984).

Furthermore, TPI>1 and GI>1 (Figure 11) tends to indicate the depositional environment of the coal is generally wet forest swamp zone varying from telmatic to limnotelmatic condition (samples 03ES.01, 03, 04, and 05; 03YK.06; 03HS.01 and 02; 03RH.01 and 02). High amount of vitrinite A or structured vitrinite coincides with the wet forest swamp rich in high plant producing high lignified tissue. However, samples 03ES.02 and 05; 03HS.01, and 03RH.01 tend to indicate fen depositional environment influenced by limited marsh clastic input, evidenced by the almost similar content between structured and unstructured vitrinite, and also slightly rich in mineral matter (Table 1).

Additionally, Figure 11 displays that the dominant coal samples fall under lower delta plain, with minor upper delta plain, transgressive, and regressive areas.

Styan and Bustin (1983) concluded that peat originated from shrubs may produce various types of coals. Peat deposited in a limnic condition, within rapid accumulation and is slightly oxidized will produce coal that rich in desmocollinite and vitrodetrinite, but poor in telinite, exinite, and inertinite. Those types of coals, other than containing high content of desmocollinite and vitrodetrinite, they are also rich in telocollinite. In conclusion, the vitrodetrinite is derived from both shrubs and woody plants.

The GI - TPI combination can predict a degradation level of woody tissue structure of plant remnants. Due to the limited aerobic degradation process of cell structure, the inertinite content is very low. This condition is shown by the high GI and low TPI (Lamberson *et al*., 1991). Furthermore, organic matter degradation highly depends upon temperature (Teichmüller and Teichmüller, 1982). Within temperature varying from 35 to 40^{o}C (tropical climate), bacteria present within peat change rapidly cellulose under a biochemical process.

Teichmüller and Teichmüller (1982) stated that in Sumatera, in woody plant peat swamps of several decimeter depths below peat surface, the peat is deeply degraded. The coal originated from tropical plants is more highly degraded than the Miocene brown coal deposited in a subtropical condition. Limited aerobic degradation can be due to a periodical dry season or lowering of the groundwater level (McCabe, 1984).

Rimmer and Davies (1988) stated that the lack of telinite indicates a slow burial and high pH of swamp water. On the other hands, low values of inertinite reflect an occurrence of low degree of oxidation. Association of cutinites with varieties of vitrinite B (Figure 9a) especially with corpocollinite, suggests a leaf source for the peat. The abundance of resinite-rich leaf remains observed, may indicate the shrubby vegetation rather than forest one (Figure 9a).

Teichmüller and Teichmüller (1982) stated that the presence of resistant maceral, such as sporinite, liptodetrinite, inertodetrinite, corpocollinite, and humic detritus, together with a high content of mineral matter is probably due to a transportation. Moreover, Stach *et al*. (1982) and Teichmüller (1989) emphasized that the inertodetrinite, liptodetrinite, and clays suggest a subaquatic facies.

Syngenetic pyrite, *e.g.* framboids, is an important substance in facies analysis, since its precipitation was contemporary with peat accumulation. Mackowsky (1982), Teichmüller and Teichmüller (1982), Styan and Bustin (1984), and Casagrande (1987) accepted that in general, high pyrite contents in coal are associated with the occurrence of marine incursion. On the other hands, epigenetic pyrite recognized locally and filling in cleats and cracks of the macerals tends to indicate that precipitation was started after gelification.

Conclusions

- Coal lithotypes determined predominantly comprises banded (BD) and dull banded (DB) in a similar quantity, followed by dull (D), with minor banded bright (BB) types. The dullness character of vitrinite-rich coal is interpreted due to the significant content of dry and wet macerals, and is also supported by the presence of vitrinite B.
- Coal beds are mainly characterized by high contents of vitrinite (71.2 % - 97.2 %). Exinite and inertinite content is in a similar content, present in a low to moderate quantity showing amount of 0.8 – 18.2 % and 0.4 – 18.8 %, respectively. A low to moderate quantity mineral matter comprises clay minerals, with low values of pyrite and carbonates.
- Main peat-forming plant communities contained stable lignin and rich in cellulose. They were probably composed of herbaceous and shrub types with a high level of groundwater table. A mixed reed moor or limited clastix influx marsh with moist forest swamp facies is assumed for these coals. The assumed facies are in accordance with the result of GI and TPI characteristics.
- Predominance of desmocollinite or unstructured vitrinite in some sample suggests that the main peat-forming plant communities were poor in stable lignin and rich in soft cellulose, probably dominant in herbaceous type with a smaller contribution from forest swamp type. On the other hands, some samples rich in structured vitrinite tend to indicate that the main peat-forming plant communities were rich in stable lignin and cellulose, and are suggested to be dominant in higher contribution from forest swamp type.
- A low amount of inertinite is indicative of the absence of severe oxidation/ dehydration during accumulation of the peat.
- Organic facies of the coals studied tends to show a variation of wet limnic-telmatic zone, in a limited-clastic influx marsh, with increasing maceration and microbial attack activity, to telmatic wet forest swamp under rapid burial condition, mildly oxic to anoxic with good tissue preservation, of dominant lower to upper delta plain depositional environment.
- Vitrinite reflectance data indicate the coal rank falls under subbituminous C - A level.
- The presence of syngenetic pyrites and carbonates suggests that a marine incursion took place during coal deposition in the mire.

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