Geochemical characteristics of a tropical lowland peat dome in the Kota Samarahan-Asajaya area, West Sarawak, Malaysia

Mohamad Tarmizi Mohamad Zulkifley · Tham Fatt Ng · Wan Hasiah Abdullah · John Kuna Raj · Mustaffa Kamal Shuib · Azman Abdul Ghani · Muhammad Aqeel Ashraf

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Abstract Augered tropical lowland peat samples (KS.TP.02 to 10) were characterized, classified (von post) and subjected to source rock analyses and biomarker gas chromatography mass spectrometry analyses. Lateral variations in the organic matter types within the top 0–0.5 m layer were found to occur from the margin to the mid-section to the center/near-center (i.e., thicker areas) of the studied peat dome. The organic matter types of these three regions correspond to kerogen types II, III, and II, respectively. The lateral vegetation succession, phasic community zonation and organic matter types (II and III kerogen) are most likely associated with tropical lowland peat domes. The Pr/n-C17 and Ph/n-C18 ratios for the peat samples from the same locations are low and indicate anoxic to suboxic and reducing depositional environmental conditions for the wet tropical lowland peats. The S/(S+R) ratios are relatively low, indicating the immaturity of the peats in terms of hydrocarbon production. The dominant biomarker hopane compounds have 13–39 carbon atoms, with dominant peaks exhibiting an odd over even carbon number predominance, indicating the terrestrial depositional environment of the peats. The Pr/Ph ratios most likely indicate anoxic (the marginal, relatively wet “moat area”) to suboxic (the mid-section and the basin center) depositional environmental conditions. The ββ hopanes biomarkers that indicate immaturity include ββ C30 hopane (17β, 21β (H)-Hopane) and ββ C31 hopane (17β, 21β (H)-Homohopane). Other common hopanes present are C29 hopane (Norhopane), 22Sβ C31 hopane (17α, 21β (H)-Homohopane) and 22Rβ C31 hopane (17α, 21β (H)-Homohopane).

Keywords Tropical lowland peats · SRA (source rock analyzer) · Organic matter · Coal precursor · Phasic community zonation · Hopanes

Introduction

To form peat, the rate of biomass (organic matter) production must be greater than that of chemical breakdown (Andriesse 1988). Peats are generally considered to be partially decomposed biomass (vegetation). Anaerobic, swampy conditions, which prevent the microbial activity needed to chemically break down organic materials, are generally assumed to be largely responsible for the accumulation of partly decomposed biomass/organic matter in the form of peat. Anaerobic conditions are created by the specific hydro-topography of a marsh, swamp, bog or mire. The properties of such hydro-topographic units depend on many environmental factors, including climate, landforms, local geology and hydrology (Andriesse 1988).

Peats are formed by limited decomposition and, hence, the accumulation of organic soil materials. These organic materials can consist of undecomposed, partially decomposed and highly decomposed plant remains. Tropical lowland peats usually contain undecomposed and partly decomposed branches, logs and/or twigs. These peats form a fragile ecosystem that is domed in shape and almost purely organic (Paramananthan 2011).
Origin and characteristics of peat deposits

The paludal deposits of Sarawak occur in large basin swamps and in small interior valleys that have mostly developed near coastal areas in relatively recent times (Murshedza et al. 2002). Radiocarbon (14C) dating from Baram in northern Sarawak indicates that the sea was at the inland margin of the peat swamp approximately 5,400 years ago (Wilford 1959; Murshedza et al. 2002). Peat basin swamps are often dome-shaped, with thick ombrogenous peat occupying the central portion of the peat dome (Anderson 1961, 1964, 1974, 1983; Anderson and Muller 1975; Cameron et al. 1989; Esterle and Ferm 1994; Murshedza et al. 2002; Paramananthan 2011). Ombrogenic peats (Paramananthan 2011) are composed mainly of broken tree trunks, branches, leaves, roots and fruits (Yogeswaran 1995; Bujang 2004; Anderson and Muller 1975) and are relatively mineral and ash free. However, the marginal peats surrounding the base, along the margins of the peat dome and along the lower banks of streams draining the peat swamps are dominated by topogenic peat (Paramananthan 2011), which consists mainly of slightly to moderately decomposed plant matter and fine clastic mineral sediments (moderate to high ash content).

Location and physiography

The study area (Fig. 1) covers an area of approximately 25 km² and is located between longitudes 01°26'30"N and 01°29'46"N and latitudes 110°27'44"E and 110°30'58"E. The area is mostly government owned under the Forestry Department of Sarawak (Malaysia).
The topography of the Kota Samarahan area is generally flat with isolated hills on the floodplains of the Batang Samarahan and Sungai Tuang Rivers. The elevation of the floodbasin is low and seldom higher than 5 m above mean sea level. The area is prone to high tide flooding with the exception of a few localities on natural levees along rivers, the central area of the peat dome/basin and man-made bunds.

Objective of the study

The objective of this article is to report and discuss the organic geochemical characteristics of tropical lowland peats occurring in the study area.

Local geology of the study area

Two sedimentary facies exposed in the study area are the peat (paludal) deposits and the floodplain deposits, which overlie estuarine/deltaic sediments.

Peat in the western (Plaie) peat forest of the study area

Peat in the Plaie area is composed of slightly to moderately decomposed plant material ranging from H3 to H8 on the von post degree of humification scale (Table 1). The peat that was encountered in this study can be classified as fibric, hemic, hemic to sapric and sapric peat. The thickness of the peat layers ranges from 0.2 to 2.0 m, thickening westward. The peat encountered has brown to dark brown to very dark brown colors, including the following colors: 10 YR 3/3 (dark brown), 10 YR 3/4 (dark yellowish brown), 10 YR 5/2 (grayish brown), 10 YR 5/1 (gray), 10 YR 4/1 (dark gray), 7.5 YR 3/2, 7.5 YR 3/3, 7.5 YR 3/4 (dark brown), and 7.5 YR 2.5/2-2.5/3 (very dark brown) according to the Munsell soil color chart. The groundwater levels in the western part of the Kota Samarahan (Plaie) peat area are approximately 0.3–0.5 m below ground surface (Figs. 2, 3, 4, 5, 6; Table 2).

Table 1 The von post classification system and von post degree of humification (H1 to H10) for peat (adapted from Andriesse 1988)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>Completely undecomposed peat, which, when squeezed, releases almost clear water. Plant remains easily identifiable. No amorphous material present</td>
</tr>
<tr>
<td>H2</td>
<td>Almost entirely undecomposed peat, which, when squeezed, releases clear or yellowish water. Plant remains still easily identifiable. No amorphous material present</td>
</tr>
<tr>
<td>H3</td>
<td>Very slightly decomposed peat, which, when squeezed, releases muddy brown water but from which no peat passes between the fingers. Plant remains still identifiable, and no amorphous material present</td>
</tr>
<tr>
<td>H4</td>
<td>Slightly decomposed peat, which, when squeezed, releases very muddy dark water. No peat is passed between the fingers, but the plant remains are slightly pasty and have lost some of their identifiable features</td>
</tr>
<tr>
<td>H5</td>
<td>Moderately decomposed peat, which, when squeezed, releases very “muddy” water with a very small amount of amorphous granular peat escaping between the fingers. The structure of the plant remains is quite indistinct, although it is still possible to recognize certain features. The residue is very pasty</td>
</tr>
<tr>
<td>H6</td>
<td>Moderately highly decomposed peat with a very indistinct plant structure. When squeezed, approximately one-third of the peat escapes between the fingers. The residue is very pasty but shows the plant structure more distinctly than before squeezing</td>
</tr>
<tr>
<td>H7</td>
<td>Highly decomposed peat. Contains abundant amorphous material with very faintly recognizable plant structure. When squeezed, approximately one-half of the peat escapes between the fingers. The water, if any is released, is very dark and almost pasty</td>
</tr>
<tr>
<td>H8</td>
<td>Very highly decomposed peat with a large quantity of amorphous material and very indistinct plant structure. When squeezed, approximately two-thirds of the peat escapes between the fingers. A small quantity of pasty water may be released. The plant material remaining in the hand consists of residues, such as roots and fibers, that resist decomposition</td>
</tr>
<tr>
<td>H9</td>
<td>Practically fully decomposed peat, in which there is hardly any recognizable plant structure. When squeezed, it forms a fairly uniform paste</td>
</tr>
<tr>
<td>H10</td>
<td>Completely decomposed peat with no discernible plant structure. When squeezed, all the wet peat escapes between the fingers</td>
</tr>
</tbody>
</table>

Floodplain deposits

In the western Plaie area and a portion of the Kg Sui area, floodplain deposits are observed to be overlain by peat deposits (Figs. 2, 6). The backswamp floodplain deposits, which are behind the levees, consist predominantly of clays and silts, with minor to abundant plant remains (Lam 1989). Typical auger log sections of the floodplain deposits are shown in Figs. 3, 4 and 5.

Estuarine/deltaic deposits

Estuarine/deltaic deposits underlie the floodplain and peat deposits. These underlying deposits are observed to be deposited at depths ranging from 1.0 to 2.0 m (at auger locations KS.TP.02, KS.TP.08 and KS.TP.09) and are believed to be marine (Lam 1989) in origin. These deposits are observed in the field to have little or no wooden fragments relative to the overlying floodplain deposits. They
are usually sulfidic (acidic) and are observed in the field to produce yellow-colored minerals known as jarosite (Fitzpatrick et al. 1998) when exposed to and oxidized by the atmosphere.

Peat characterization

The field characterizations of the peat at locations near the peat basin boundary or margin and toward the center of the peat dome are shown in Table 2. This study focuses on peat characterization and does not consider endangered or protected species in the area. This study may also contribute to classification methods and other relevant data concerning the characterization of tropical lowland peat.

Materials and methods

The classification of peat in the field was accomplished using the von post squeeze test and the results were provided the von post degree of humification, with values between H1 and H10 (Table 3). In the field, the cores were logged and described by visual and texture characteristics. The samples were described according to the Malaysian...

The source rock analyzer (SRA) is a nonisothermal open-system tool (compatible with Rock–Eval) used to measure parameters, such as S1 (volatile hydrocarbon content), S2 (remaining hydrocarbon generative potential), S3 (carbon dioxide content), TOC (total organic carbon) and T_max values (Table 4). The SRA (TPH/TOC mode) was used to measure the parameters of peat samples collected from the margin of the peat dome to the center of the peat dome at locations KS.TP.02, KS.TP.07, KS.TP.08, KS.TP.09, and KS.TP.10 (Figs. 2, 6) and from a depth of 0–0.5 m. The samples were oven dried at 40 °C for 3 days before they were crushed into a fine powder and analyzed using the SRA.

Organic matter extraction was performed on the powdered samples using a Soxhlet apparatus with an azeotropic mixture of dichloromethane (DCM) and methanol (CH₃OH) (93:7) for 72 h. Via the column liquid chromatography method, the extracted organic matter was then separated by into aliphatic, aromatic and polar fractions using petroleum ether, dichloromethane and methanol, respectively. Subsequently, the aliphatic hydrocarbon fractions were analyzed by gas chromatography (Agilent 6890 N series GC) and gas chromatography mass spectrometry (GCMS). A flame ionization detector gas chromatograph (GC-FID) with an HP-5MS column and a programmable temperature range of 40–300 °C with a rate of change of 4 °C/min was used for GC analysis. The samples were held for 30 min at a temperature of 300 °C. The GCMS analysis was performed on a V 5975B inert MSD mass spectrometer with a gas chromatograph attached directly to the ion source (70 eV ionization voltage, 100 mA filament emission current, 230 °C interface temperature). The results acquired from the GC and GCMS analyses were used for biomarker identification of the peat samples based on the retention time and a comparison with previously published data (Philp 1985) according to their locations in the studied peat dome.

The aliphatic fractions of three extracted representative peat samples (Figs. 2, 3, 4, 5, 6) from the basin periphery,
the mid-section and the basin center/near-center (or deeper part of the basin) were subjected to GCMS analyses. The total ion current (TIC), m/z 85 and m/z 191 fragment ions were used for this study and are displayed in Figs. 6, 7, 8, 9, 10 and 11. The peaks of these fragmentograms have been identified on the basis of retention times and the available literature (Farhaduzzaman et al. 2012; Hakimi et al. 2010; Wan Hasiah 1999; Waples and Machihara 1991; Philp 1985).

Petrographic maceral studies (Mohamad Tarmizi et al. 2013) of the peat samples were conducted to identify the diagenetic stages involved in the peatification or humification process and were based on peat diagenetic studies (Stout and Spackman 1987; Jaafar 1998).

**Results**

**SRA analysis results**

The SRA results of the sampled peat and organic soils are shown in Table 4. As expected, all SRA $T_{max}$ values obtained from the analyzed quaternary peat deposits indicate immaturity and all values are below 430 °C (Table 4), with a range of 387–413 °C. The marginal peats at KS.TP.02 show the highest $T_{max}$ of 413 °C, and KS.TP.09 has the lowest $T_{max}$ of 387 °C (Table 4).

The hydrogen index (HI; mg HC per g TOC) is the normalized hydrogen content of a rock sample. The type of kerogen is derived from this value, i.e., type I kerogens are hydrogen rich, type III kerogens are hydrogen poor, and type II kerogens are intermediate between types I and III (Table 4). The HI values decrease with sample maturity. The hydrogen index may be lowered by weathering or mineral matrix interactions, which cause a reduction in the S2 value (Espitalie et al. 1977).

Marginal peat at KS.TP.02 has a HI value of 337 HC/g TOC (type II; oil prone). The HI value is observed to increase from the margin of the peat basin toward the center. The HI value increases from 207 HC/g TOC (type III; gas/oil prone) at KS.TP.07 to 407 HC/g TOC (type II; oil prone) at KS.TP.10. There is a lateral variation of organic matter types from type II (oil prone) at the margin to type III (gas/oil prone) in the mid-section area and back again to type II (oil prone) near the basin center (Table 4). In general, there is a mixture of organic...
matter of kerogen types II and III occurring horizontally across the tropical lowland peat basin within the 0–0.5 m depth interval.

GCMS analysis results

Figure 7 shows the TIC gas chromatogram of the alkane fraction from sample KS.TP.02 (0–0.5 m), and Fig. 8 shows the m/z 85 fragmentogram obtained from the same sample. Figures 9, 10 and 11 show the biomarker hopane distribution for samples KS.TP.02 (0–0.5 m), KS.TP.08 (or KS.TP.08BB; 0–0.5 m) and KS.TP.09 (0–0.5 m), respectively. The geochemical ratios are provided in Table 5.

Discussion

From the field identifications, von post classifications and SRA analyses of the five augered peat samples (KS.TP.02 to KS.TP.10), the main observations and findings are as follows.

1. The field identifications and classifications (von post) of the tropical lowland peat show that there is lateral variation in the peat humification levels. The peat shifts progressively through fibric, fibric to hemic, sapric and hemic to sapric peats from the margin toward the center or near-center areas of the tropical lowland peat dome or basin.

2. The results of the SRA analyses show that there is lateral variation in the organic matter type of the upper 0–0.5 m layer from the margin toward the center or deeper part of the tropical lowland peat dome. The organic matter types within the peat dome shift from predominantly types II to III and back to type II kerogen, corresponding to the margin, the mid-section and the center or near-center (the deeper part of the dome), respectively.

3. Any associations between the variations in the organic matter type of the tropical lowland peats and the varying distances from the periphery to the center or near-center of the peat dome (within the scope of this study) are most likely caused by a combination of factors, which include the following.
(a) Horizontal vegetation zonation and lateral variations in the dominant species of the plant assemblages vary with distance from the periphery to the center/near-center (deeper part) of the tropical lowland peat dome. Woody material (tree logs, broken branches, bark and roots) contributed by the dominant species (e.g., *Shorea* sp.) likely produces peat with organic matter predominantly in the form of type III kerogen. Waxy leafy material contributed by dominant species of shrubs and ferns may produce peat dominated by organic matter in the form of type II kerogen.

(b) Lateral variations in the peat humification levels (von post humification levels of H1 to H10) and their related dominant diagenesis peatification stages (Phase I, II, III, IV, V and post-phase V) occur from the periphery toward the center/near-center/deeper part of the tropical lowland peat dome in the study area. In this study, fibric peats (found in the marginal area of the dome, which features lower levels of decomposition) and hemic to sapric peats (near the central area of the dome, which features relatively higher humification levels)
may also be associated with organic matter in the form of type II kerogen.

4. The observations in this study may support the concept of lateral vegetation variation and horizontal vegetation zonation (Anderson 1961, 1963, 1983; Paramananthan 2011). The inferred vegetation successions [or Phasic Communities (PC)] that were observed in the field and supported by pollen analyses (article in prep.) in the studied tropical lowland peat dome include PC I (Mixed Peat Swamp Forest) and PC II (Alan Swamp Forest).

5. In general, there is a mixture or a combination of organic matter/kerogen types II and III within the tropical lowland peat basin surface, and the lateral variations in organic matter type may support the lateral vegetation variation concept (Anderson 1961, 1963, 1983; Paramananthan 2011). Hence, the lateral vegetation succession, phasic community zonation and organic matter types (kerogen types II and III) are most likely related in tropical lowland peat domes or basins. This study indicates that the organic matter types (based on SRA-HI data) of the basin periphery, the mid-section and the basin center/near-center areas are organic matter/kerogen types II, III and II, respectively.

The hydrocarbon generation potential of coals has been widely discussed in the literature (Khorasani 1987; Thompson et al. 1985; Wan Hasiah and Abolins 1998; Wan Hasiah 1999; Farhaduzzaman et al. 2012). Conventional coal petrographic studies are usually carried out to evaluate the evolutionary history of the analyzed coals, wherein the macerals, microlithotypes and lithotypes provide evidence on the nature and type of plant community, duration and intensity of decomposition in the peatification process and the related depositional setting. The interpreted coal evolutionary history provides the basis for further interpretation of the related paleogeography and paleoclimate of the peat-coal precursor basins (Teichmuller 1989; Stach et al. 1982; Farhaduzzaman et al. 2012). Hence, this study attempts to study the relationships or associations between the present tropical lowland peat depositional environment and the maceral types, kerogen types (from SRA data) and biomarker distributions based on organic petrology (Mohamad Tarmizi et al. 2013) and organic geochemistry methods.

### Table 2

<table>
<thead>
<tr>
<th>Auger hole/sample no.</th>
<th>KS.TP.02</th>
<th>KS.TP.07</th>
<th>KS.TP.08</th>
<th>KS.TP.09</th>
<th>KS.TP.10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of peat (m)</td>
<td>0.2</td>
<td>0.2</td>
<td>1.0</td>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Classification of peat type with depth (von post classification)</td>
<td>0–0.2 m: H3</td>
<td>0–0.2 m: H3–H4</td>
<td>0–0.5 m: H7–H8</td>
<td>0–0.5 m: H7–H8 0.5–1.0 m: H6–H7</td>
<td>0–0.5 m: H6–H7 0.5–1.0 m: H5–H6</td>
</tr>
<tr>
<td>Classification/type of peat with depth</td>
<td>0–0.2 m: fibric</td>
<td>0–0.2 m: fibric to hemic</td>
<td>0–0.5 m: sapric (amorphous)</td>
<td>0–0.5 m: sapric (amorphous) 0.5–1.0 m: hemic to sapric (amorphous)</td>
<td>0–0.5 m: hemic to sapric 0.5–1.0 m: hemic 1.0–1.5 m: fibric to hemic</td>
</tr>
<tr>
<td>Peat type (Paramananthan 2011)</td>
<td>Topogenous peat</td>
<td>Topogenous peat</td>
<td>Topogenous peat</td>
<td>Topogenous peat</td>
<td>Ombrogenous peat</td>
</tr>
<tr>
<td>Groundwater level (distance from surface in meters)</td>
<td>0.3 m (below surface)</td>
<td>0.3 m (below surface)</td>
<td>0.3 m (below surface)</td>
<td>0.3 m (below surface)</td>
<td>0.5 m (below surface)</td>
</tr>
<tr>
<td>Color of peat (Munsell color code)</td>
<td>0–0.2 m: 10 YR 3/3</td>
<td>0–0.2 m: 7.5 YR 3/4</td>
<td>0–0.5 m: 7.5 YR 2.5/2</td>
<td>0–0.5 m: 7.5 YR 3/3</td>
<td>0–0.5 m: 7.5 YR 2.5/2</td>
</tr>
<tr>
<td>Elevation (Garmin GPS) a.m.s.l.</td>
<td>7.9</td>
<td>6</td>
<td>7</td>
<td>9.2</td>
<td>9.2</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>HI</th>
<th>Kerogen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;150</td>
<td>Type IV (gas prone)</td>
</tr>
<tr>
<td>150–300</td>
<td>Type III (gas/oil prone)</td>
</tr>
<tr>
<td>300–600</td>
<td>Type II (oil prone)</td>
</tr>
<tr>
<td>&gt;600</td>
<td>Type I (oil prone)</td>
</tr>
</tbody>
</table>
From the petrographic (Mohamad Tarmizi et al. 2013) and SRA analyses, there appears to be an association between the peat samples’ kerogen types and related maceral types (at different levels of decomposition and diagenesis) and the distance from the periphery toward the center of the peat basin. This observation further relates to or supports the concept of horizontal vegetation variation, as proposed by Anderson (1961, 1964, 1983) and Anderson and Muller (1975). The concept of horizontal variation and zonation may explain the reason why This study also explains which dominant plant type or assemblage of tree, shrub or plant species contribute either relatively more waxy leafy shrub material or relatively more woody material to the peat along a horizontal, near-surface layer from the peat basin margins to the center of the tropical lowland peat dome (Tables 6, 7).

Horizontal or lateral zonation in tropical lowland peat domes

Anderson (1961, 1964, 1983) and Anderson and Muller (1975) studied the domed topography of tropical peat deposits and the relationship among the concentric zonation of the surface vegetation, the increasing peat thickness and acidity and the decreasing nutrient availability and the horizontal distance between the margin and the center of peat basins. The variations that occur in the peat type within the deposits reflect the succession and lateral migration of the surface vegetation and the related environment associated with coastal progradation (Anderson and Muller 1975). Buwalda (1940), in Paramananthan (2011) reported six different vegetation types and zones occurring in the Indragiri area in Sumatra. Anderson (1961, 1963, 1964) also described six vegetation zones occurring in the lowland peat forests of Borneo, including Brunei.

Anderson (1961, 1963, 1983) conducted a comprehensive study of the ecology of the Tropical Lowland Peat Swamp Forests of Borneo. The Tropical Lowland Peat Swamp Forests in Sarawak, Malaysia, and adjacent Brunei exhibit lateral or horizontal changes in vegetation types from their peripheries to the centers of the domed-shaped peat swamps, and each of the six dominant lateral vegetation zones was designated a “Phasic Community” by Anderson (1961). Six distinct PC or

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**Table 4** Source rock analysis (SRA) parameter data of the peats and organic soils sampled in a tropical lowland peat forest in the Kota Samarahan-Asajaya area of western Sarawak in relation to organic matter/kerogen type (Espitalie et al. 1977)

<table>
<thead>
<tr>
<th>Sample code</th>
<th>TOC</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>T_{\text{max}}</th>
<th>HI</th>
<th>OI</th>
<th>S2/S3</th>
<th>Organic matter/kerogen type (Espitalie et al. 1977)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KS.TP.02 (0–0.2 m)</td>
<td>15.43</td>
<td>11.83</td>
<td>52.05</td>
<td>6.89</td>
<td>413</td>
<td>337 (type II)</td>
<td>45</td>
<td>7.55</td>
<td>Type II (oil prone)</td>
</tr>
<tr>
<td>KS.TP.07 (0–0.2 m)</td>
<td>32.69</td>
<td>13.07</td>
<td>67.70</td>
<td>11.43</td>
<td>393</td>
<td>207 (type III)</td>
<td>35</td>
<td>5.92</td>
<td>Type III (gas/oil prone)</td>
</tr>
<tr>
<td>KS.TP.08 (0–0.5 m)</td>
<td>50.80</td>
<td>24.96</td>
<td>134.95</td>
<td>13.43</td>
<td>391</td>
<td>266 (type III)</td>
<td>26</td>
<td>10.05</td>
<td>Type III (gas/oil prone)</td>
</tr>
<tr>
<td>KS.TP.09 (0–0.5 m)</td>
<td>48.61</td>
<td>31.46</td>
<td>156.45</td>
<td>12.63</td>
<td>387</td>
<td>322 (type II)</td>
<td>26</td>
<td>12.39</td>
<td>Type II (oil prone)</td>
</tr>
<tr>
<td>KS.TP.10 (0–0.5 m)</td>
<td>49.62</td>
<td>26.10</td>
<td>202.08</td>
<td>13.43</td>
<td>397</td>
<td>407 (type II)</td>
<td>27</td>
<td>15.05</td>
<td>Type II (oil prone)</td>
</tr>
</tbody>
</table>

TOC total organic carbon, wt. %, S1 volatile hydrocarbon (HC) content, mg HC/g rock/source material, S2 remaining HC generative potential, mg HC/g rock/source material, S3 carbon dioxide content, mg CO$_2$/g rock, PI production index = S1/($S1 + S2$), $T_{\text{max}}$ temperature ($^\circ$C) at which the maximum release of hydrocarbons occurs from cracking, HI hydrogen index = $S2 \times 100/\text{TOC}$, mg HC/g TOC, OI oxygen index = $S3 \times 100/\text{TOC}$, mg CO$_2$/g
zones were recognized based on their floristic composition and vegetation structure (Anderson 1961; Paramananthan 2011). These communities were numbered phasic community I at the margin to phasic community VI in the center of the peat swamp (Table 6). Tie (1990) and Paramananthan (2011) later summarized the main changes that characterize these concentric, horizontal or lateral zonations.

Association between dominantly leafy or woody plant input and organic matter/kerogen type

The horizontal zonation and lateral variation of dominant species of plant assemblages (Anderson 1961, 1963, 1983; Esterle and Ferm 1994; Paramananthan 2011) associated with varying distances from the periphery to the center of
**Fig. 10** m/z 191 mass fragmentogram of peat from a lowland tropical peat swamp at auger sample location KS.TP.08 (0–0.5 m)

**Fig. 11** m/z 191 mass fragmentogram of peat from a tropical lowland peat swamp at auger sample location KS.TP.09 (0–0.5 m)
the tropical lowland peat dome are supported by field and petrographic observations and SRA analyses, which indicate that woody material (tree logs, broken branches, bark and roots) contributed by relatively dominant tree species (e.g., *Shorea* type) likely produce peat with predominantly type III kerogen or organic matter (Table 7). However, the waxy leafy material generated by relatively dominant species of shrubs and ferns predominantly produces peat composed of type II kerogen organic matter (Table 7).

### Table 5 Geochemical (GCMS) ratios and characteristics of 3 aliphatic fractions of peat sampled from the basin periphery, the mid-section and near the center of the tropical lowland peat basin (Plaie peat forest) in the Kota Samarahan-Asajaya area

<table>
<thead>
<tr>
<th>Sample no/approximate location on dome</th>
<th>n-alkane range</th>
<th>Odd over even predominance (OEP)</th>
<th>Maximum peak</th>
<th>Pr/Phy (&lt; or &gt;1)/ anoxic to suboxic</th>
<th>Pr/n-C17</th>
<th>Ph/n-C18</th>
<th>S/(S + R)</th>
<th>Organic matter type/kerogen (based on SRA-HI data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KS.TP.02 (0–0.5 m)/margin</td>
<td>n-C_{13} to n-C_{33} OEP</td>
<td>n-C_{29}</td>
<td>0.97 (&lt;1)/anoxic</td>
<td>0.31</td>
<td>0.27</td>
<td>0.18</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>KS.TP.08BB (0–0.5 m)/mid-section</td>
<td>n-C_{15} to n-C_{39} OEP</td>
<td>n-C_{31}</td>
<td>1 (&gt;1)/suboxic</td>
<td>0.36</td>
<td>0.18</td>
<td>0.12</td>
<td>III</td>
<td></td>
</tr>
<tr>
<td>KS.TP.09 (0–0.5 m)/near the dome center (relatively higher elevation and lower groundwater table)</td>
<td>n-C_{13} to n-C_{33} OEP</td>
<td>n-C_{27}</td>
<td>1 (&gt;1)/suboxic</td>
<td>0.21</td>
<td>0.18</td>
<td>0.12</td>
<td>II</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6 The main characteristics of the six phasic communities that occur as horizontal or lateral zones (based on Anderson 1961, 1963, 1983; Paramananthan 2011)

<table>
<thead>
<tr>
<th>PC (phasic community)</th>
<th>Forest type</th>
<th>Main tree species association</th>
<th>Other relevant features of tree and ground flora</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Mixed peat swamp forest</td>
<td><em>Gonystylus</em>-*Dactylocladus-*Neoscortechinia association</td>
<td>Structure and physiognomy similar to mixed dipterocarp forest on mineral soils; many species with pneumatophores, stilt roots and buttresses</td>
</tr>
<tr>
<td>II</td>
<td>Alan swamp forest</td>
<td><em>Shorea albida</em>-*Gonystylus-*Stemonurus association</td>
<td>Similar to PC1 but with very large, scattered <em>Shorea albida</em> trees; large trees are usually hollow with stag-headed crowns; <em>Pandanus andersonii</em> and <em>Nepenthes bicalcarata</em> frequent</td>
</tr>
<tr>
<td>III</td>
<td>Alan bunga forest</td>
<td><em>Shorea albida</em> association</td>
<td>Middle story sparse; lower story moderately dense; cauliflower-like crowns of <em>S. albida</em> distinctive on air photo</td>
</tr>
<tr>
<td>IV</td>
<td>Padang alan forest</td>
<td>*Shorea albida-*Litsea-*Parastemon association</td>
<td>Very slender stems with a pole-like appearance; dense understory 3–6 m high; <em>Nepenthes spp.</em> quite frequent</td>
</tr>
<tr>
<td>V</td>
<td>Padang Paya Forest</td>
<td><em>Tristania</em>-*Parastemon-*Palaquium association</td>
<td>Understory sparse; herbaceous plants largely absent; some pitcher plants</td>
</tr>
<tr>
<td>VI</td>
<td>Padang keruntum forest</td>
<td><em>Combretocarpus</em>-<em>Dactylocladus</em> association</td>
<td>Stunted, xeromorphic, with pneumatophores; <em>Myrmecophytes</em> spp. and <em>Nepenthes spp.</em> numerous; sedge and sphagnum moss occurs</td>
</tr>
</tbody>
</table>

Association between peat decomposition levels and organic matter type

In addition to the type of plant input (i.e., relatively more leafy or relatively more woody material in the decomposing peat), which may have an influence on the organic matter types in the peats, the decomposition or humification level of the peats may also be associated with the organic matter type. It was observed that the dominant maceral type (red textinite, gray textinite, texto-ulminite, eu-ulminite, humocollinite or humodetrinite) and the corresponding dominant diagenesis stage (Phase I, II, III, IV, V or post-phase V, respectively) may be associated with organic matter of types II or III in this study. Sample KS.TP.02, with lower levels of decomposition (fibric), has relatively higher HI values and type II organic matter (based on SRA interpretation). Sample KS.TP.10 (hemic to sapric), although highly decomposed, still has some structure or plant tissue (hence, the “hemic” level included in the humification range) and features relatively higher leafy, spores and pollen contributions (from the predominantly leafy plants of the proposed phasic communities II, III and IV (Alan Swamp Forest, Mixed Alan Bunga Forest and Padang Alan Forest zone, respectively). Therefore, this peat has relatively higher HI values and is composed of mainly type II organic matter.
Discussion of the GCMS analyses of sample KS.TP.02 (0–0.5 m) (near basin margin)

Figure 7 shows the TIC gas chromatogram of the alkane fraction from sample KS.TP.02 (0–0.5 m), located near the peat basin margin. Figure 8 shows the m/z 85 fragmentogram obtained from the same sample. The alkane fractions from the sample are predominately composed of long-chain \( n \)-alkanes greater than \( n \)-C\textsubscript{13}, up to \( n \)-C\textsubscript{33}. Within the range of \( n \)-C\textsubscript{13} to \( n \)-C\textsubscript{33}, the most dominant peak is \( n \)-C\textsubscript{29}. Within the terrestrial plant envelope, which ranges from \( n \)-C\textsubscript{23} to \( n \)-C\textsubscript{33} in the fragmentogram (m/z 85), the odd-numbered \( n \)-alkanes are strongly dominant, and this pattern is indicative of the true terrestrial depositional environment of the peats.

The \( n \)-alkanes from \( n \)-C\textsubscript{13} to \( n \)-C\textsubscript{22} lie mainly within the bacteria and fungi envelope of the m/z 85 fragmentogram. From the m/z 85 gas chromatogram of the alkane fraction, the pristane/phytane ratio is 0.97. Because the ratio is less than 1, it is indicative of an anoxic/reducing depositional environment, which signifies wet tropical lowland peats with relatively high groundwater tables.

Discussion of the GCMS analyses of sample KS.TP.08 (0–0.5 m; near the mid-section area)

The \( n \)-alkanes from \( n \)-C\textsubscript{15} to \( n \)-C\textsubscript{22} lie mainly within the bacteria and fungi envelope of the m/z 85 fragmentogram. From the m/z 85 gas chromatogram of the alkane fraction...
from sample KS.TP.08 (or KS.TP.08BB) (0–0.5 m), the pristane/phytane ratio (1) for the peats lies in the range of 1–3, which is indicative of a relatively more suboxic environment of deposition, less aquatic/subaqueous conditions and relatively deeper, fluctuating groundwater levels. Again, this may be due to the relatively higher elevations of the mid-section area and the dome center (compared with the Pr/Ph ratio (<1) of marginal peats, e.g., sample KS.TP.02]. The Pr/nC17 ratio is 0.36, whereas the Ph/nC18 ratio is 0.18 (indicative of reducing environmental conditions). Thus, these ratios support the present suboxic and reducing depositional environmental conditions during the deposition of peat sample KS.TP.08.

Discussion of the GCMS analyses of sample KS.TP.09 (0–0.5 m; near the basin center)

From the m/z 85 gas chromatogram of the alkane fraction from sample KS.TP.09 (0–0.5 m), the pristane/phytane ratio is 1, which is within the 1–3 range that is indicative of a suboxic depositional environment. Near the peat basin center, the pristane/phytane ratio is in the range of 1–3. This value is indicative of a relatively more suboxic depositional environment, relatively less aquatic/subaqueous conditions, and relatively deeper, fluctuating groundwater tables. These conditions are most likely due to the increasing elevations from the mid-section area toward the dome center/near-center area [compared with the Pr/Ph ratio (<1) for marginal peats, e.g., sample KS.TP.02]. The Pr/nC17 ratio is 0.21, and the Ph/nC18 ratio is 0.18, indicative of reducing environmental conditions. Thus, these ratios still support the presence of a suboxic reducing depositional environment during the deposition of the tropical lowland peat sample KS.TP.09.

Conclusions

The Source Rock Analysis results (compatible with Rock-Eval) show that there is a lateral variation of organic matter types, ranging from types II to III (kerogen). This pattern is most likely caused by a combination of factors, including the horizontal zonation and lateral variation in the dominant species of the plant assemblages based on the varying distance from the periphery to the center of the tropical lowland peat dome. Generally, organic matter of types II and III (kerogen) is present and the lateral variations in the organic matter types may support the lateral vegetation variation and horizontal zonation concept.

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