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Spatial Variability in Macro- and Microtextures of A Tropical Intermontane Peatland: Preliminary Investigation into The Kutai Lake Peat System, East Kalimantan, Indonesia

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Abstract - Peat deposits of the Muara Siran, East Kalimantan area, were investigated for their vertical and lateral succession, to examine the characteristic variability, particularly its macro- and microtextures. The deposits are situated in the Kutai Basin, in the vicinity of several Cenozoic coal deposits. Peat samples were taken from twenty-seven coring sites in the area, using a MacCaulay peat corer. The Muara Siran peatlands lie between the Kedang Kepala and Belayan Rivers. Siran Lake lies between these rivers and within the peat system. The peat thickness varied from 0.5 m to 12 m. Decomposed sapric peat formed the basal and margins of the deposit, overlain by moderately-decomposed hemic peat in the central part of the peatlands, though both sapric and hemic peat types are interbedded at the margins of the mire. The fibric peat types were found mostly at the top of the mire and only distal from any active streams. Twenty-four samples of peat were freeze-dried for petrographic analyses of both plant part and maceral analyses using a reflected microscope. On the average, the dominant plant parts were stems and wood (*i.e.* secondary xylem). Maceral composition was mostly from the huminite group (on the average 89%), particularly the macerals humodetrinite and textinite. Macroscopic peat type and microscopic composition are linked. Fibric peat was found to be rich in wood and textinite. Hemic was mostly composed of stems and wood with textinite and humodetrinite as the most abundant macerals. Sapric peat has near equal proportions of stems, wood, and macerated tissue. Humodetrinite is the most abundant maceral in sapric. The average ash and sulfur content were low, 1.29 wt.% and 0.11 wt.%, respectively. Understanding the physical characteristics of inland peat as in Muara Siran peatland is essential to build knowledge of how inland peat is formed and what makes it different from coastal peat. Muara Siran is a unique, relatively small peatland in the central eastern Kalimantan which is still considerably pristine, hence may serve the aim of this study well.

Keywords: Holocene, tropical peat, Muara Siran, spatial variability, micro-/macrotextures

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Introduction

Background

Peat deposits of the Muara Siran area are part of the Middle Mahakam Wetlands (Hidayat *et al.*, 2011) or the Kutai lowland (Chokkalingam *et al.*, 2005), see Figure 1. This lowland extends 35 km in a northwest-southeast trend and 130 km in a southwest-northeast trend (Hope *et al.*, 2005), overlain by a large river system. This lowland

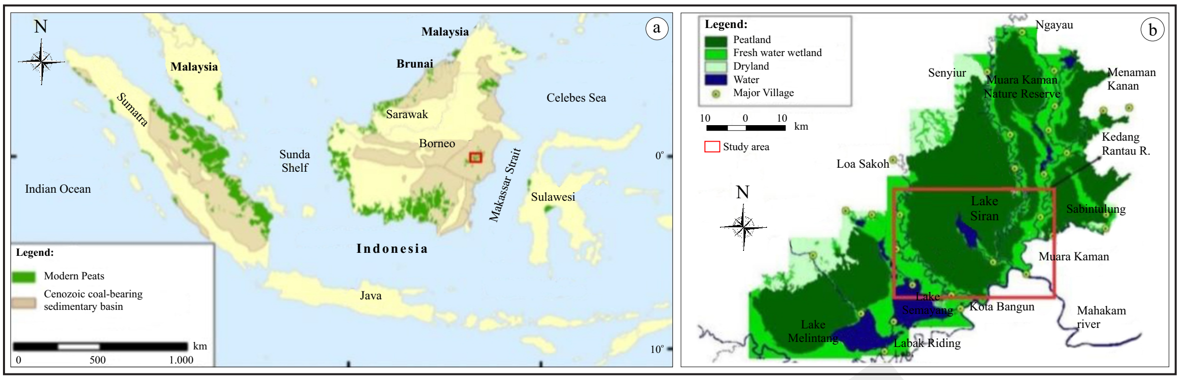

Figure 1. (a) Peatland in this study (marked by red box), plotted in the peat distribution map in SE Asia (modified after Friederich *et al.*, 2016). (b) The studied area located in the village of Muara Siran (modified from Chokkalingam *et al.,* 2005).

is bordered by sandstone hills to the east, whose heights range from 0 - 24 m asl. (Hope *et al.*, 2005). The studied area forms part of the Kutai Basin, the largest coal-bearing basin in Southeast Asia (Friederich *et al.*, 2016, see Figure 1). Peat is deposited behind the natural levee formed by river sedimentation. The peats were from abundant supply over thousands of years of organic matter. The average of peat thickness in Kutai Basin is 8 m, although in several sections, it may reach up to 15 m (Chokkalingam *et al.*, 2005). The term Kutai peatland will be used in this paper to refer to the peat deposit in this area.

The Kutai peatland is a typical inland peatland, formed in an inland basin as far as 80 km to the west from the east coast, whose formation is controlled solely by river accretion (Hope *et al.*, 2005). This peatland is part of an extensive surface freshwater ecosystem, which covers approximately 5,000 km^2. A characteristic of this tropical forest swamp is that it is frequently flooded (de Jong *et al.*, 2015). The largest river in this area is the Mahakam, which is 920 km in length and in places 1 - 4 km wide (Gönner *et al.*, 2014). The river is supplied by numerous tributaries, such as the Kedang Kepala, Kedang Rantau, Belayan, and Enggelam.

The Kutai peatland is subject to fire exacerbated by El Nino, but often with strong anthropogenic causes. Fire affects about 17 - 24% of the area, commonly occurring in the proximity of human settlement (Chokkalingam *et al.*, 2005) and rivers (Hope *et al.*, 2005). Fire intensity has increased over the last 1,500 years, most probably due to anthropogenic activities. Significant fires occurred in 1982 - 1983 and 1997 - 1998, linked to the El Nino cycle, which burned almost 85% of the area (Hope *et al.*, 2005).

The vegetation of Kutai peatland varies greatly, influenced by hydrology, nutrient availability, and severity of fire damage across the area. Typical vegetation is Dipterocarpaceae, Anisopteraceae, and Myrtaceae. Generally, the vegetation is able to adapt to waterlogged, low pH, and low nutrient conditions (Hope *et al.*, 2005). The vegetation is characterized as a tropical rainforest, with tree heights reaching 25 m and girths less than 80 cm. Undisturbed forest may consist of 2,000 - 3,000 trees per hectare (approx. 1,000 trees per acre). The areas close to streams have lost woody trees (from human influence), and at present are occupied by shrubs and grasses (Hope *et al.*, 2005).

The studied area for this paper is focused on peat deposits formed in the vicinity of the Siran Lake (Figure 1). The base of the peat deposit is clay, mostly composed of kaolinite, smectite, mica, chlorite, vermiculite, and quartz, similar to the base of peat deposits from the areas surrounding Melintang Lake, Enggelam Lake, and the Kedang Kepala River (Hope *et al.*, 2005).

The purpose of this study is to investigate the characteristics and variability of peat deposits surrounding the Muara Siran region, particularly its macro- and microtextures. The macrotexture is denoted as peat type and determined through field observation, while microtexture comprises several parameters observable through microscopic analyses. The relationship between the macro- and microtextures of the Indonesia peat has been evaluated by several authors including Esterle (1990), Moore and Hilbert (1992), Neuzil *et al.* (1993), *etc.* However, the macro- and microtextures of Muara Siran peat has not been studied yet. The result will add more insight on Indonesia peat physical characteristics. Eventually, the finding of this study serves as a pioneer for more upcoming research on Muara Siran peatland.

Geological Setting

The Kutai peatland consists of at least thirty-two minor lakes (with a total area of ~20 km^2) and three major freshwater lakes, which are: Jempang (150 km^2), Semayang (130 km^2), and Melintang (110 km^2) (de Jong *et al*., 2015). The water from these lakes are blackish, acidic, ion-poor, oxygen-depleted, but rich in humic acid (Bennet and Gombek, 1992).

Ott (1987) suggested that the major lakes in the Kutai lowland were formed from gravitational sliding of unconsolidated fine-grained sediment during the Paleogene. The filling of the Kutai Basin, according to Satyana and Biantoro (1996), was divided into two stratigraphic phases. The first phase took place during the Paleogene, characterized by shale deposition to the west part of the basin. This happens as a result of sea transgression from the east, triggered by sea level rise. The second phase resulted from uplift of the Kuching High in the west part of the basin during the Late Oligocene to Early Miocene, which triggered a sedimentation reversal to the east. The sudden change of slope direction destabilized the central part of the basin, which at the time consisted of a large volume of shale at the base and silisiclastic sediment over it. Ott (1987) proposed that the change of slope eastward together with the basal shale created a slipping plane, which drove large scale avalanches toward the eastern part of the basin.

This movement resulted in a large void in the western part of the basin, while the eastern part was denser because of the supplementary mass. The continental plate forming the Kutai Basin was thinner in the western part, hence a density imbalance occurred. Such conditions forced an isostatic rebound to take place (Ott, 1987), resulting in the uplift of the lighter western part of the plate to balance the denser eastern part. Since the western part consisted of basement whose density was higher than the eastern part silisiclastic sediments, the isostatic force did not cause the western part to reach its original topographic height. Therefore, geographically, the western part of the basin became a lowland changing gradually to anticlinorium to the east. The isostatic rebound is suspected to have left several small basins, which, in turn, were filled by freshwater, forming the present day Kutai Lakes.

The annual rainfall of the Kutai peatlands is around 2,000 mm with relative humidity ranging from 72 - 90% (Gönner *et al*., 2014) and an average surface temperature of 25 - 30°C (Chokkalingam *et al*., 2005). The climate of the area is primarily influenced by the Indo-Australia monsoon, the Intertropical Convergence Zone, and the El Nino Southern Oscillation/ENSO (Meehl and Arblaster, 1998; cited in Hidayat *et al*., 2011). The peak rainfall usually occurs in December and May, and the least rainfall is usually from June until September (Hidayat *et al*., 2011).

Water levels between dry and rainy seasons fluctuate around 5 - 6 m respectively, in the lakes (Chokkalingam *et al*., 2005; Hope *et al*., 2005). The prominent water level fluctuation is also reflected by the shift in the lakes coverage, which, in dry season, may shrink to 96% of its original area (de Jong *et al*., 2015; Gönner *et al*., 2014).

The Kutai peatland formed around the Middle Holocene, started at least 7,600 B.P. (Hope *et al*., 2005). The formation of the peatland was triggered by the backward erosion of the Mahakam River, which created wetlands adjacent to the levee systems (Dommain *et al*., 2011). Vegetation previously occupying the area where the peatland formed was *Pandanus* sp. and sedges which are semi-aquatic. Peat deposits were at first mixed with fine-grained sediments deposited by the nearby rivers (Hope *et al*., 2005), as a result of terrestrialization in the basin behind the levee (Dommain *et al*., 2011). The community of vegetation then developed to a forest swamp, progressing further inland. A higher frequency of flooding caused by sea-level rise supports this vegetation growth further away from the river. The Kutai peat deposit differs from the Central Kalimantan and Palangkaraya ones, as it shows no evidence of an initial stage controlled by marine processes. Its base is neutral to slightly alkaline sediments. It does not form a significant dome shape, and it consists of both topogenous and ombrogenous peat types (Hope *et al*., 2005).

Peat accumulation rates in the Kutai peatlands have been reported to be 1.89 mm annually (Dommain *et al*., 2011). This peat deposit is younger, compared to the Central Kalimantan peat deposit; the Central Kalimantan peats started forming between the last glacial period and Early Holocene. However, it is older than coastal peat deposits, which started forming from Middle Holocene (Dommain *et al*., 2011). It is thought that the peat accumulated relatively quickly in the Kutai peatlands, as a result of sea-level rise and aggradation of the Mahakam River. However, since 6,800 B.P. the rate of accumulation, is less as a consequence of sea level stability (Dommain *et al*., 2011).

Materials and Methods

Field Description and Sample Collection

Field observation comprised peat sampling, peat identification, and surface vegetation recognition. Location and altitude were determined using the GPS Trimble Series 4600LS and verified on a local map.

Peat samples were collected from cores, obtained by a hand-operated MacCaulay peat sampler (or sometimes referred to as a Russian D Corer). The peat corer consists of an extension bar and corer bit, equipped with a 50 cm container. Peat cores of 50 cm length could be obtained in one coring process. To obtain cores of greater depth, another extension bar was added (Figure 2). The maximum depth of attainable peat was 13 m. Peat coring was stopped once nonpeat sediment was obtained in the base. In cases where penetrating the deposit was blocked due to a large log, the coring point was moved less than 2 m from the original coring point. The depth of the impenetrable wood was noted.

Coring was conducted at twenty-seven sites; seventeen surrounding Siran Lake, and ten in the eastern margin of the deposit, associated with

Figure 2. Peat sampling processes. (a) Planting the auger, (b) Rotating the peat sampler, (c) Auger part, (d) Freshly taken peat core.

the Kedang Kepala River (Figure 3). Sampling location was determined based on accessibility and relative distance to the nearby water body Muchitawati, 2018; Septantia, 2018.

Peat cores were described according to a field classification developed by Wüst *et al.* (2003; Table 1), and modified after Esterle (1990). The main parameter of describing peat were colour, according to the Munsell Soil Colour Chart 10YR (Wüst *et al*., 2003), and a squeezing test which allowed the degree of humification to be determined (from the colour of the water being squeezed) and the predominate peat type to be assigned. The Munsell Soil Colour Chart 10YR consists of seven colour spectrums, denoted by number 2 to 8. Each spectrum consists of two to six shades, which higher number indicates lighter shade. Peat usually falls into spectrums 3 and 4 based on the chart, while nonpeat sediment possesses colours 5 or 6 on the spectrum. The darker the colour, the more decomposed the peat. Fragment and matrix proportions were roughly measured based on how much material was left in the palm after the squeezing test. The material left was considered as a fragment, while the smaller particles which seeped off during squeezing were matrix.

The total length of all peat cores collected was 136 m. Peat samples were stored in half tubes of PVC, and wrapped tightly with wrapping plastic to prevent leakage and contact with oxygen. If the peat was too flaccid and could not be removed from the corer into the PVC container, it was put in a zip-lock plastic bag and wrapped tightly.

Laboratory Analyses

Further analyses comprised microscopic and geochemical analyses. Microscopic analysis was done in the laboratory of sedimentology, Department of Geological Engineering, University of Gadjah Mada. Geochemical analysis was performed by Centre of Research and Development for Mineral and Coal (Tekmira), Ministry of Energy and Mineral Resources. Microscopic analyses were conducted to obtain data on particle size, plant part type, and macerals. Geochemical analyses encompassed sulfur and ash yield analyses. Samples for microscopic analyses were chosen from the sampling sites #5, #8, and #11 (Figure 3), representing the western, middle, and eastern parts of the deposit, respectively. These sites were chosen to laterally depict

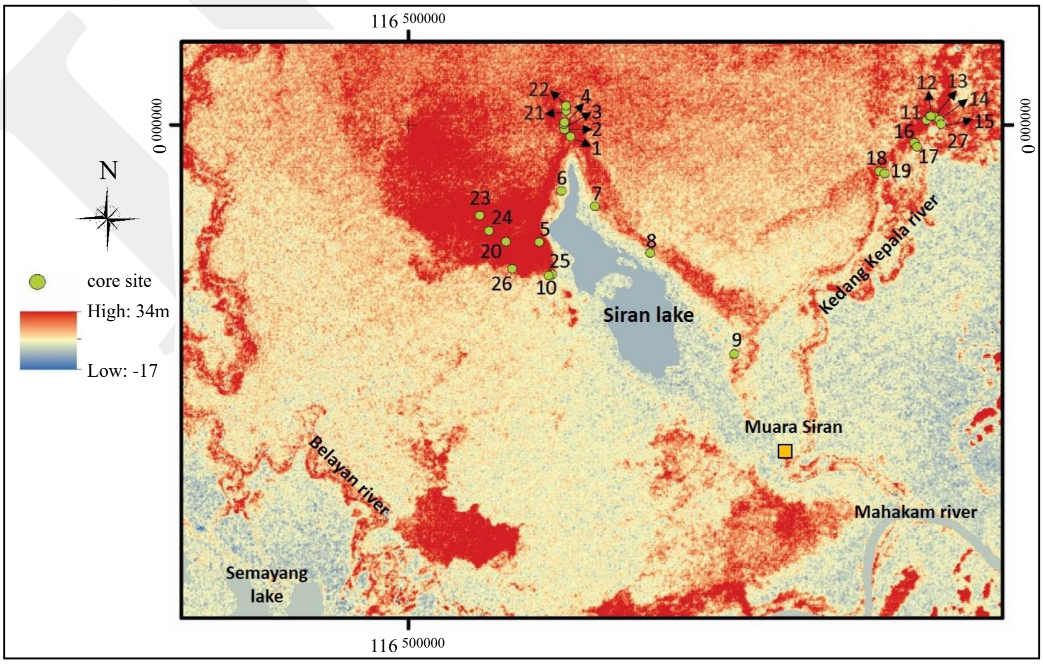

Figure 3. Core site locations plotted on DEM image. The red shade indicates higher elevation. The rivers are identified by the zig-zagging shape (modified from USGS, 2014).

Table 1. Peat Textural Classification (Esterle, 1990; Wüst *et al.*, 2003)

Type	Fragment		Characteristics	Subtype	Abbreviation
Peat	*Fibric*	>66%	Light brown, fragment-rich, mostly fibers, roots, leaves, and branches. Upon squeezing, release clear to tea-coloured water.	Coarse fibric	Fc
				Fibric	F
	Hemic	33% - 66%	Dark brown, fragment are planted in matrix. Upon squeezing release murky water.	Coarse hemic	Hc
				Hemic	H
				Fine hemic	Hf
	Sapric	<33%	Dark brown-blackish, little fragment, mostly small, matrix-rich. Upon squeezing leave gelatinous-texture.	Woody sapric	Sw
				Sapric	S
				Short sapric	Ss
				Sapric with muck	Sm
Nonpeat sediment	*Organic-rich mud*		Gray, inorganic matter-rich. Sometimes, plant fragment may still be found. Leave smeary texture, upon squeezing.	Organic-rich mud with abundant fragment	Mow
				Organic-rich mud with few fragment	Moo

variability of macro- and microscopic characteristics in east-west direction of the peat deposit. Twenty-four peat samples were obtained from these three sites, consisting of eleven samples from site #5, ten samples from site #8, and four samples from site 11. Each sample represents different type of peat labelled according to its position in the site. For example, sample 5/3 refers to peat sample of the third order from the top of core 5. The selected samples were then freeze-dried according to the preparation method by Esterle (1990) to remove moisture. The process took three days, resulting in dried, undisturbed peat. The dried peat was used for making polished blocks under procedure ISO 7404-2 (2009), similar to making a coal polished block. Petrographic observation used an Olympus BX53 System Microscope, with a reflected microscope using a 10x objective. The peat was microscopically characterized using both white light and fluorescence light, the latter was used to better identify lipid type organic components. Petrographic analysis was conducted using a point counting method with 2 mm spacing on a surface of 2 × 2 cm for each polished block. Using this method, there were about 170 - 200 points obtained for each polished block; for all blocks on all samples. Therefore, a total of 4,566 points were counted, of which 822 were nonpeat (voids/pores). Particle size was classified into six categories based on Esterle (1990). The recorded particle size was the longest axis of a particle observed under a microscope (Figure 4). Plant part was identified based on a modified classification by Moore and Hilbert (1992) and Esterle (1990) as shown in Tables 2 and 3, while macerals were identified using the Esterle (1990) peat maceral classification with little modification (Table 4).

Ash yield analysis was based on the American Standard for Testing Material (ASTM) D-3174 (2009) procedure, using thirty-eight samples representing all types of peat found in the studied area. Sulfur content analysis was conducted using a Leco CHNS Analyser for seventeen samples based on ASTM 4329 (2009).

Results

Megascopic Characterization

There are three major types of peat: fibric, hemic, and sapric, in decreasing order of preservation (Table 1). Each major type can be divided into several subtypes based on fragment abundance. Upon squeezing, fibric produces tea-coloured water, hemic produces murky water, while sapric produces a gelatinous texture, much like a common toothpaste (Esterle, 1990).

In the studied area, fibric (F) was mostly composed of wood, bark, stem, and long fibers. Coarse fibric (Fc) commonly contained fibers with lengths reaching up to 15 cm. The fibers usu-

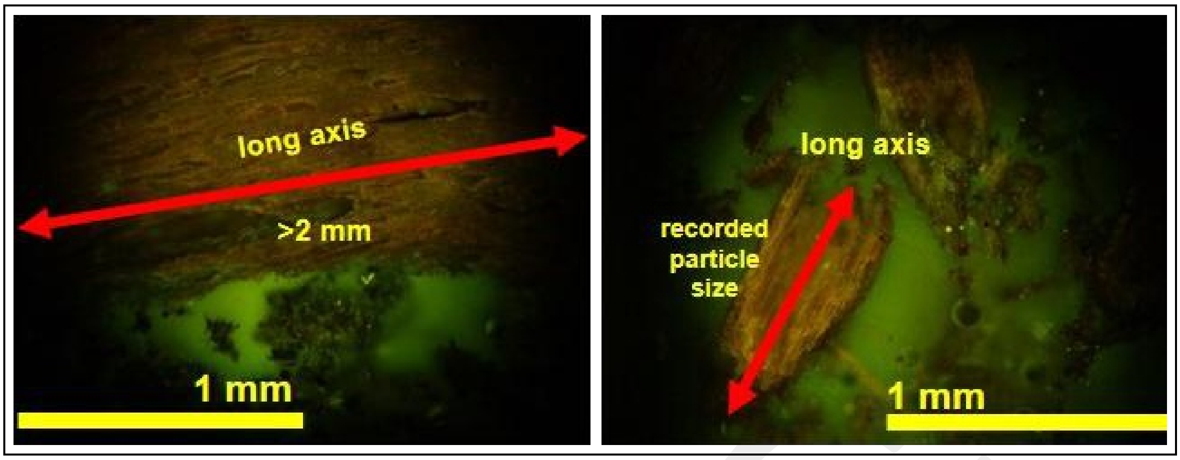

Figure 4. Photomicrographs of particle size measurement done under reflection microscope in fluorescence mode. The plain green colour indicates bioplastic solution used to bind the particles together in the polished block. The brownish feature is the plant particle. The plant size recorded is taken by measuring the longest axis of the particle seen at the centre of the field of view.

Table 2. Plant Part Classification Used in This Study (Modified from Esterle, 1990; Moore and Hilbert, 1992)

Plant Part	Description
Leaf	palisade cells (corpohuminite), perpendicular to epidermis/cuticle, spongy mesophyll, parenchyma tissue, midveins or veins, stomata
Empty rootlet	hollow cylinder defined by epidermis or cuticle; may contain attritus
Wood tissue	secondary xylem tissue only (square-shape cells radiating outwards from the centre), usually show raycells; secondary xylem fragments; no epiderm or periderm
Bark tissue	filled cork cells, square, parallel to epiderm or cuticle; suberinized cell walls
Primary root	cylinder with primary xylem; epidermis, periderm or cuticle; cortex; endodermal cells surrounding xylem; epidermal cells surrounding cortex; xylem-phloem are preserved inside endoderm
Stem	contain no endodermis, vascular bundles are either scattered throughout the cross-section of the stem or as discrete bundles near the cutter edge; cylinder with secondary xylem with epidermis or periderm (if not decorticated)
Macerated tissue of undetermined origin	macerated tissue, usually cortex/parenchyma, unindentifiable group of three or more cells
Matrix	cell wall fragments; cell fillings; intact spore/pollen; seed/fruting body; resins; disaggregated cuticle; fungal sclerotinite

Table 3. Comparison of Plant Part Terminologies between this Study and Previous Researches

Esterle (1990)	Moore and Hilbert (1992)	This study
Rootlet with primary tissue (Rootlet I)	Root, primary	Primary root
Rootlet with secondary tissue (Rootlet II)	Undifferentiated stem/root with primary growth; Undifferentiated stem/root with secondary growth	Stem
Empty rootlet	-	Empty rootlet
Leaf	Leaf	Leaf
Bark tissue	Fragment of cork cells	Bark
Wood tissue	Secondary xylem fragments	Wood
Tissue	Macerated tissue of undetermined origin	Macerated tissue of undetermined origin

ally come from disintegration of stems or roots. Fragments of leaves were rare. Hemic usually consists of wood and bark. Roots and fibers were occasionally found. Leaf fragments were rare. Hemic was the most abundant peat type which constitutes the deposit. It was divided into three

Table 4. Peat Type Constituting Each Key Core-site. Core-site 5 Represents the East Part of the Deposit, while Core-site 11 Does the West Part

Core-site	Segment	Segment Length (cm)	Peat Type	Core-site	Segment	Segment Length (cm)	Peat Type	Core-site	Segment	Segment Length (cm)	Peat Type
5	1	50	F	8	1	50	F	11	1	50	Sw
5	2	50	S	8	2	15	Fc	11	2	50	S
						35	Hf	11	3	50	S
5	3	50	S	8	3	50	Hc	11	4	15	H
5	4	50	S	8	4	50	H			20	Mow
5	5	50	H	8	5	50	Hc	11	4	15	Moo
5	6	50	S	8	6	50	Hc	11	5	50	Moo
5	7	50	S	8	7	50	F				
5	8	50	H	8	8	50	H				
5	9	50	H	8	9	50	Ss				
5	10	50	Hc	8	10	5	S				
5	11	50	Sw			30	Mow				
						15	F				
5	12	50	Sw	8	11	50	Moo				
		10	Mow			5	Moo				
				8	12	20	Hf				
						25	Moo				

subtypes based on its fragment abundance, comprising coarse hemic (Hc), hemic (H), and fine hemic (Hf). Sapric consisted of small fragments, usually stem. The texture of sapric is gelatinous and when squeezed, moves around the fingers. Sapric, with abundant wood, roots, and fibers (Sw), is denoted as woody sapric in this study, since it usually contained fragments of large wood among amorphous material (Figure 5). Sapric, with few short roots, fibers, and wood, was denoted as short sapric (Ss) in this study.

The NE - SW peat-transect line (Figure 6) depicts the general vertical and lateral variation of the studied area. Additional transects directed in a NNE - SSW direction was also conducted to understand the three dimensional variation (Figure 7). Transect direction was chosen based on the most likely trend of a core site association. Core sites that were not crossed by the transect line were projected perpendicularly to the arranged transect line.

Spatially, fibric peat tended to be found in the area near Siran Lake, particularly in the northern part. This area was made up of *Shorea sp.* with girths ranging 0 - 30 cm, thin bark, and quite dense (about 30 cm) spacing. The areas around core sites 4, 21, and 22 were a community of pitcher plants occasionally found in the basal of the trees. Peat thickness in this area ranged 1.5 - 12.5 m. Fragments of wood were common, as well as fibers.

Shorea trees dominated the western part of Siran Lake. *Pandanus* plants were common among the trees. The thickness of the deposit in this area varied between 4.5 - 12.5 m. Generally, the peat in this area was thicker than that on the east side of the lake. The peat thickened to the northwest of the lake. The farthest core site (core site 23) was 12.5 m thick, which is the thickest part. Cores in the eastern area of the lake commonly showed peat interbedded with inorganic-dominanted sediment. In contrast to the western part of the lake, a community of sedges was common in this area, instead of *Pandanus*. This area showed traces of past fires with burned logs and dried plant bodies often observed. Core site #9 was quite isolated, relatively far from other core sites. The surface vegetation was distinctive with thick-bark trees with relatively low spatial density (more than 0.5 m space between trees).

Figure 5. Peat type in the studied area. (a) Fibric, (b) Hemic, (c) Sapric, (d) Nonpeat sediment. The length of the core barrel is 50 cm, with 10 cm diameter.

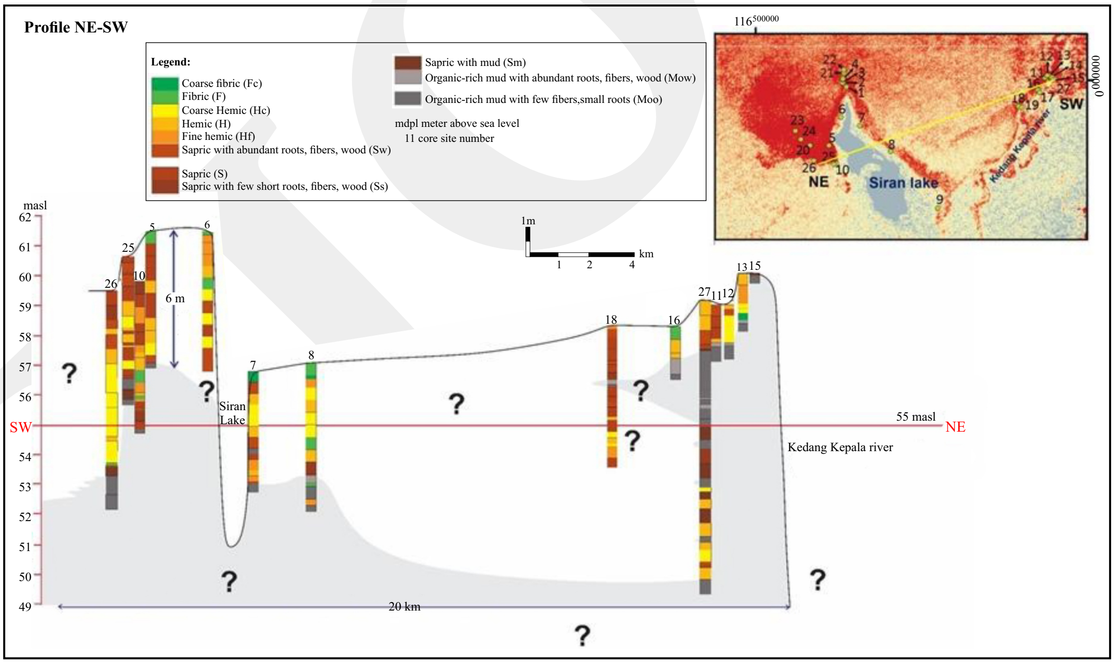

Figure 6. General transect of the Muara Siran peat deposit, directed NE-SW.

The tree diameters were larger than the usually found *Shorea* trees at other core sites.

Peat cores taken in the eastern margin of the deposit, bordered by the Kedang Kepala River, comprised core sites #11 to #19 and #27. The location of core sampling followed the westward creeks of the Kedang Kepala River. Peat in this area was generally thin (less than 5 m thickness), except at core sites 18 and 27, which reached 6 m and 8.5 m, respectively. Both cores exhibited frequent interbeds of inorganic sediment in the middle and basal parts. The surface vegetation

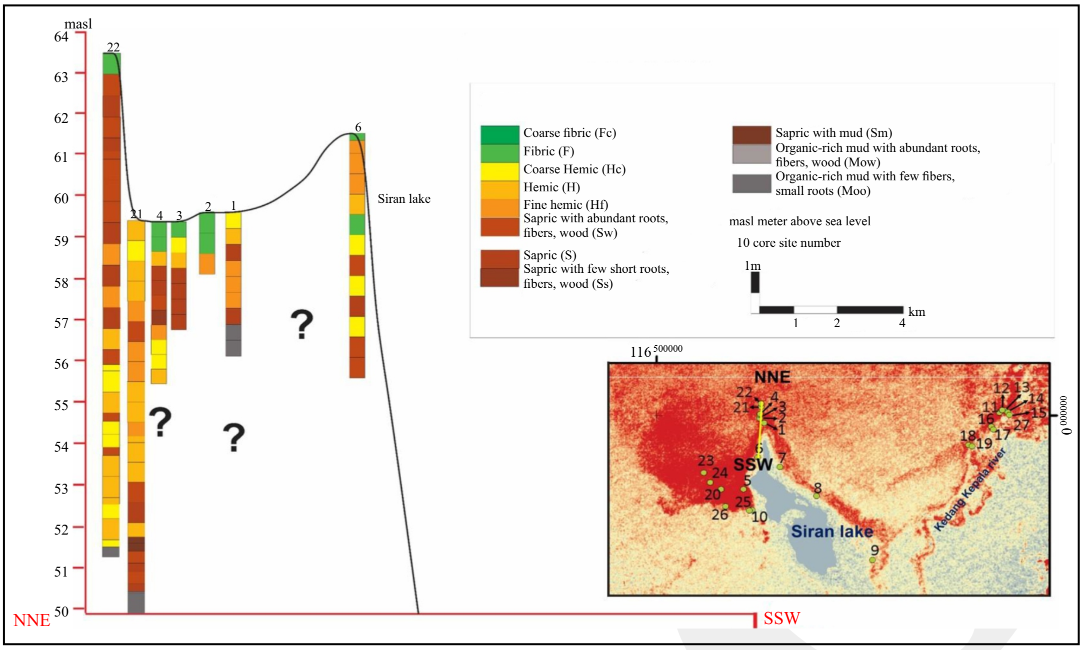

Figure 7. Peat profile along transect NNE-SS.

in the areas of core sites 11 to 19 and 27 contrasted with that of the area around Siran Lake. The vegetation was larger in size, woody, and more heterogeneous. Communities of *Pandanus*, shrub, and sedges were common. The pH level was higher, especially in the part where core sites were close to the creek. This was probably due to the influence of circulated water bringing oxygen, affecting the low level of acidity of the water. Several spots reflecting past fires could be seen during the field work. Fire affected areas were indicated by a clearing with occasional burned logs and dried leaves. The only living plant in these areas was sedge.

All types of peat could be found in this area. Peat with a high degree of preservation could be found overlying the inorganic sediments, such as fibric and coarse hemic. Sapric with abundant wood fragments was quite common intercalated with hemic. Fragments of leaves and fibers were scarce, in contrast with wood and burned wood fragments. Table 4 shows the composition of peat type for each key core, #5, #8, and #11.

Microscopic Characterization

As mentioned above, microcomponents observed in the microscopic analysis comprised particle size, plant part type, and maceral. Particle size was measured based on the longest axis of peat particle in the microscopic field of view. This was to distinguish particles with lengths much greater than their widths, such as fiber, to particles with lengths and widths similar in size, such as matrix. If the shortest axis was selected to represent the particle size, there would be difficulty in marking fragment and matrix. The diameter of field of view was 2 mm, so that any particle that could not be observed entirely in the field of view would be automatically categorized as >2 mm in size. Particle size was classified into six classes, according to Esterle (1990), comprising: <0.1 mm; 0.01 - 0.1 mm; 0.1 - 0.3 mm; 0.3 - 1 mm; 1 - 2 mm; and 2 - 10 mm.

Plant part type in this study was identified based on a modified classification from Esterle (1990) and Moore and Hilbert (1992; Table 2). The resulting classification was a simplified version of the two previous classifications, as there were some types from those classifications unused in the modified classification. The differences in terminology used in this study compared with previous research can be seen on Table 3. This study on peat classification type produced seven types of plant parts and matrix material.

The identification of macerals was based on the classification by Esterle (1990), with a slight modification to adjust the terminology to the updated maceral classification by the International Committee on Coal Petrology/ICCP (ICCP, 2001; Pickel *et al*., 2017; Sýkorová *et al*., 2005). According to the classification, there were eleven distinguishable macerals in the peat (Table 5).

The general results of the microcomponent identification in the studied area are displayed in Figures 8 to 10. Peat particles of 0.01 - 1 mm were made up of more than 60% of the total observed particles. Particles of the 0.3 - 1 mm category were the highest proportion at 77%, while particles of the smallest size category were the lowest at 44%. Particles of size 0.1 - 1 mm shared relative uniform abundance, at approximately 20%.

Matrix material in the peat was dominant, with abundance reaching almost 50% in all samples. Other than matrix, wood and stem were the two most abundant plant parts (Figure 9). Wood tissue overlain with bark was categorized as stem. When the bark is absent, it is categorized as wood. Therefore, stems and wood, in principle, were two particles sharing similar characteristics.

Maceral distribution for all samples showed that humodetrinite was dominant with an abundance reaching 45% (Figure 10). Textinite was the second most abundant at 33%. Sclerotinite or fungal-derived particles were the least abundant of the macerals, accounting for only 0.05%. The huminite group dominated with the average of 89% total. Corpohuminite was minor among other huminite macerals, usually found incased within bark material. Oxidized tissue dominated the inertinite group, consistent with the studied area being subjected to fires. Liptinite group macerals were dominated by cutinite (leaf cuticles). The other liptinite comprised a mixture suberinite and chlorophyllinite. Cutinite was commonly associated with bark, as well as suberinite.

The relationship between plant part type and macerals, as shown in Table 6, describes the dominancy of the huminite group macerals in all plant part types. Almost all plant part types were dominated by textinite, especially wood. A distinction could be seen in the matrix, which, unlike plant parts, was mostly composed of humodetrinite, instead of textinite. Leaf and macerated tissue also showed a prominent variation which was composed of relatively uniform proportions of humodetrinite and textinite. The macerated tissue, especially, showed similar abundance of humodetrinite, textinite, and degradotextinite.

Table 5. Peat Maceral Classification Used in This Study

Maceral subgroup	Maceral[1]	Modified terminology in this study[2]	Abbreviation (in this study)	Origin[2]
Telohuminite	*textinite*	*textinite*	***Tx***	ungelified plant cell walls with open lumens
	ulminite	*other huminite*	***Oth***	gelified plant cell walls with collapsed lumens and coalescing walls
Detrohuminite	*attrinite*	*humodetrinite*	***Hdr***	fragments or shards of cell walls or cell fillings
	densinite	*other huminite*	***Oth***	humic colloidal gels
Gelohuminite	*gelinite*			amorphous colloidal plant material
	corpohuminite	*corpohuminite*	***Cp***	cell fillings from tannins, cell wall degradation residues, or humic gels
Inertinite	*fusinite* *macrinite* *semifusinite*	*oxidized tissue*	***Oxt***	oxidized plant material
	funginite *secretinite*	*sclerotinite*	***Scl***	fungal material
	inertodetrinite *micrinite*	*inertodetrinite*	***Idt***	fragments or shards of oxidized material
Liptinite		*cutinite*	***Ctn***	cuticle
		resinite	***Rs***	resins
		spore/pollen	***Sp/po***	spore and pollen
		other liptinite	***Otl***	suberin, waxes, chlorophyllinite

[1] Modified after ICCP (2001); Sykorova *et al.* (2005); Pickel *et al.* (2017)
[2] Taken from Esterle (1990)

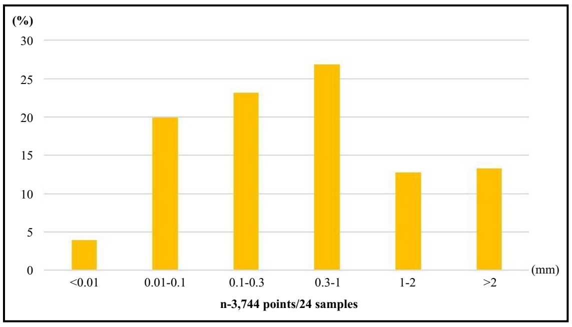

Figure 8. Plant particle size distribution for all petrographic samples. The x axis corresponds to the particle size in millimeter, while the y axis is the percentage.

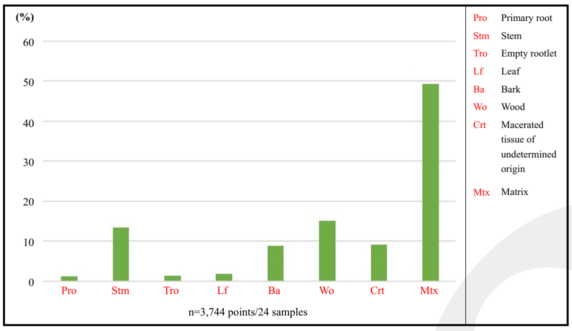

Figure 9. Plant part distribution for all petrographic samples. The y axis is the percentage.

Corpohuminite tended to be found in leaf and bark. Oxidized tissue showed a strong association with the macerated tissue.

Peat Type Macroscopic Characterization

Overall, peat type has a direct correlation with the large (>2 mm) particles identified microscopi-

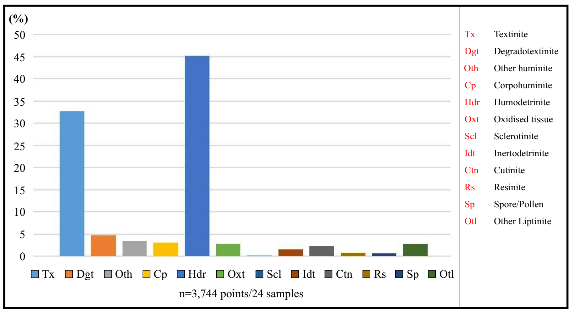

Figure 10. Maceral distribution for all samples of sites 5, 8, and 11. The y axis is the percentage.

cally (Figure 11). Comparison of plant part types with macroscopic peat type shows that sapric is dominated by matrix, while coarse hemic possesses the least abundance of matrix (Figure 12). Hemic was dominated by stems, and fibric was dominated by wood. Stems were dominant in the coarse hemic, while stem abundance for all other peat types is quite uniform. Leaves were found mostly in the coarse hemic and woody sapric peat types, while hemic has the highest proportion of primary root material.

All peat types are dominated by the huminite group of macerals (Figure 13). Fibric, coarse hemic, and hemic were dominated by textinite. Textinite abundance decreased drastically in woody sapric and sapric. These two peat types were mostly composed of humodetrinite. Oxidized tissue found mostly in the woody sapric.

The plant part and maceral can be seen in Figures 14 and 15. Stem is characterized by

Table 6. Relationship between Plant Part and Macerals in The Matrix

Plant parts	Macerals													SUM	SUM (without epx)
	Epx	Tx	Dgt	Oth	Cp	Hdr	Oxt	Scl	Idt	Ctn	Rs	Sp/ Po	Otl		
Epx	822													822	
Pro		32	3	0	3	5	1	0	1	0	0	0	1	46	
Stm		323	43	10	33	63	9	0	1	16	0	2	3	503	
Tro		40	1	0	3	2	4	0	0	0	1	0	0	51	
Lf		22	3	4	8	18	2	0	1	4	0	2	3	67	
Ba		208	6	2	31	21	18	0	3	29	0	1	9	328	
Wo		484	13	6	12	11	31	0	2	0	2	0	3	564	
Crt		96	88	17	9	71	37	0	2	18	0	0	5	343	
Mtx		19	20	90	16	1505	3	2	47	17	26	18	79	1842	
SUM	822	1224	177	129	115	1696	105	2	57	84	29	23	103	4566	3744

Abbreviation see Table 5.

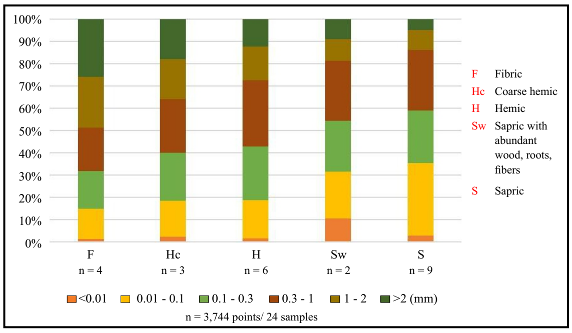

Figure 11. Particle size and plant part type relationship.

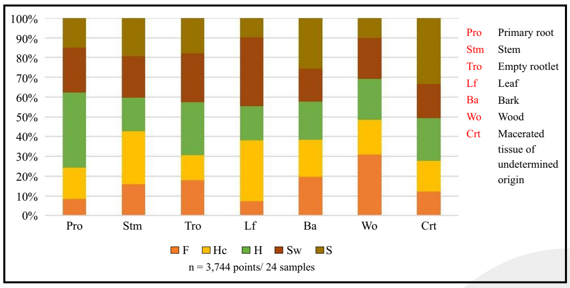

Figure 12. Diagram showing a proportion of a particular plant part within different peat types.

vascular bundle, an organ which function is to transport nutrient and water from the root to the

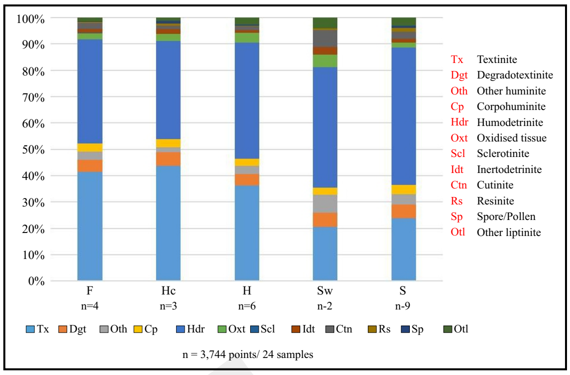

Figure 13. Maceral distribution related to peat type.

leaves. Primary root is featured by double circles, which are endoderm layers. Leaves are identified by thick brownish outer layer, covering yellowish structure-less layer known as palisade tissue.

Pollen is mostly circle in shape and consists of two outer layers, oxidized in most views, looks dark. Corpohuminite is identified from its structureless feature, usually as infilling with dark red to brown colour. Liptinite is spotted from its bright colour, usually bright yellow, some even display red shades.

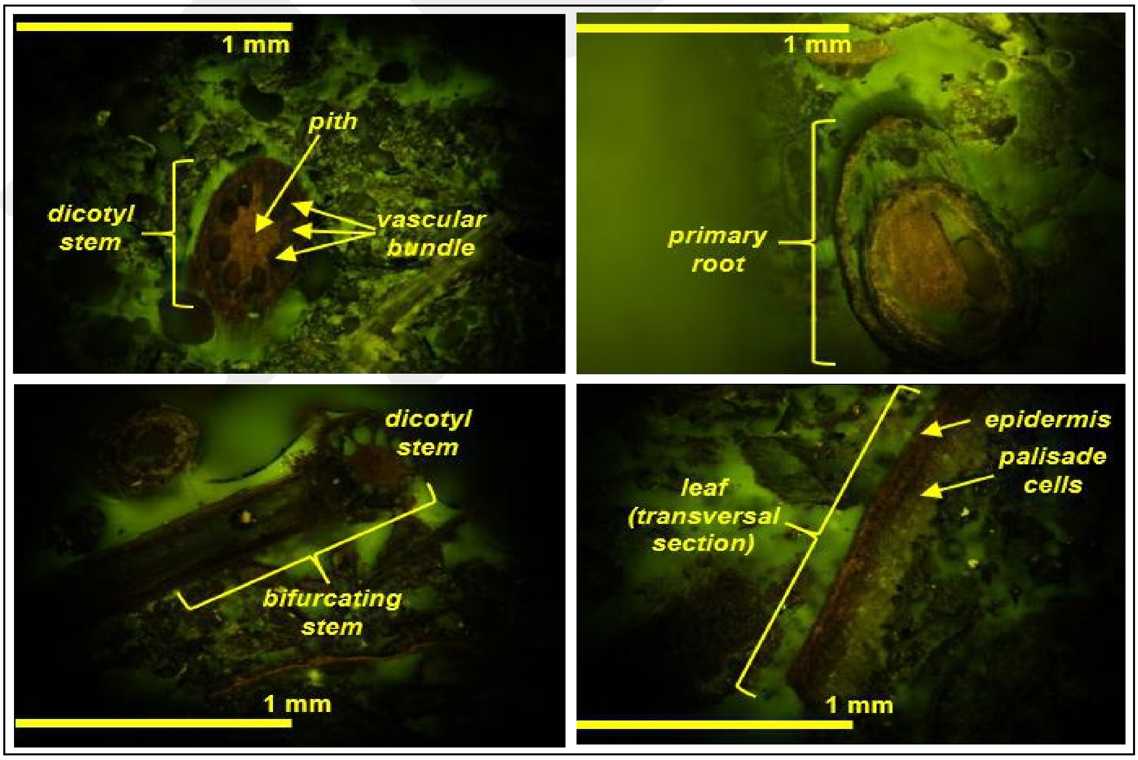

Figure 14. Photomicrographs of plant parts under fluorescence light and 10 × objective magnification.

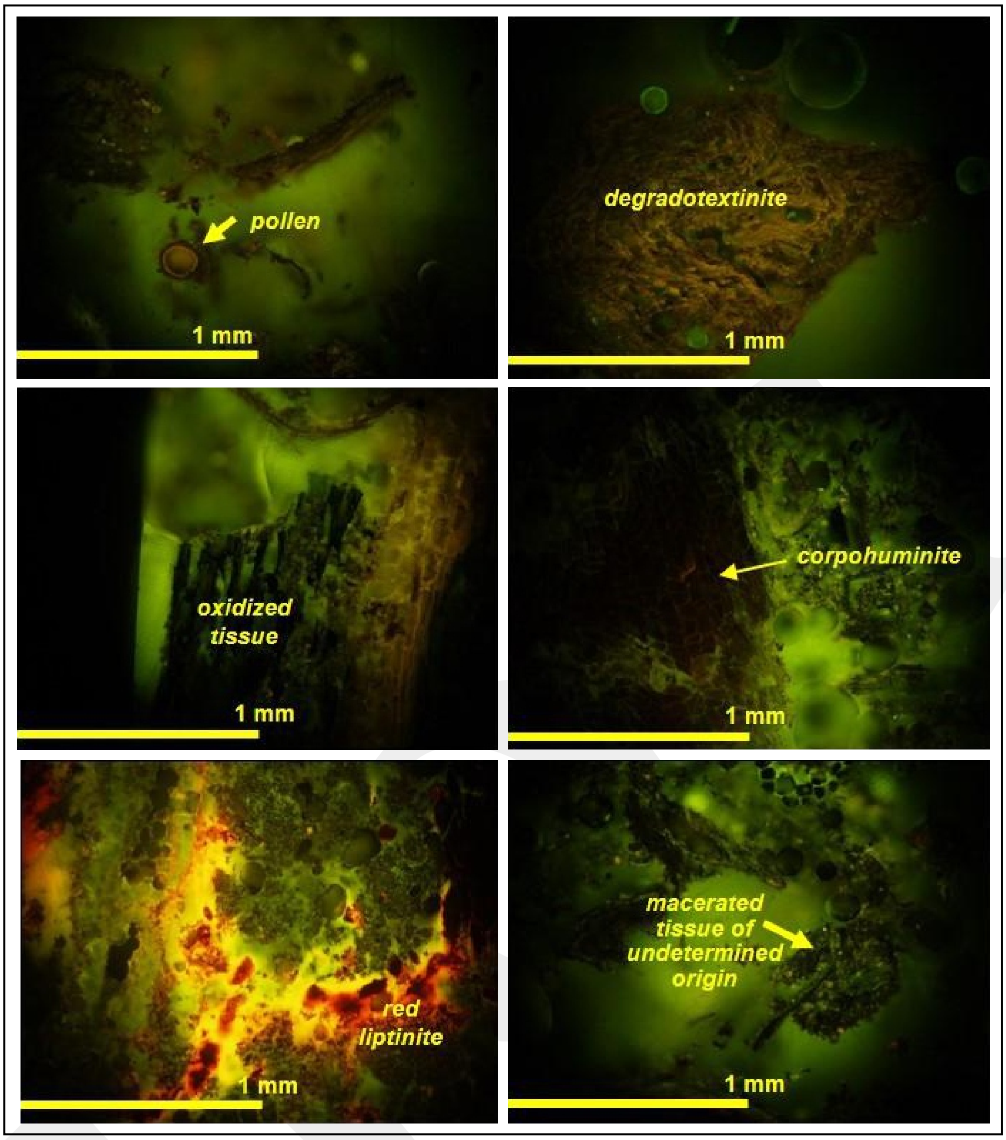

Figure 15. Photomicrographs of macerals in peat under fluorescence light and 10 × objective magnification.

Relationship Between Peat Type and Plant Type

There is a reverse relationship between the size of organic material and proportion of matrix (Figure 16). The abundance of identifiable plant part material is in linear correlation with the larger size of the particle. On the other hand, matrix abundance correlates with small particle size that is less likely to determined. Based on this observation, it is implied that the degree of preservation in peat is reflected by the proportion of particle size.

Fibric peat consists of the most abundant 2 mm fragments, compared to the other peat types (Figure 11) reflecting its high degree of preservation. Plant fragments in fibric peat are dominated by wood, while roots are rare. This is thought to be a result of the abundance of woody vegetation as the source material. The dominant maceral composing fibric was huminite, particularly textinite and humodetrinite. Cutinite was quite abundant in the fibric, compared to the other peat types.

Coarse hemic in the field mostly contained woody fragments in the form of square-shaped fragments of branch, ± 1 cm in size. Some samples exhibited a very well-preserved state, with brown reddish fragment and identifiable

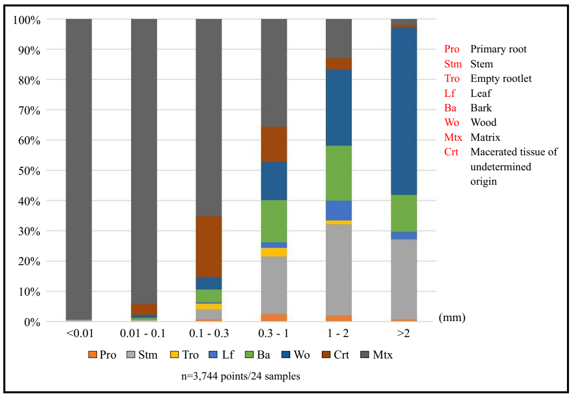

Figure 16. Particle size distribution *vs.* plant part type.

fibrous structures. The lighter colour implied less decomposition. Microscopically, coarse hemic was abundant with particles of 0.3 - 1 mm size. The particles from categories 1 - 2 mm and >2 mm showed similar proportions in coarse hemic. Very fine particles (<0.1 mm) were mostly composed of matrix and humodetrinite. The major maceral composing this peat type was similar to fibric. Stem is the major plant part, commonly characterized by periderm and epidermis.

Hemic was dominant with particle size ranging from 0.3 - 1 mm, although its proportion was rather similar, being category of 0.1 - 0.3 mm. The abundance of large particles (>2 mm) decreased significantly (about 5%) in hemic, compared to coarse hemic and fibric. Wood was dominant in the hemic, while stem and macerated tissue of undetermined origin had similar proportions. Huminite still dominated in hemic, but differed from coarse hemic and fibric, with its mix dominated by humodetrinite. Compared to coarse hemic and fibric, hemic marked an increase in decomposition level, reflected by the proportion of its disintegrated tissue and the prominent rise of maceral originating from cell wall debris.

Woody sapric mostly contained particles from size category of 0.1 - 0.3 mm. It was dominated by woody tissue and differed from sapric, which was mostly composed of macerated tissue of undetermined origin. The major maceral of sapric was humodetrinite with a low proportion of textinite. Sapric also contained the highest proportion of oxidized tissue compared to all other peat types.

This may be due to its distribution in the margin of the deposit, where it tends to get exposed and be subjected to fire.

Diagrams showing distribution of plant part and maceral for each sample in key cores are presented in Figures 17 and 18. Both diagrams express the dynamic of mire development. The proportion of matrix may suggest a shifting in the mire preservation state.

When matrix proportion decreased, the mire was able to support preservation; thus, peat type of a higher preservation degree would be formed. The opposite condition would reflect otherwise.

Ash And Sulfur Variation

Ash yield analysis was conducted on thirty-eight peat samples, while sulfur yield was tested on seventeen samples (Table 7). In general, fibric contains the least average % ash yield, followed by hemic and sapric. However, there is no clear relationship between ash distribution and peat type. In the studied area, high- ash content peat tends to be found at the edge of the deposit implying that ash yield was more likely influenced by the location of the coring sites. The highest sulfur content was found in sapric peat, while the lowest was found in the fibric. Sulfur content ranged from 0.06 - 0.19 wt% (air-dried basis [ad]), and averaged 0.11wt% (ad).

Discussion

Model of Peat Type Variation

A generalized model of the Muara Siran peat deposit has been established (Figure 19). Hemic and sapric peat types are intercalated in the eastern margin of the deposit, associated with the Kedang Kepala River. In the central part, hemic dominates, while sapric tends to be at the base of the peat deposit, directly overlying inorganic sediment. Fibric is mostly found in the top–central of the deposit. The deposit is thick on the west side of Siran Lake and becomes thin to the east. Fibric is likely to be found in the northern area

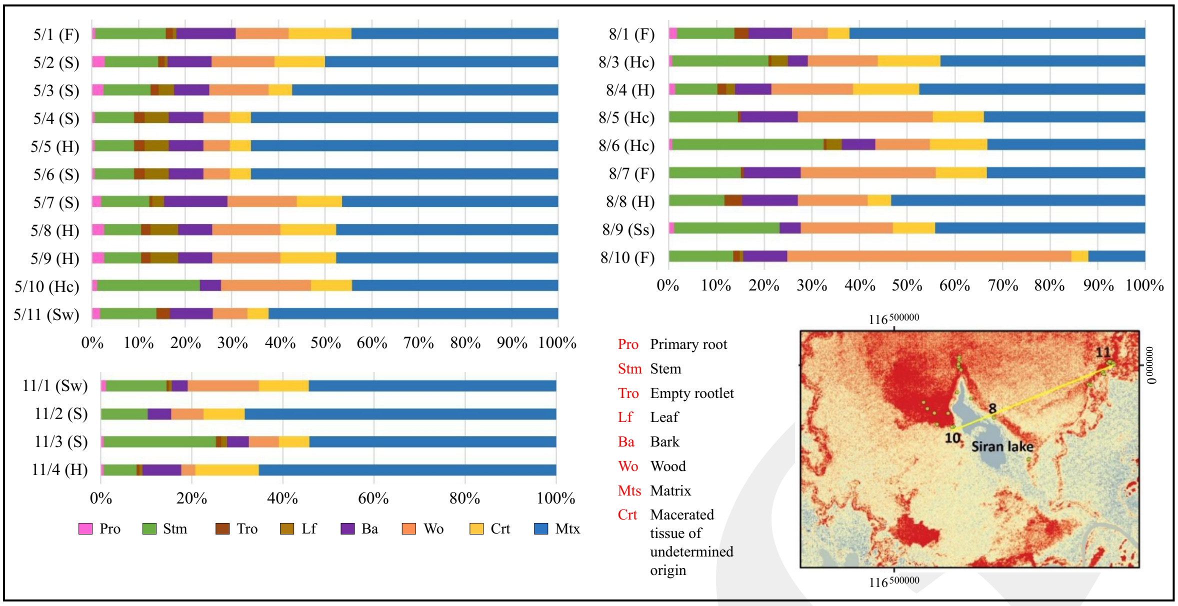

Figure 17. Unoriented proportion of plant part in all samples of each key core. X axis corresponds to the percentage of plant part in each sample. Y axis represents key core (number before "/") with sample number (number after "/"). Abbreviation for peat type is explained in Table 1.

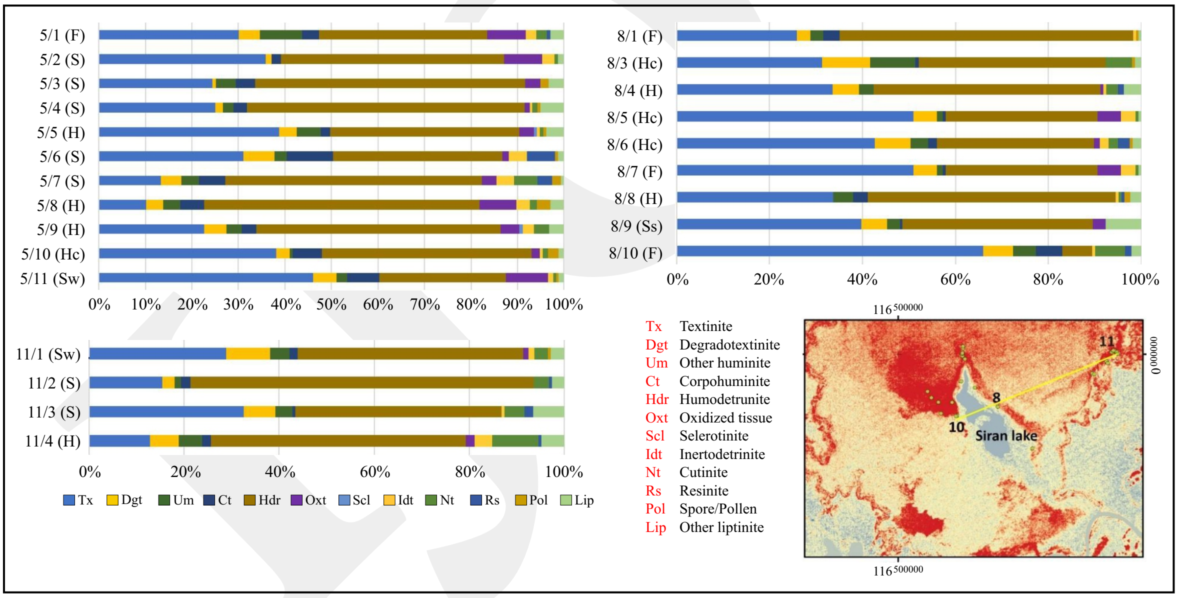

Figure 18. Unoriented proportion of all maceral samples in each key core. X axis corresponds to the percentage of maceral in each sample. Y axis represents key core (number before "/") with sample number (number after "/"). Abbreviation for peat type is explained in Table 1.

of Siran Lake, thus indicating the deposit is the thickest in this direction.

Ash yield and sulfur content tend to be high in the peat associated with nonpeat sediment, which is in the basal and margin parts of the deposit (Figure 19). This may explain why ash and sulphur content are high in sapric type, as it mostly forms the basal and margin and contact the nonpeat sediment. The model is consistent with previous researches (Esterle, 1990; Neuzil *et al*., 1993) indicating that ash yield in tropical peat deposits are generally the highest at the base of the deposit, while the lowest in the top-central part.

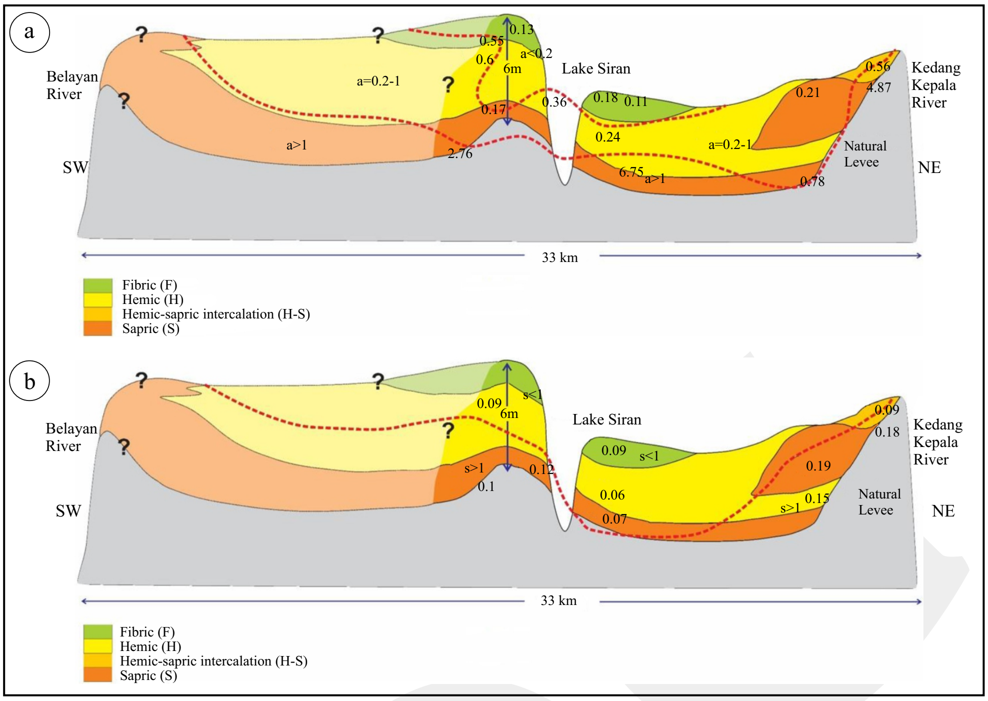

Figure 19. Generalized model of the Muara Siran peat deposit. The less intense colour indicates interpretation, as there is no data taken in that area. (a) Ash and (b) sulfur distribution model (wt.%). The dotted line borders the interpreted ash content in figure (a) and sulfur content in figure (b) of the deposits.

Comparison with Peat Texture from Previous Studies

It is important to compare the result with previous studies especially the inland peat deposit characteristics, as it may lead to different interpretation on how the deposit was formed and any process affecting the formation. In this case, the results mainly compare to the work from Esterle (1990) who conducted a comprehensive tropical peatland study in Sarawak and Sumatra.

Fibric peat, in the work by Esterle (1990), occurred mainly at the top of the peat deposit, while in this study highly-preserved peat could be found directly overlying the non-peat sediment. This is evident in core site numbers #13, #22, and #24. This new finding suggests that arborescent plants, as the most probable source of fibric, may initiate a peat-formation stage, and that semi-aquatic plant communities such as shrubs, sedges, and grasses are not always required to initiate the development of a peat swamp forest. The work of Esterle (1990) also found that fibric is dominated by fibers, originating from sedges, shrubs, or, generally, stunted vegetation adaptable to an acidic environment. This community of vegetation occupies the central part, or the heart of the peatland, and is a sign of the mature development of the peat swamp forest. However, the zone where this vegetation lives was not found in this study, and the fibric was found in the zone inhabited by uniform woody plants. Moore *et al.* (1996) showed the sapric was on top of Palangkaraya peat due to the fluctuation of water level resulted in secondary formation of oxidized material.

In terms of maceral proportions, the inertinite group in this study exhibited prominent differences with Esterle's work (1990). Sclerotinite was very scarce, in contrast with their abundance in Baram peat deposit (Esterle, 1990). The small proportion of sclerotinite indicated that peat was deposited under limnic conditions with a constant water level, which restrained the growth of fungi (Anggayana *et al.*, 2014).

Formation of Kutai Peatland

The development of peat deposit of Muara Siran (Figure 20) is consistent with tropical

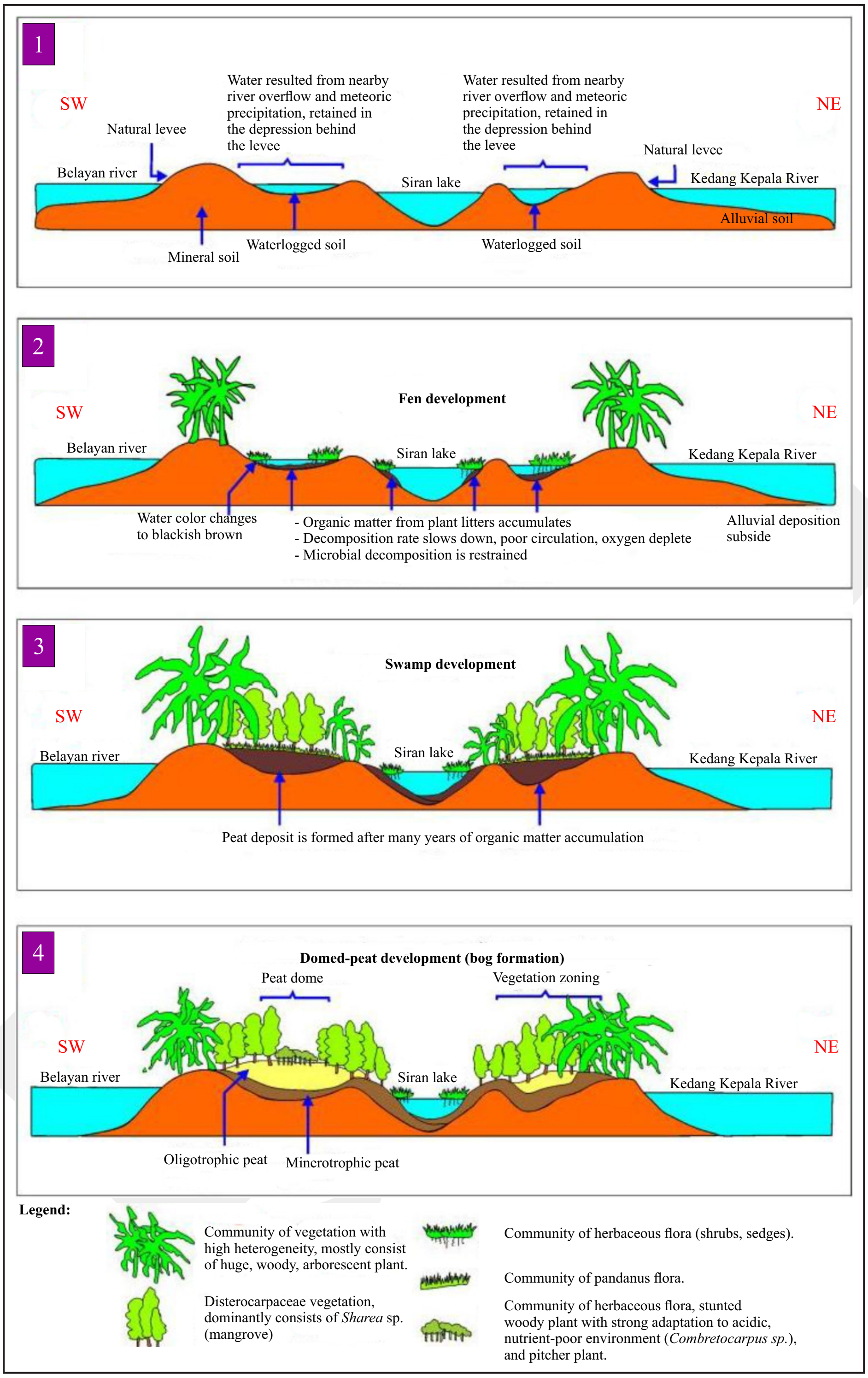

Figure 20. Muara Siran peat deposit formation, not to scale (modified after Flores, 2013). At the beginning, there were only Kedang Kepala River in the east side of the studied area, Siran Lake in the centre, and Belayan River in the east, acting as a large freshwater body. Constant floods at both rivers created natural levees which trapped freshwater at the backside of the levee and formed waterlogged system. At the second stage, colonies of vegetation began to grow, dominated by arborescent plants, particularly around the edge of the river, and herbaceous plants near the isolated water body. This vegetation acted as the sources for plant litters that kept accumulating, covering the basal sediments. These litters formed the peat deposits. The third stage marked by the growth of a new plant community, characterized by their small girths. This vegetation grew relatively far from the circulated water bodies, at part where the water was stagnant. The last stage is characterized by the colony of herbaceous flora at the most inner part of the deposits, where the water is most acidic and less in nutrient

domed-peat formation as proposed by Esterle and Ferm (1994), based on Anderson (1964). The initiation started with the presence of large water bodies, including the Kedang Kepala River to the east, Siran Lake in the centre, and the Belayan River to the west. Since the water bodies formed before peat started to accumulate, it is suggested that the peat formation followed a terrestrialization scheme as with other Kutai peat deposits in general (Dommain *et al*., 2011; Hope *et al*., 2005).

In the first stage, the adjacent river deposited clastic sediment, which then formed a natural levee along the eastern and western margins of the studied area. The levee was occupied by freshwater vegetation, restraining occasional clastic sediment deposition driven by river overflow into the depression behind the levee. The dead material from vegetation started to form peat associated with inorganic sediment. Since the area was close to circulating water bodies and continuous deposition, it enabled oxygen contact and nutrients infiltrated the accumulated peat. Thus, peat deposited in this area was not highly preserved. Sapric and hemic were found intercalating in this zone.

The centre part was relatively far from the river influence, thus the nutrient infiltrates and oxygen circulation were minimal. The development of the vegetation community was started by freshwater herbaceous plants that inhabited the surface of the isolated water body (Siran Lake). This plant community was characterized by its less robust structure, floating above the water surface, including shrubs, *Pandanus*, and sedges. This stage was where a freshwater marsh formed. When this vegetation died, organic matter started to accumulate in the margin and base of the lake. The nature of these types of vegetation (monocots, little xylem, and thus little lignin) allowed more intense, thus peat of a less preserved degree was formed, ranging from sapric to fine hemic.

Further development of the vegetation community marked the swamp forming stage. In this stage, the vegetation community of larger arborescent plants started occupying wetlands surrounding the lake. This vegetation is more resistant to decay (*i.e*. more xylems, high lignin content) than arborescent plants and thus peat of a higher preservation level was deposited in this area, commonly peat of the hemic type.

Further accumulation of peat outpaced inorganic sediment accumulation in both the western and eastern parts of the studied area, with the result of forming a domed surface. The difference in height between the central part and the margin was a physical barrier to flood waters. With a lessened effect of flooding, the central−top part of the peat body was comparatively more preserved with less nutrient infiltration, and thus more acidic and nutrient poor. Fibric peat was likely formed in such an environment.

The domed peat is interpreted to have been developed in the western and northern parts of Siran Lake, indicated by the presence of fibric peat and the thickness of the deposit. The presence of fibric indicates peat which has accumulated under ombrotropic conditions (*i.e.* peat formed within a nutrient-poor environment). Peat accumulating close to the active inorganic sedimentation, such as in the western and eastern margins next to the rivers and around the lake, are considered as minerotrophic.

At the base of many of the peat core locations, a blackish peat layer occurred. Under this layer was inorganic sediment. Microscopic examination of these data showed them to oxidized plant material, that is burned vegetation. This is consistent with previous studies (Hope *et al*., 2005; Hidayat *et al*., 2011) which suggest that fire occurred quite frequently in the Kutai peatlands.

Conclusions

The Kutai peatlands represent a large mire system that has developed through complex geological and geomorphical conditions. Although the surface peat has been investigated in a few studies, virtually no work has been completed which characterizes the peat at depth. This study has shown some important macro- and micro-textural relationships of the peat that will help understand how the peat formed, developed, and is being anthropogenically modified.

The peat types in the Muara Siran area consists of fibric, hemic, and sapric, with decreasing levels of preservation in that order. Fibric peat constitutes the central–top part of the peat in the studied area; moderately-decomposed hemic commonly constitutes the central and marginal areas of the peatlands, and the decomposed sapric peat predominantly constitutes the margin and basal parts. Fibric is mostly composed of wood tissue and textinite. Hemic is composed of stem and wood with dominant macerals of textinite and humodetrinite. Sapric is mostly composed of matrix and humodetrinite. The average particle size is 0.1 - 1 mm.

Peat was formed by the terrestrialization process. The formation of Muara Siran peat deposit is highly related to Siran Lake. According to Ott's proposal (1960) about the formation of Kutai Lakes, it is likely that Siran Lake was formed in the same way as the other bigger Kutai Lakes, *e.g*: Melintang, Jempang, and Semayang. The growth of vegetation which eventually formed the peat deposits began at the back of river levee and Siran Lake body. The fire history of Kutai peatlands suggested that Siran peatland experienced substantial loss of peat up to 3.4 m, which allowed water from nearby river to enter (Hope *et al*., 2005). This makes possible for nutrients to enter the peatland, thus, support terrestrialization process.

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