Sedimentology and Petrography of Sajau Coal Formation in Berau Basin, East Kalimantan, Indonesia

Edy Sunardi[1], Ahmad Helman Hamdani[2]

[1]Lab. of Sedimentology & Quaternary Geology;
Faculty of Geology, University of Padjadjaran, Bandung, Indonesia

Abstract: ***The coal maceral identification have been undertaken to determine the sedimentology and petrography characteristics of the Sajau Formation coal in the Berau Basin, East Kalimantan and their depositional environment. The coal bearing Sajau Formation are represented by clays, carbonaceous clay, sandstones, sandy and lime clays and up to 13 coal seam (A – M coal seam). The Sajau coal belong to the lithotype category of matrix soft brown coals, immature stage and at low phase of coalification represents a transition from peat to lignite. The microscopic investigations revealed the coal is characterized by great maceral diversity, which dominated by huminite group, which constitute between 72.08–95.36 vol. %vol of the coal; following by liptinite macerals with range of 5.24 to 15.24 vol. %, and inertinite approximately 2.68% - 8.60 vol.%. The Sajau coal can be separated into three microfacies based on maceral assemblages: (1) high humocolinite coal represents the in the upper section. This facies was derived from herbaceous plant in lower delta plain, (2) moderately humocolinite coal together with high humotelinite which are developed in the upper delta plain in the wet to dry and (3) low humocolinite coal in the lower section of the seams was origin in the fluviatile dominated influence environment (overbank mire). The coal petrological properties, as well as the indices of the coal facies shown low TPI, GI, VI and moderately GI, reveal that the coal was deposited under a rheotrophy - mesotrophy to an ombrogenous hydrology regime in continuously wet limnic to limno-telmatic conditions with occasionally dry season. The coals are a result of deposition of either from the dominantly herbaceous vegetation, mixed with woody trees, forming in three depositional environments from fluviatile dominated environment (overbank mire), upper delta plain and lower delta plain. The varied pollen assemblages which correlate with the palynofloras of bog-forest, fresh water and mangrove affinity suggested that the Sajau coal deposited within a number of mire environments, from fresh water, wet swamp to bog forest as same conclusion with the maceral analysis.***

Keywords: Macerals, Coals, Depositional Environment, Sajau Formation, Berau Basin

1. Introduction

The study of macerals in coals can provide valuable information about the materials contributing to the former coal swamp depositional environments. Coal macerals analyses have been applied to study many coals and lignite from different areas [1,2,3,4]. Macerals have also been investigated in recent peat deposits that may act as analogues for ancient coal forming mires [5] . There are relationship of maceral composition with the pollen assemblages to determined vegetation type in Carboniferous coals [6,7,8], and from Miocene to Holocene peat In Indonesia [9]. However, many researchers have shown [10-11] , that in the Tertiary age coals in Central Borneo, Indonesia, do not consistent correlations between pollen assemblages with specific types of organic macerals components.

Several studies have been published on the petrography of coal in Berau Basin, but few works have been carried out only for Miocene Coal of Latih Formation [12, 13, 14]. Until this time there has been no detailed and systematic coal petrography study conducted for the Sajau Coal lignite in Berau Basin (Figure 1).

The present work provides detailed integrated study of the coal organic petrology with combined of the coal palynology to characterization of coals from the Pliocene Sajau. Formation in Berau Basin, East Kalimantan (Indonesia). The aim of the research is to identified the source material of the coal, paleofloral change succession and finally to reconstruct the paleo-depositional environment of the Sajau coal in the basin.

Figure 1: Map showing location Research location of Berau Basin, in Kalimantan Island, Indonesia

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2. Geological Setting

The geological setting of the Berau Basin has been summarized here according to the following authors: [15,16]. On the Surface Geological Map of Tanjungredeb Sheet in the scale of 1:250,000, the geology of the Berau basin and its surroundings is presented on the sheets [16]. The location of the Berau Basin on a simplified geological map of Tanjungredeb is shown in Fig. 1 together with some other important coal deposits.

The Berau Basin is located onshore in NE Kalimantan and was initiated simultaneously with the formation of the Sulawesi Sea by rifting of north and west Sulawesi from east Kalimantan [17] during the early Tertiary and which also led to the formation of the Makassar Strait. The evolution of Berau Basin with the formation of tectonic units is related to evolution of Makasar Strait as rifting tectonics during Early Eocene, and then followed by anti—clockwise rotation of Kalimantan with respect to the collision of micro-continent in Eastern Indonesia.

Berau Basin encompasses a wide variety of faults, structural elements and trends. Tectonics of the basin was initiated by extension and subsidence during the Middle to Late Eocene formed wrench faults arid resulted in the formation of major NW-SE oriented arches and had stopped by the end of Early Miocene [18,19]. The area was more tectonically stable from Middle Miocene up to Pliocene with deltaic sedimentation from the west. During this phase, the combinations of basin subsidence and gravity induced listric faulting created accommodation space for an increased volume of deltaic sediments (Latih, Domaring and Sajau Formations), which also caused the formation of rollover anticline structures in the area. The coal seams development in the Berau Basin took place in three periods; initiated in the period of Middle Eocene until the Middle Eocene section with the discovery of coal in Sembakung Formation [20] within syn-rift depositional conditions; second period of coal formation associated with the regionally shifting from dominantly transgressive to dominantly regressive environments of deposition also appears to represent a change from an extensional to a compressive tectonic regime during the Early Miocene until the middle Miocene with the discovery of coal in the Latih formation . The third period of coal formation takes place in the Pliocene formations with is developed in Sajau Formation . The. Coal samples in the present study originate from the Sajau coal in the Berau Basin.

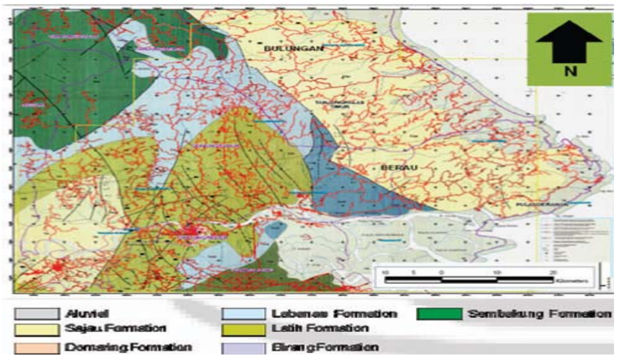


Figure 2: Geological map of Sajau Area showing the location coal samples of Sajau coal Formation in Berau Basin (Situmorang and Burhan, 1995).

3. Materials and Methods

The Sajau Formation is a complex succession of lignite beds and interbedded clastic (sandstone and siltstone). Coal samples were collected from a shallow borehole (around 50 – 150 m depth) in the direction on NE-SW. The coal samples have been taken for analyzed organic petrography, and palynology. Whereas, the coal paleo-environment will be understood either vertically or horizontally.

To analyses the general composition of the Sajau coal, twelve (12) samples which representative of each coal seam for standard petrography analysis were chosen. For microscopic investigations the samples were crushed to a maximum size of 1 mm (20 mesh), dried to remove moisture and then mounted with epoxy resin, ground and polished. Maceral analysis was performed with Leica MPV microscope in Corelab Laboratory with both white incident light and fluorescence modes (magnification 500X) and 20×/0.40, 50×/0.85 and 100×/1.25 objectives for oil immersion investigations. At least 500 points were counted, using automatic point counter. In order to determine the content of huminite and inertinite maceral. For the determination of liptinite maceral content, the count was repeated in fluorescence mode. Macerals were identified according to the classifications of the International Committee for Coal Petrology [21] and [4]). Huminite reflectance was measured on a Leica MPV microscope. At least 30 points were measured per sample. The reflectance measurements were taken on Eu- ulminite B grains that have a visible and homogeneous structural form. The macerals within coal are distinguished in three main groups:

a) Huminite that originates mainly from humic plant material, rich in cellulose and lignin, such as stems, roots etc.; the term *Huminite* is applied for recent organic matter up to the rank stage of lignite to sub-bituminous coal, whereas at higher coalification (bituminous coal to anthracite) the term vitrinite is used instead [21] ,
b) Liptinite, which originates from hydrogen-rich plant remnants such as spores, resins, waxes etc., and
c) Inertinite that includes oxidized macerals, as well as fungal remains

Palynologic material was obtained using standard maceration procedures of Geological Laboratories, Ministry of Mines and Energy, Republik Indonesia in Bandung. Organic material after maceration was mounted on a microscope cover-slip with poly-vinyl alcohol, allowed to air-dry, and the cover slip attached to a microscope glass slide with bioplastic. Each palynological strew-mount slide was then scanned under the microscope in an orderly fashion. A minimum of 300 palynomorphs was counted for each sample, and relative percentages calculated. Palynomorphs were identified to the generic-species level where possible.

4. Result and Discussion

4.1 Organic Petrography

The type and amount of maceral group in Sajau coal samples were shown in Table 1 the microphotographs of maceral type were shown in Figure 3-4.

The percentage of maceral groups (in vol. %) in boreholes clearly show that the most abundant maceral group is the huminite macerals as typical for humic coals between 72.08–95.36 vol. % with mean 83.64 vol.% and standard deviation of 2.66 vol;.%,. The liptinite group shows low contents in the up to 13.46 vol. % with mean 10.30 vol. % and standard deviation of 3.07 vol/ %. Mostly of the inertinite group were a lowest maceral group in samples which has percentages between 2.68% - 8.60 vol.% except two sample B and D coal seam have 13.70 vol. % and 15.10 vol;. % .

4.1.1 Huminite Maceral Group

The organic petrography analysis shown that Sajau coals are exceedingly rich in huminite (Fig. 3). All the subgroups and macerals from this group have been recorded in considerable amounts. The maceral subgroups humodetrinite, humotelinite and humocolinite were identified. The humocolinite subgroup are the predominantly maceral (4 to 54 vol.%) represented by corpo-huminite and gelinite; humotelinite subgroup represented by texi-nite, texto-ulminite and ulminite which varies moderately in coal seam from 21.84 to 45.60 vol%. The humodetrinite subgroup is the smallest contents (6 to 31 vol.%) consisting of detrital of attrinite and densinite.

Humocolinite is disseminated throughout the coals mostly as corpohuminite occurs usually as thin bands, but sometimes some globular or elongated shape with equal or higher reflectance than surrounding huminite; and gelinite is observed represented by totally gelified plant tissue fragments. Most of the pores in gelinite are filled by micrinite or pyrite.. Most of the corpohuminite fills the texto-ulminite cell walls. From all samples analyzed, there were tendency increasing humocolinite content from basal to the top of coal section; i.e. in lower part (A to D coal seam) is less than 15% and gradually increase in the middle part (E, F and G) 21 to 40% then finally 40 to 53% in the top of section (H to M coal seam).

The structural huminite maceral was predominantly of humo-telinite sub group maceral in most of the coal seam. The structural huminite texinite is the most abundant maceral compared with the texto-uliminite and e-ulminite in basal and middle coal seam, while in the upper section the texinite were rare. Textinite is represents remains of well-preserved ungelified wood and grass tissues and is characterized by clearly defined cell structure and open cell. The cell cavities are usually empty or filled with resinite.

Due to biochemical gelification most of the cell walls are deformed. Transitions of texinite to texto-ulminite can frequently be seen. Both macerals have dark grey. Texto-ulminite is a partially gelified plant tissue, and shown the humic substance and clay minerals were fills of the cell lumina. The significantly eu-ulminite was seen in the samples, it is like bands, which alternates with the texto-ulminite and textinite..

The amount of the macerals from the subgroup humodetrinite is relatively lows. These macerals were in association with clay minerals consolidate in all other macerals. Humodetrinite subgroup is represented by both attrinite and densinite macerals. The most abundant maceral from this subgroup is attrinite. It is it is composed of small detritic particles very fine mixed with humic gels and minerals. Attrinite often shows weak brownish fluorescence, as a result of the cellulose, still preserved within the detritic particles

Table 1: Coal maceral composition in Sajau Coal

COAL MACERAL	COAL SEAM												
	A	B	C	D	E	F	G	H	I	J	K	L	M
HUMINITE	84.32	80.88	81.32	72.08	84.85	78.64	84.14	76.62	90.46	90	81.46	95.36	87.23
Humotellinite	45.60	40.48	39.26	43.68	44.66	44.02	25.34	21.84	23.98	26.54	31.44	35.36	25.84
Texinite	28.20	30.65	25.32	32.10	21.20	23.62	12.16	1.32	0.00	0.00	0.00	2.12	1.24
Texto-ulminite	12.26	8.62	9.82	9.66	15.14	19.12	8.06	14.28	18.86	14.12	15.32	21.10	15.28
Ulminite	5.14	1.21	4.12	1.92	8.32	1.28	5.12	6.24	5.12	12.42	16.12	12.14	9.32
Humodetrinite	25.75	29.46	31.66	24.38	15.37	13.32	18.30	11.40	13.32	13.92	7.90	6.00	8.11
Atrinte	17.60	16.42	16.40	8.24	6.18	6.16	12.18	9.28	8.20	7.80	3.62	2.72	5.24
Densinite	8.15	13.04	15.26	16.14	9.19	7.16	6.12	2.12	5.12	6.12	4.28	3.28	2.87
Humocolinite	12.97	10.94	10.40	4.02	24.82	21.30	40.50	43.38	53.16	49.54	42.12	54.00	53.28
Corpohuminite	11.72	7.82	6.28	2.35	22.26	12.14	38.68	32.12	37.14	34.12	27.40	36.18	36.12
Gelinite	1.25	3.12	4.12	1.67	2.56	9.16	1.82	11.26	16.02	15.42	14.72	17.82	17.16
LIPTINITE	12.90	5.16	11.52	11.97	9.68	12.20	10.20	13.46	12.02	7.48	14.52	7.50	5.24
Cutinite	4.14	3.12	5.40	3.95	3.20	3.40	3.00	3.40	4.12	0.00	2.20	0.00	0.00
Sporinite	2.20	0.00	0.00	1.00	2.60	1.80	2.60	6.16	4.54	3.80	5.80	2.60	2.10
Fluorinite	0.00	0.00	0.00	0.00	0.00	1.40	0.00	0.00	0.00	1.00	1.30	1.80	1.00
Resinite	3.20	2.04	2.02	5.20	1.20	1.20	2.60	0.00	0.00	0.00	1.10	1.00	0.00
Suberinite	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Liptoderinite	3.36	0.00	4.10	1.82	2.68	3.40	2.00	2.90	3.36	2.68	4.12	2.10	2.14
INERTINITE	2.68	13.70	7.07	15.10	5.22	8.60	4.70	2.22	2.36	2.12	3.10	4.52	2.46
Fusinite	1.19	8.32	5.28	10.10	1.42	4.00	2.04	1.12	1.24	1.12	2.10	1.80	1.26
Semifusinite	-	-	-	-	1.20	1.40	1.20	-	-	-	-	1.12	1.20
Inertoderinite	1.49	4.38	1.49	3.80	2.60	3.20	1.46	1.10	1.12	1.00	1.00	1.60	-
Sclerotinite	0.30	-	0.30	-	-	-	-	-	-	-	-	-	-
Macrinite	1.00	1.00	-	1.20	-	-	-	-	-	-	-	-	-
Total Macerals	99.90	99.74	99.91	99.15	99.75	99.44	99.04	92.30	104.84	99.60	99.08	107.38	94.93
Mineral Matter	7.12	1.20	2.12	2.30	2.30	4.20	2.12	14.28	12.22	3.28	4.26	7.18	8.38

The amount of the macerals from the subgroup humodetrinite is relatively lows. These macerals were in association with clay minerals consolidate in all other macerals. Humo-detrinite subgroup is represented by both attrinite and densinite macerals. The most abundant maceral from this subgroup is attrinite. It is composed of small detritic particles very fine mixed with humic gels and minerals. Attrinite often shows weak brownish fluorescence, as a result of the cellulose, still preserved within the detritic particles. Vertically, there were shown decreasing proportion of attrinite and densinite in coal seam; i.e. higher contents of attrinite and densinite in the lower section (more than 20 vol.%) and moderately (between 15 to 20 vol.%) At the middle part of coal seam (E-G) then finally was low in the upper part of coal section (less than 15%).

4.1.2. Liptinite Maceral Group

The liptinite maceral groups (Fig. 4) were easily identified from their color in range of fluorescence light from bright yellow to yellow-green in accordance to the low rank of the coals. The amount of the macerals from this group, with an exemption of the sporinite, cutinite and resinite were low (Table 3). As observed under blue light excitation, the H2-rich liptinite group is represented by sporinite (spore-pollen), cutinite (cuticles), resinite (resins/waxes), suberinite, and liptodetrinite (detritus). In basal part of coal seam (coal seam A-G) the cutinite and resinite maceral were predominantly liptinitic maceral group than other macerals type (2.0 – 5.40 vol. %); while in the upper part of coal seam (H-M) sporinite is the dominantly maceral (2.60 - 6.16 vol.%). Cutinite has been identified as leaf protection; shown color in fluorescent light is yellow, yellow-brown to yellow-green. In reflected light it shows very dark grey color with strong internal reflections, but in distinction with the other liptinite macerals can easily be identified, because of its specific shape sporinite maceral was established as flattened elongated shape, as well-shaped and preserved bodies or as single particles with different sizes (Fig.4). Suberinite is a rare maceral in Sajau coals, with have fluorescent color in light is yellow-brown or yellow-green. In reflected light it has slightly darker grey color; and seen as long linear bodies. Resinite is observed as globular/ rounded isolated bodies and as cell fillings it was observed as spherical, oval or long bodies mainly into the textinite. The discrete bodies vary in color from yellow, yellowish-green to brown to reddish-brown. Fluorinite was rarely seen only in J-M coal seam and shown of small round bodies with strong fluorescence in yellow-brown and yellow-green. The liptodetrinite was varied from 1.82 to 2.5% in the coal seam. Liptinite maceral group are relatively resistant components under aerobic degradation, enriched, and increased amounts of the liptinite group macerals may therefore indicate higher levels of degradation in the peat swamp.

4.1.3. Inertinite Maceral Group

The inertinite macerals were varied between 2 to 15 vol. percent. Most in the upper part coal seam (H-M) have a low inertinite content (less than 5 vol. %) compared to the basal and middle part of coal seam (A-G). Inertodetrinite and fusinite are mostly inertinite submaceral in coal samples. High percentages of inertinite, especially the structured fusinite or indicates long exposure time for the peat surface during rapid basin subsidence. Although, there are the possibilities autochthonous formation for some of the inertinite which indicated by high content of fusinite. The abundance of inertrodetrinite in most coal seam demonstrated that it is more likely the other source of the inertinite to be blown into the swamp from distant fires. Inertodetrinite may also indicate the presence of local and regional fires during deposition. Surface fires tend to produce large quantities of ash that accumulates on the surface, most of which is not preserved in-situ, but wind-blown and preserved as pieces of inertodetrinite [3]. Petrographically inerto-detrinite appears as small, bright, fragmented maceral pieces.

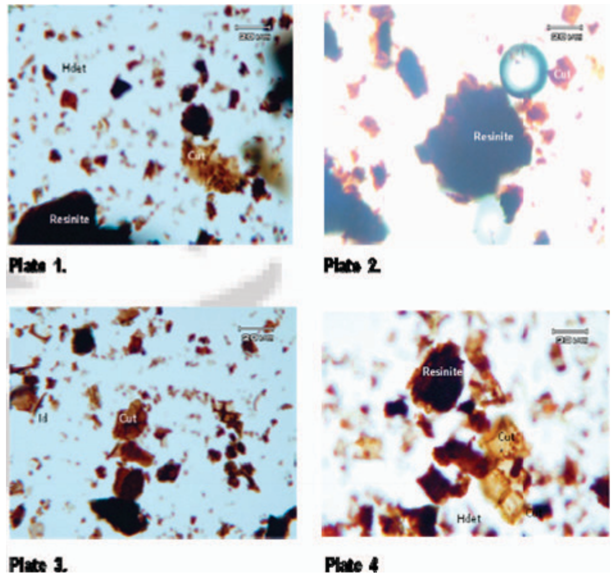


Figure 3: Microphotographs of macerals in the Sajau coal: (Plate 1) clay minerals and humodetrinite matrix, resinite, cutinite; (Plate 2) resinite and other liptinite subgroup in humodetrinite matrix; (plate 3) Cutinite, inertodetririnite; (Plate 4)) cutinite, resinite in humodetrinite matrix.

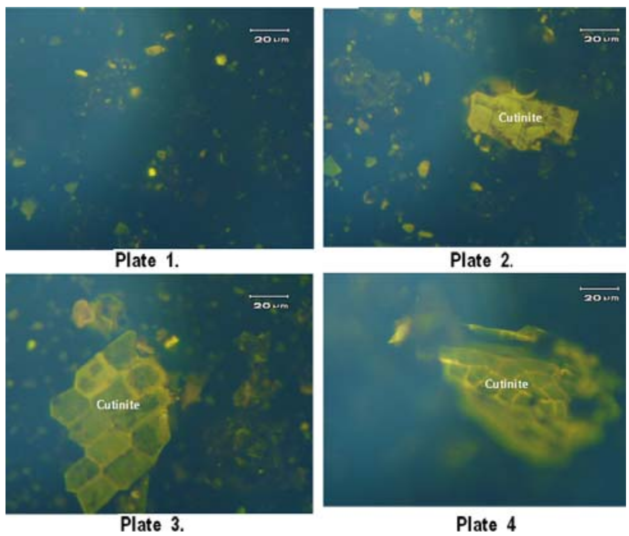


Figure 4: Microphotographs of macerals in the Sajau coal: (Plate 1) cutinite and sporinite in humodetrinite matrix; (Plate 2) cutinite and sporinite in humodetrinite matrix; (plate 3) cutinite, sporinite and liptodenite in humodetrinite matrix; (Plate 4)) cutinite, in humodetrinite matrix

4.2 Mineral Matter and Pyrite

Clay minerals were determined in this study as the main constituents of the mineral matter are usually dispersed, but Some thin clay layers occur as a coal parting. The high liptinite content of the A and H-I coal seam corroborates the fact that the amount of mineral mater is generally high in coals with high liptinite. The ash content determined from the proximate analysis shown that are generally high (7 – 18 wt. %) were correlating with the mineral matter from the microscopic identification. Mostly of pyrite was found content is relatively high in the form of framboidal structure as classified an epigenetic pyrite which indicated enhanced activity of sulphate-reducing bacteria, probably related to carbonate and sulphate-rich waters in the basin during peat formation (Figure 5). Mostly of pyrite minerals was found in the upper part of coal section (coal seam H-M) from 2 – 3,5 % comparing in the basal part of coal section (below 1 %); due to the effect of overburden carrying material forming pyrite (e.g. iron minerals) in the upper layer were decrease with increasingly depth. The iron probably enters the swamp adsorbed on clays. Carbonate minerals are rare and usually found in traces in cleat or fills the cavity, mostly as blocky crystals.

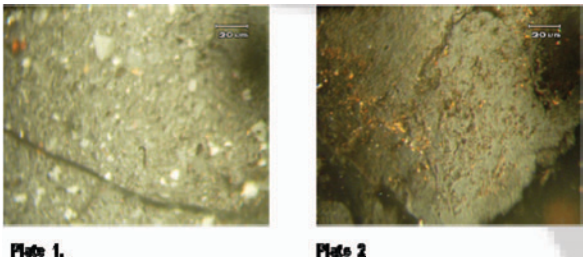


Figure 5: Microphotographs of macerals in the Sajau coal: (Plate 1) framboidal pyrite, cutinite; (Plate 2) framboidal pyrite cutinite and sporinite in humodetrinite matrix.

4.3 Coal Facies

Coal macerals are plant and environment-dependant in the coal formation, therefore the maceral ratios used for paleoenvironmental interpretations. For the first time [22]. Introduces Diesswel Diagrams for two coal indices; i.e. TPI (Tissue Preservation Index) and GI (Gelification Index) for interpretation of paleoconditions for Permian bituminous coals. The ratio is confirmation of relative abundance of decay resistant against non-resistant plants; is not only a measure of the degree of humification suffered by the maceral precursors but it also given an indication of the proportion of wood which has contributed to the peat and which was preserved in it [22] The conifers have higher preservation potential comparing to the angiosperm trees [23, 24,25] were modified Diessel indices for the lignite and soft brown coal. For the present study, the author modified the indices as follow

$$TPI \quad \frac{Htel + SFus + Fus}{Hdet + Hcol + Idet}$$

$$GI \quad \frac{Huminite}{Inertinite}$$

The same approach to assessing the coal paleo environmental conditions in the mire [2] by two maceral indices; i.e., Ground Water Index (GWI) and Vegetation Index (VI). The GWI has shown a comparison between of strongly to weakly gelified macerals and the mineral matter input. As the numerator of the formula a detritital mineral matter content is used. The VI indicated the affinity of maceral of forest with those of herbaceous and marginal aquatic affinity. Therefore, this ration should be good for the vegetation type. Calder's indices were calculated for Sajau coals using the following formulas:

$$GWI \quad \frac{Htel + Hdet + Mineral\ Matter}{Htel}$$

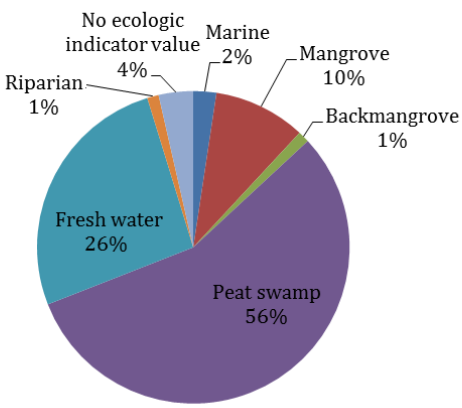
$$VI \quad \frac{Htel + Fus + SFus + Sub}{Hdet + Id + Lip}$$

4.4 Palynology

Palynofloral data from 4 (four) coal seam samples (A, F, I and M coal samples) are presented in the form of a pie pollen affinity environment diagram in Fig. 6, which illustrates the relative percentages of palynomorph occurrences with their environments. Illustrations of representative palynomorph taxa were presented in Fig. 7.

All palynofloral assemblages studied here, reveal a mixing of marsh- fresh water swamp – wet swamp - bog and mangrove elements, with dominated by derived genera from herbaceous vegetation. These pollen taxa present that suggest that terrestrial and marine environments may have had an influence on the deposition of the peat.

The abundance of *Scolocianus magnus*, *Stenochlaenidites papuanus*, *Myrtacidites* further evidence that the environment was predominantly freshwater because *Magnoliophyta*, is a common constituent of peats that have colonized freshwater freshwater bog-forest communities. The low content of mangrove's pollen in all samples (less than 10%) indicated that the mangrove pollen is not autochnous in the mire and transported by winds or possibly by tidal activity during peat development. The discovery of increasing dinoflagellate Cyst from 2% the middle and upper coal seam (6% - 9%) indicate that there are significant marine may have had an influence on the deposition of the peat.



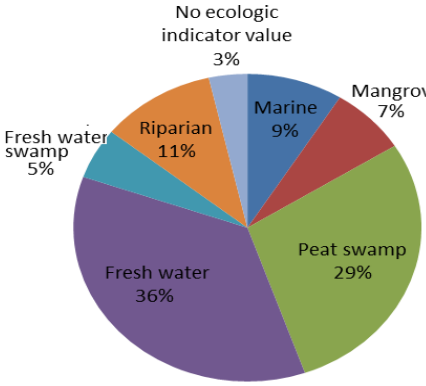


Figure 6: Pie pollen affinity environment diagram

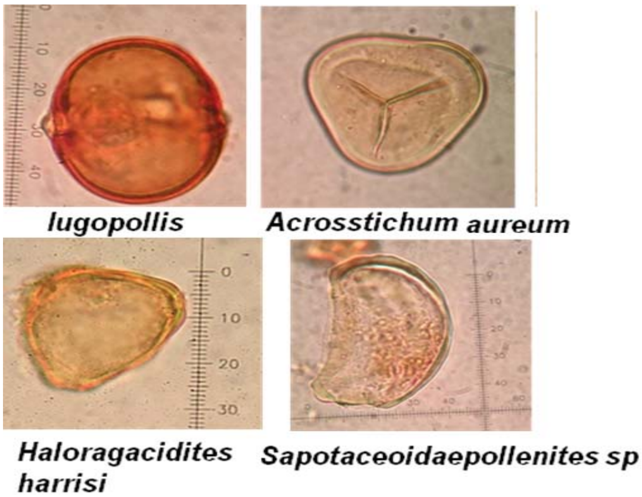


Figure 7: Representative of palynomorph taxa in Sajau coal

4.5 Discussion

The coal maceral assemblage's composition of huminite and the variation in liptinite and inertinite content have been described in the all Sajau coal seam. Further discussed genesis and depositional environments of coal and coal paleomire where the coal accumulation. To better understand the development of coal in Sajau Formation; also performed a comparison with modern peat based on previous research on Holocene Peat in Northwest Kalimantan, Indonesia by [9] which states that no significant changes in the condition of the formation and accumulation of peat from the Miocene to the present day. The same conclusion has been revealed by research on the lignite of Sarongga Formation in Southeastern Kalimantan, Indonesia by [10,11]

Based on the maceral assemblage, especially the huminite content, and mineral matter content, the Sajau Coal succession should be grouped into three i.e. (I) high humocolinite (more than 40%), (II) moderately humocolinite (20% - 40%); and (III) low humocolinite (less than 20%).

(1) High Humocolinite Coal Facies

The high humocolinite coal facies consists of H – M coal seam which was located in the upper part of Sajau coal succession. The coal seam mostly was underlain and overlain by mudstone. or claystone and occasionally by fine sandstone respectively. The mudstone also was found as a parting in the upper coal seam (coal seam L and M) and clay parting at the base (coal seam H and I), calcite and pyrite were also found fills the cleat. The coal lithotypes dominated by bright and banded bright lithotypes in basal and upper part, while in the central part developed dull coal seam.

The abundance of humotelinite (21 to 35 vol.%) together with the humocolinite (42 to 53 vol. %) with low humodetrinite (less than 15 vol.%) in upper section of Sajau Coal indicated that the main precursors are mixed vegetation of woody and herbaceous plants which the herbaceous plant was a high contributor. The dominantly of the sporinite than the resinite and cutinite supported the herbaceous plant was a source of peat.

The values ratio of TPI ranges from 0.38 to 0.67 and GI ranges from 4.17 to 9.39. The Diessel's diagram (1986) plots of TPI/GI (Fig. 8) indicate that all the coal seam were lies in area of a limited influx clastic marsh. The Calder's diagram (1991) plots of GWI/VI (Fig. 9) all coal seam suggest that the coal originated in the swamp environment in limnic-telmatic and rheotropic to mesotrophic hydrological conditions. The peat evolution in upper coal seam of Sajau coal shows an episodic peat accumulation process from rheotropy to mesotrophy (planar peat to doming peat).

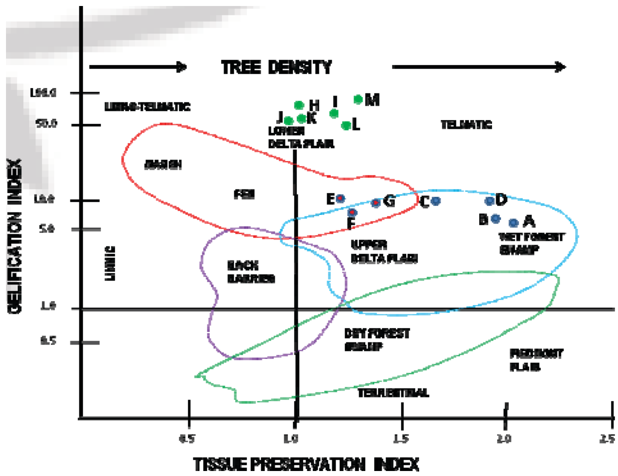


Figure 8: Diessel's diagram of coal maceral of Sajau coal.

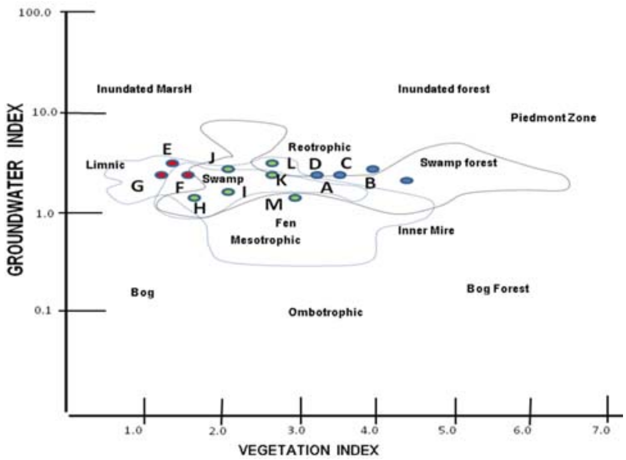


Figure 9: The Calder's diagram of coal macerals of Sajau coal

In the upper part of Sajau coal section, sulfur content are moderately high (between 1.07% – 3.87%) and most variable at the bottom (H and I coal seam), where they reach a maximum of 3.17 %, but fall rapidly upwards to values around 1 %. Sulphur contents correlate well with ash yields and with GWI, which both decrease to the upward direction. Overall the sulfur content in the upper section (H – M coal seam) are more higher than in the basal coal section (A-D coal seam). This fact can be explain by a gradual establishment of more marine influenced in the upper section comparing in basal section during peat development. The study of pollen in coal seam in the upper part of Sajau coal section supported that due to increasing abundance of marine dinoflagellate Cyst (6 - 9%) than previously coal sample in basal section (A coal seam) and middle section (F coal seam) between 0% - 2% .

The high humocolinite coal are contain syngenetic framboidal pyrite in the upper section of Sajau coal seam demonstrates that there are advanced humification of the plant tissue due to enhanced bacterial activities in sulfate reducing bacterial environment. Framboidal pyrite originates from pyritization of sulfur bacteria which might have coexisted along with the sulfur metabolizing bacteria [23,24]. Based on the macerals association and the occurrences of syngenetic pyrite; it is deduced that coal seam H – M were formed from a topogenous peat deposited under wet forest swamp conditions. This interpretation is verified by the high proportion of ash, mineral, sulfur, pyrite and iron contents in the Central Busang and

(2) Moderately Humocolinite Coal Facies

The moderately humocolinite coal facies was located in the middle part of Sajau coal succession (E,F and G coal seam) which associated with mudstones as roof and floor, is dominated by bright and banded bright lithotypes, and with dull coal developed in the upper part. The coal facies was characterized by moderately humocolinite (21.30 to 40.50 vol. %); and humodetrinite (13.32 to 18.30 vol.%) with high content of humotelinite (25.34 to 44.66 vol.%). The predominantly of humocolinite in coal seam together with humotelinite suggested that coal was development in a swamp rich in wood and that wood was a major contributor of the coal in E, F and G coal seam. This supported also by higher content of resinite and cutinite than the sporinite.

The E and F coal seam in the middle part of Sajau coal section have a TPI more than 1.0 (Table 1) and the GI value ranges from 1.75 to 2.08. The Diessel's diagram (1986) plot of TPI - GI (Fig. 7) deduced that E and F coal seam were deposited in wet forest swamp; whereas the G coal seam was developed in back barrier area. The value of GWI and VI are 0.28 to 0.93 and 0.14 to 1.11 respectively. The value of GWI - VI plots of coals for this seam suggested that G coal seam was fall into swamp with marginal aquatic/herbaceous plant under mesotrophic hydrology condition; while E and F coal seam is located in transition from swamp to bog under ombotrophic hydrology condition. The upper delta plain in the wet to dry condition is the most probable environment of middle part of Sajau coal section.

The palinology investigation in F coal seam indicated that the pollen were dominated by pollen's fresh water and peat swamp affinity environment (82%) of with the limited marine influence was identified by existence marine dinoflagellate Cyst (2%).

(3) Low Humocolinite Coal Facies

This microfacies consists of A, B, C and D coal seam which were located in basal part of Sajau coal succession; which associated with mudstones and sandstone as roof and floor. Sandstone and mudstone also was found as a parting and locally as a clay lenses within the coal. The characteristics this facies are low content of humocolinite (less than 20 vol.%) with high humotelinite (39.26 to 45.60 vol.%) and moderately humodetrinite (24.38 to 31/66 vol.%). The coal seams were dominated by bright and banded bright lithotypes, with banded and dull coal developed in the lower part (coal seam A). The high amount of textinite and ulminite is a result of accumulation of wood plants and well preservation of the plant tissue. The liptinite group is rich in all coal seam (5.16 to 12.90 vol. %) with the cutinite. resinite and liptodetrinite predominated; while the sporinite are low; it is suggested that the coal section of coal seam A-D were mostly derived of Conifer plants at the time of peat accumulation.

In the A coal seam was found some spores and pollen of forest trees of various Ordo of Coniferales and Pinnales such as Lygistipollenites florinii, Podocarpus polystachyus, and Taxodium type in coal seam A demonstrate that the Conifer plant is a major contributor to the peat development.

The TPI of the coal seam ranges from 1.06 to 1.82 and the GI ranges from 0.53 to 0.79. The Diessel's diagram of TPI and GI (Fig.5) suggests that coal seam A –D were deposited in bog; predominantly derived by woody plants [1, 23]. Transitional limnic to telmatic environment is probable due to the locally clay lenses within coal which is found in the coal seam. The Calder's diagram (1986) of plotting GWI-VI shown that seam coals A – D lie in the area where both vegetation index and groundwater index values are low; which the lowest GWI values is only in coal seam D (0.07). On the paleomire diagram all the coal seam were fall into bog forest environment under mesotrophic to ombrotropic hydrological condition. The sulfur content of the coal seam A-D were low (below 1%); suggested that no significance marine influence during peat development; instead peat growth occurred in a fresh water environment [11]. In the ombrogenous mire (raised bog) were reported have low sulfur content [26] and the environment more oxidizing and acidity; whereas the mire were not favorable for pyrite formation. The fluvialtile dominated influence environment (overbank mire) should be possible for the lower Sajau coal seam.

5. Conclusion

The abundance of subgroup macerals humocolinite and humotelinite (texto uliminite, eu-ulminite) reveals that the Sajau coals were supported still on stage the biochemical gelification which subjected to the temperature not more of 400 C which was a good environment for bacterial activity to destroy the organic matter. Most of the samples from Sajau coal in Berau basin are characterized by low TPI, GWI, VI and moderately GI values, suggesting increased contribution of herbaceous vegetation, which is usually easily decomposing through the humification process or strong decomposition of the plant material, due to severe humification of wood tissues. Vertical variations of the TPI and GI values indicated that in the lower section mostly Conifer's plant was a major precursor and gradually mixed herbaceous and woody plant in the middle part then finally in the upper section mostly of herbaceous plant as a precursor peat development. Based on the Diessel's and the organic petrography data demostrate that the deposition of the Sajau coals was processed in limno-telmatic to telmatic environment. Three types possible of paleoenvironment including a fluviatile dominated environment such as overbank mire (A to D coal seam), upper delta plain environment (E to G coal seam) and lower delta plain environment (H to M coal seam). The Calder's diagram shown that the Sajau peat development represents cyclicity of the change from a rheotrophy - mesotrophy to an ombrogenous peat in coal seam section. This peat evolution has shown the similarities with the Indonesian's modern tropical domed peat.

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Author Profile

EdySunardi, received the Undergraduate degree in Department of Geology, Faculty of Mathematics and Natural Sciences University of Padjadjaran, Bandung, Indonesia in 1985, Master of Science degree from Earth Science Technology, Free University Brussels, Belgium in 1991 and Doctor of Science degree in Department of Geoscience from Osaka City University, Japan in 1997. He is a lecture on Sedimentology and Quaternary Geology in Faculty of Geology University of Padjadjaran. He is interested in Sedimentology and Stratigraphy research (including Magneto-stratigraphy).

Ahmad Helman Hamdani, received the undergraduate degree from Dept. of of Geology, Fac. Mathematical and Natural Sciences, University Padjadjaran, Bandung in 1980; Master of Science Degree on Geochemistry from University Indonesia in 2010, and PhD Degree in Geology from Faculty of Geology, University of Padjadjaran in 2014. Now, he is working as a lecture in Fac. of Geology, University of Padjadjaran.