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Holocene peat accumulation in a tropical intermontane mire system, Tasik Bera, West Malaysia: implication for coal formation

RAPHAEL A.J. WÜST[1], R. MARC BUSTIN[1], LEE CHAI PENG[2] AND WAN HASIAH ABDULLAH[2]

[1]Department of Earth and Ocean Sciences,
The University of British Columbia
6339 Stores Road, Vancouver, B.C.
Canada, V6T 1Z4

[2]Jabatan Geologi, Universiti Malaya
50603 Kuala Lumpur
Malaysia

Abstract: Modern wetland environments represent the first step in production of peat deposits and are therefore precursors to coal seams. The characteristics of intermontane rheotrophic peat deposits are poorly constrained as modern analogues for coals but are critically important for understanding many deposits. Extensive organic rich sediments have developed in a closed drainage system in Tasik Bera, Pahang, West Malaysia. This thick, low- to high-ash, low-sulfur, low-nitrogen peat has accumulated in a dendritic drainage basin since the Mid-Holocene (for at least 4,500 years) and provides an excellent analogue for many Tertiary coals. Three distinctive ecological environments occur in Tasik Bera that give rise to spatial variations in peat composition: a) limnetic environment, dominated by algae and aquatic macrophyt (*Utricularia flexuosa*) deposits; b) littoral environment, dominated by sedges (*Lepironia articulata*) and woody shrubs (*Pandanus heliocopus*); and c) forest swamp dominated by trees and woody shrubs (*Eugenia spp., Thoracostyachyum baucanum, Pandanus sp.*). Detailed peat-depth transects and cores in the northern part of Tasik Bera model the vertical and lateral distribution of peat. Peat character is influenced by vegetation, topography, channel geometry and mineral matter input. Kaolinite and minor other clays with occasional laminae of fine silt (quartz rich) underlay organic rich deposits. Close to the northern outflow of the basin, adjacent the rivers Sungai Jelai and Sungai Bera, sand and silt form the base of the peat.

The Tasik Bera lake system was formed by damming by fluvial sediments of Sungai Bera, which restricted drainage and led to a high water table and to paludification (initial geogenic accumulation of organic matter) in the basin. Subsequently, due to low rates of decomposition and net peat accumulation, the basin progressively underwent terrestrialization. Arborescent organic rich deposits are widespread throughout the basin. The onset of the mire system in the Tasik Bera basin was dominated by swamp forest. South of Pos Iskandar, extensive forest swamp in three former tributaries, show highly humified (high C/N-ratio), woody, hemic to sapric peat up to 480 cm thick with intercalations of fine sand, silt and clay deposits towards the base. Open water and littoral vegetation yield fibric, hemic and sapric peat with an average thickness of 250 cm, dominate the northern part of Tasik Bera, up to the outflow into Sungai Bera. It is suggested that the upward vertical succession of decreasing woodiness and increasing lightness in color observed are comparable to features in Tertiary brown coals, i.e. color, texture, plant part composition.

The tropical freshwater peat deposits at Tasik Bera would yield a low sulfur, low to high ash thin banded stony coal seam of about 30 to 50 cm thick within a lateral extent of 250 to 350 km^2.

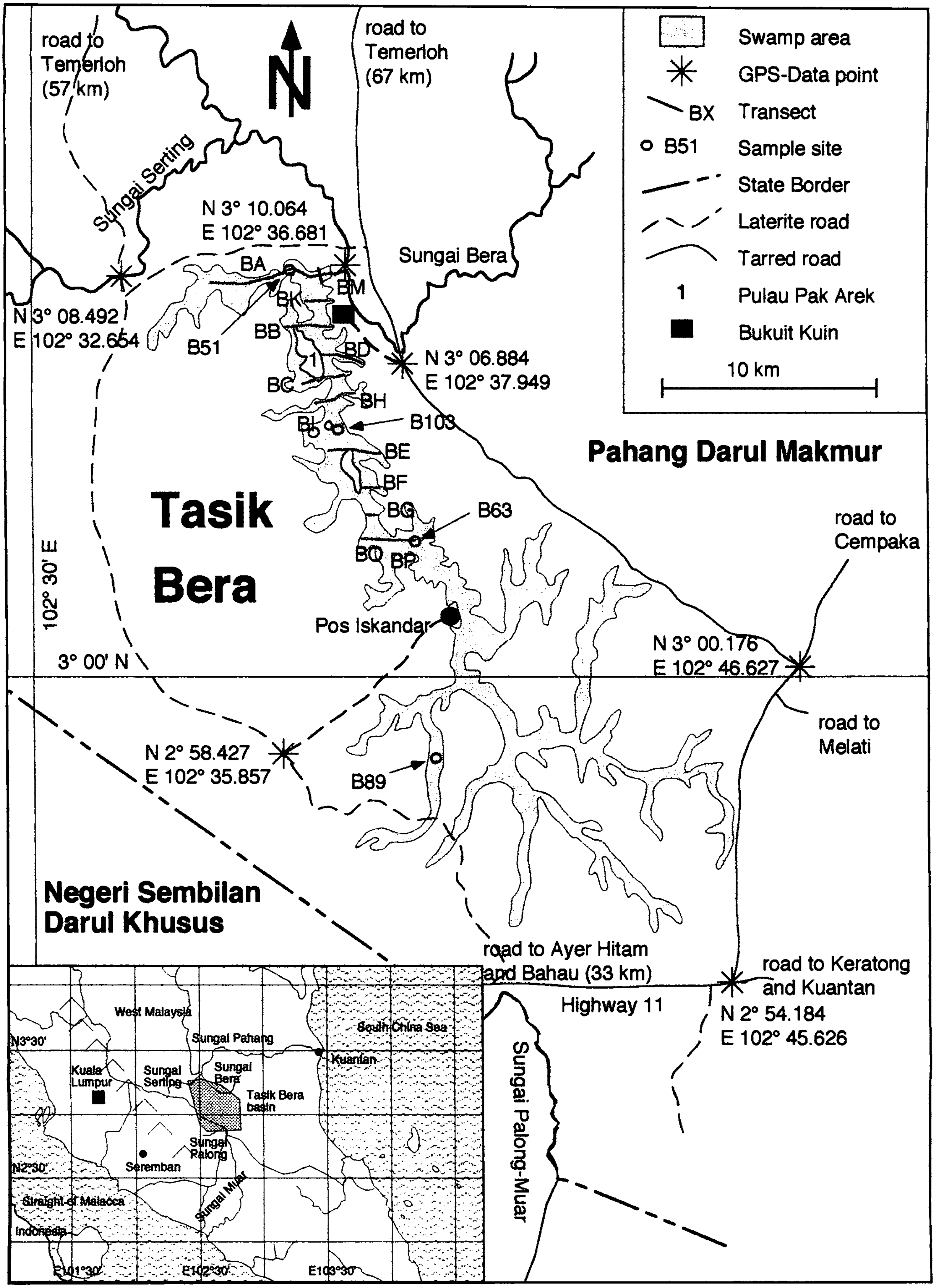

Figure 1. Location of the Tasik Bera study area showing the swamp extend, traverses and sample locations.

Table 1. Precipitation measurements (in mm) between 1992-1996 around the Tasik Bera area, from Felda Bera and Triang.

Felda Plantrakins: BERA						Felda Plantrakins: TRIANG					
Month \ Year	1992	1993	1994	1995	1996	Month \ Year	1992	1993	1994	1995	1996
Jan	71.1	163.3	50.0	440.4	86.0	Jan	69.0	103.3	104.8	258.8	171.3
Feb	11.3	20.0	136.0	205.4	174.4	Feb	175.7	102.9	117.6	34.6	65.8
Mar	21.3	191.0	222.7	88.9	39.0	Mar	67.8	220.7	143.5	99.1	123.0
Apr	12.7	198.6	234.4	172.4	536.0	Apr	51.0	172.8	211.8	146.3	185.7
May	154.6	91.6	196.6	119.6	154.0	May	165.1	124.9	156.6	141.1	162.9
Jun	6.8	71.8	67.8	165.6	188.6	Jun	98.3	102.9	122.1	248.7	306.3
Jul	24.3	96.0	46.4	3.5	136.1	Jul	156.9	99.3	10.9	50.8	84.5
Aug	43.1	263.9	237.2	165.3	130.5	Aug	109.7	133.1	204.8	87.2	224.4
Sept	187.4	125.2	91.1	66.2	110.1	Sept	207.6	214.1	34.6	118.1	126.5
Oct	229.1	182.6	275.5	282.7	260.7	Oct	247.6	390.9	221.6	311.2	311.2
Nov	298.4	242.0	425.7	247.3	168.1	Nov	268.5	351.6	267.1	407.0	187.9
Dec	272.5	269.7	486.1	472.9	140.9	Dec	157.9	332.4	93.2	233.5	339.6
Total	**1,332.6**	**1,915.7**	**2,469.5**	**2,430.2**	**2,124.4**	**Total**	**1,775.1**	**2,348.9**	**1,688.6**	**2,136.4**	**2,289.1**

INTRODUCTION

Understanding accumulation, spatial distribution and composition of modern peat deposits constrain models of ancient peat forming environments of similar settings, thereby providing insight as to the controls on coal distribution and characteristics. Peat composition (type of organic matter, mineral matter, nitrogen and sulfur content), degradation as well as spatial distribution control coal quality and geometry and therefore economic value.

Coastal rheotrophic and ombrotrophic peat deposits have been extensively studied in the past and recognized as analogues for coal deposits (Cameron *et al.*, 1989; Neuzil *et al.*, 1993; Staub and Esterle, 1994; Esterle and Ferm, 1994; Moore *et al.*, 1996; Phillips and Bustin, 1996). Carboniferous, Cretaceous and Tertiary coal deposits are mainly thought to be derived from woody plants. Therefore, coal analogue studies have focused on arborescent peat deposits of the tropics.

Although intermontane, limnic coal deposits have been described in the literature (Hacquebart and Donaldson, 1969; Mackowsky, 1976; Kim, 1979; Ethridge and Flores, 1981; Yagmurlu, 1986; Moore and Shearer, 1993; Calder, 1994), potential modern analogues have received little study. Studies to date have not gone beyond siting the association between high ash and low sulfur content and the correlation of clastic and organic sedimentation in these fluvial settings.

Tasik Bera represents the largest natural freshwater lake and swamp system in Malaysia and therefore has been chosen as an ideal site to investigate the accumulation of limnic peats. The area is located in the southern part of peninsula Malaysia at about 3°N and 102°30'E, in the southeastern corner of the state Pahang and the northwestern state Negeri Sembilan in the central part of West Malaysia (Fig. 1). The objective of this study is to examine the internal and external characteristics of the Tasik Bera basin and its deposits, in order to constrain a depositional model of intermontane peat and thus coal-forming environments. A comparison of spatial distribution of the organic matter and peat composition within the swamp system should provide insight as to peat distribution in modern basins.

PREVIOUS STUDIES IN THE TASIK BERA AREA

In 1961, the first scientific investigation in Tasik Bera was undertaken by botanists from the University of Malaya and the Singapore Botanic Garden and resulted in a report on the fauna and flora of the Tasik Bera swamp area (Merton, 1962).

In 1968, a Japanese-Malaysian joint research group started a four-year ecological study of Tasik Bera studying organic material production, vegetation and fish ecology (Furtado and Mori, 1982). Morley (1982), who analyzed the palynology of two cores, conducted a study of sedimentation and vegetation changes. Two radiocarbon dates, obtained from one core at depths of 8.60 m and 3.90 m, showed that the peat accumulation rate over the last 4,500 years was not constant.

In November 1994, Malaysia became a contracting party to the Convention on Wetlands of International Importance, especially as a waterfowl habitat (Ramsar Convention). The Asian Wetland Bureau (AWB) initiated an integrated management project at Tasik Bera. Forest conversion to rubber and palm oil production as well as logging around the site decreased in size the original area of jungle forest and swamp forest. The goal of the AWB project is "to conserve and enhance the biodiversity of Tasik Bera Ramsar Site and its buffer zone, and ensure the wise use of its wetland resources" (Benstead *et al.*, 1993).

In 1995, Phillips and Bustin did a preliminary investigation into the peat deposits and the geological evolution of the northern area of Tasik Bera (Phillips and Bustin, 1998).

CLIMATE

The climate is humid tropical to monsoonal with a mean average temperature of 29.5°C. Annual rainfall averages 1,300–2,500 mm (lowest precipitation value is from 1992, Table 1) with two monsoon seasons (April–May and September–January). The peat deposits are normally submerged by water or are at least water saturated. Water level fluctuation throughout the year and consequently drop in water level below the soil surface in the swamp forest system due to seasonality is common. During the El-Niño event in 1997, water level dropped up to 50 cm below normal "dry" conditions resulting in drying out the top 50 cm of the peat deposit through much of the study area. Emergence of both southern swamp forest (with *Eugenia spp* and *Tristania spp.*) and northern littoral area (with *Lepironia articulata* and *Pandanus heliocopus*), where water level is usually higher, occurred. Such conditions favor and promote decomposition and degradation of the organic matter.

GEOMORPHOLOGIC AND GEOLOGIC SETTINGS

Tasik Bera is located in the geologically defined Central Belt of Peninsular Malaysia, which is characterized by marine sediments of Lower Carboniferous to Triassic age that are overlain unconformable by Jurassic-Cretaceous continental deposits and Quaternary alluvium. The foothills of a low mountain range composed of Permian conglomerate with volcanic clasts, sandstone and carbonaceous shale border Tasik Bera to the northwest. These Permian sediments become finer grained further south where they abut against a granitic intrusion to the east. Triassic turbiditic sandstones and shales are found on the eastern part of Tasik Bera. All deposits are folded with moderate to steep dips and strike roughly northwest to north. Weathering is deep (> 1 m) and local alluvial fans were deposited prior to the formation of the swamp. In a few locations around the drainage basin, alluvial deposits are currently prograding onto the peat deposits due to a higher erosion rate during the last 30 years as a product of lack of forest management. The lake level of the northern part of Tasik Bera is 25 m above sea level and the surrounding hills are up to 100 m above sea level. The organic rich sediments were deposited on top of a peneplained landscape in an intermontane dendritic basin. The base is formed of lateritic kaolinite rich massive clay, clay-rich quartz sand, or, to a lesser extend, clay-rich silt. The peat deposits in the central areas, although above water level during the last dry season, are nowhere domed. Therefore, the swamp system of Tasik Bera belongs to the rheotrophic peat deposits and falls into the "primitive" or initial stage of the Anderson peat evolution model (Anderson and Muller, 1975; Anderson, 1983).

VEGETATION AND DEPOSITIONAL ENVIRONMENTS

Tasik Bera has an unusually high biological diversity resulting from a combination of three main habitats: dry lowland dipterocarp (trees dominated by *Dipterocarpaceae*) forest; freshwater swamp forest; and freshwater lake system. The different swamp environments, which are based on vegetation and the persistence of standing water are characterized by: 1) **open water or limnic environment**. This environment has an average standing water depth of 2 m and occupies 1% of the swamp area and includes patches of open water connected by a complex of channels. The hydrophytic plant assemblages are mainly: *Utricularia flexuosa, U. aurea, Cryptocoryne griffithii, Batrachospermum* spp.; 2) **littoral or sedge marsh environment**. This environment has an average water depth of 0.8 m and occupies about 32% of the swamp area. The floral composition is dominated by sedge swamp including *Lepironia articulata, Eleocharis ochrostachys, Zachinellia* spp., *Utricularia* spp., and *Limnanthemum* spp. and woody shrubs, mainly *Pandanaceae*; and 3) **swamp forest environment**. This environment has a water depth of 0.5 to 1.5 m and occupies 67% of the area. The swamp trees are mainly *Eugenia,* spp. *Tristania* spp. *Macaraga*

Table 2. Peat classification system used in the field (from Esterle and Ferm, 1994).

Increasing humification ↓			
	WOODY	:	containing wood fragments 1–5 cm length > 5 cm noted separately.
	FIBRIC	:	yellow to orange-brown peat with > 66% fibres; long slender roots and rootlets with diameters 1–10 mm embedded in fibrous or granular matrix from which clear water can be extracted (von Post H1-3).
	COARSE HEMIC	:	orange to red-brown peat with 33–66% fibres; medium grained peat with long slender roots and rootlets embedded in granular matrix (von Post H4-5).
	HEMIC	:	reddish-brown peat with 33–66% fibres; short or equant fragments of roots and rootlets, bark and leaf fragments generally less than 1 cm embedded in a granular matrix from which clear to murky water can be extracted (von Post H6).
	FINE HEMIC	:	reddish to dark brown, medium to fine grained hemic peat with sapric matrix; partially extrudes through fingers von Post H6–8).
	SAPRIC	:	dark brown to black, with < 33% fibres; fine granular material with the consistency of paste from which water can be extruded and deforms as paste upon squeezing (von Post 8-10).
	CLAY PEAT	:	peat (usually sapric or fine hemic) containing > 25% ash yield.
	ORGANIC-RICH MUD	:	silt and clay with abundant organic fibres and fragments.

graffithiana, or *Dipterocarpus* spp. and Palmae (Furtado and Mori, 1982).

METHODS

Field methods

Cores were collected along continuous traverses across and along the basin using a Macaulay peat sampler (Fig. 1). The device allows collection of 5 cm diameter core samples in 50-cm increments from the top to the bottom of each site. Each core was described in the field according to the classification scheme of Esterle (1990) and Esterle and Ferm (1994, Table 2). The samples were wrapped in aluminium foil and placed into PVC pipes for transportation.

pH and dissolved oxygen were analyzed in the field. pH was measured with a Cardy® Model C-1 digital pH meter (pH $H_2O_{distilled}$ with a narrow H_2O:soil ratio as possible). Dissolved oxygen concentration (DOC) was measured with a YSI Model 55 handheld meter, which also allowed measurements of the oxygen saturation and temperature of the pore water. A 5 cm diameter PVC pipe, with a sealed bottom and 3 mm holes within the first 10 cm around the pipe was used to measure DOC. The PVC pipe was rapidly pushed to a certain depth of the organic deposits. DOC was measured after the pore water infiltrated into the pipe.

Reconstruction of the subsurface topography is based on 11 transects taken across the swamp system at 50 m intervals and at 25 m intervals close to the *Dipterocarpus*-forest. The core sampler was pushed down to the clay sediments and the thicknesses of clay, mud and peat deposits measured. Peat composition was not differentiated. All sites were marked on a sketch map and GPS positions were taken with a Garmin 38 or Silva Navigator XL-300 handheld devices. For this preliminary paper, two of the 11 traverses are presented (BF and BB, Fig. 1).

The subsurface data from the transects collected in the field and the core data were used to model the peat distribution across the swamp system. GPS locations close to arborescent vegetation had a deviation error up to 30 m. These points were corrected with the help of aerial photography (1:25,000) and topographic maps (1:25,000). Vertical leveling was done relative to the waterlevel in the channel or in the lake. Errors up to 30 cm in elevation from the center point (channel, lake) to the edges of the study site are possible. The vegetation (*Pandanus heliocopus, Lepironia articulata*, shrubs, swamp forest and dipterocarp forest) was mapped in the field and superimposed to the transects.

Laboratory methods

Characterization of peat sediments is essential for predicting coal quality and distribution. With coal samples, ash and sulfur content, degradation and maceral composition as well as coalification stage are usually analyzed and are the important factors influencing economic value and are hence considered here. Thus, for comparing purposes ash content, pH and particle size of three peat cores from the littoral part of the basin were analyzed. In addition, pH, ash and sulfur content of one swamp forest peat profile was analyzed.

Chemical analysis

Chemical analyses allow interpretations about the degradation and chemical composition of the deposits. In the field, Munsell color, particle size and pH description was used to indicate degree of decomposition and composition. pH was measured again with the same method used in the field with the Cardy® Model C-1 digital pH meter in the laboratory and compared to the field results. Maximum deviation of 0.12 pH units was observed when measuring the pH 4 buffer as a blind standard in the field. In the lab, maximum deviation was 0.02 (Cardy) and 0.05 (CanLab).

Physical analysis

The moisture and ash contents were determined according to standard procedures (ASTM D-2974-87, Method A and D). Peat samples were dried at 80°C or freeze dried for several days for determination of the moisture content. The moisture content is reported as a percentage of the as-received mass. The ash content was determined by igniting the oven-dried sample from the moisture content determination in a muffle furnace at 750°C for at least 2 hours. The substance remaining after ignition is the ash. It is expressed as a percentage of the mass of the oven-dried sample.

Organic carbon, nitrogen and sulfur (CNS) analyses of 20 samples were done on a Carlo Erba NA-1500 analyzer according to the analytical method of Verardo *et al.* (1990). Inorganic carbon was determined coulometricly.

The degree of humification of the organic constituents or particle size was determined according to ASTM D 2977-71 standard. Air-dried peat was separated into four designated fractions by means of an –8 mesh (2.38 mm) and a –20 mesh (0.841 mm) sieve. The fractions are: 1) extraneous matter removed from the 8-mesh sieve (fibers > 12.7 mm); 2) coarse fiber retained on the –8 mesh; 3) medium fiber retained on the –20 mesh and; 4) fine fibers which pass the –20 mesh sieve. The weight % of each fraction is reported on the as-received basis. In general, the more coarser fibers the samples contains, the less humified the peat. Subsamples of 5–25 cm length of the 2-inch diameter core were sieved and the weighed samples were plotted.

RESULTS AND INTERPRETATION

Peat stratigraphy

The Tasik Bera ecosystem includes limnic, fluviatile and lacustrine peat deposits as a result of paludification of an intermontane basin. The profiles B51, B63 and B103 were collected in the northern, littoral environment with *Lepironia articulata* and profile B89 was collected in the swamp forest in the southern part of the drainage basin in the Paya Belinau (B89, Fig. 1). All deposits are underlain by significant thickness (> 50 cm) of fluviatile or lacustrine clay-rich sediments. The sediments were deposited following the mid-Holocene sea level highstand.

Profile B51 (Fig. 2) consists of 320 cm of peat underlain by 30 cm of organic rich mud containing short (< 5 mm) organic fibres. The lowermost peat sediments are hemic to coarse hemic (320 to 194 cm) with abundant long roots and plant fragments of *Lepironia* and *Pandanus*. The lower part of these coarse hemic deposits shows abundant woody fragments, including black leaves, branches, bark and roots. The stratum from 194 to 115 cm is fine hemic dominated by pandan roots and fibres. The coarse to fine hemic peat from 115 to 59 cm contains abundant *Lepironia* and pandan root and few red wood fragments. The uppermost sapric peat consists of *Lepironia* roots and is enriched in mud. Red algae mats cover the surface.

The peats of B63 (Fig. 3) show similar stratigraphic composition as B51. The organic rich mud with wood (153 to 190 cm) is underlain by quartz-sand-rich fluviatile clays which contain black plant fragments. The sapric to hemic peat strata from 28 to 190 cm contains abundant woody fragments, including leaves, bark, branches and tree stems. The epipedon consists of sapric peat with fine root of Lepironia.

Organic-rich mud with abundant pandan roots and woody fragments is overlain by fluviatile white clay in B103 (Fig. 4). The clays contain abundant small black plant fragments. An organic-rich mud with branches, leaves and stem fragments covers the clay. Sapric, mud-rich peat with abundant woody fragments (271 to 244) followed by sapric, mud-rich peat and fine hemic peat with abundant pandan roots (244 to 189) overlay the organic rich mud. The strata from 189 to 163 cm consists of fine and coarse hemic peat with abundant woody fragments, i.e. bark, leaves, branches. The uppermost 163 cm peat deposits consists of sapric to coarse hemic peat and 20 cm of organic rich mud at the top. These deposits contain abundant *Pandanus* and *Lepironia* roots and stem fragments and fibres.

The profile B89 (Fig. 5), from the swamp forest, consists of 158 cm of predominant sapric and less hemic peat. The peat is overlying a thin organic rich mud (2 cm) and a thick (> 40 cm) dark brown, organic-rich lacustrine clay.

pH

In the Tasik Bera area, the field determined pH either slightly increases or decreases with depth. The pH determination in the lab shows that the organic rich deposits, upon exposure to the atmosphere, change acidity. The pH values measured in the lab with the Cardy and CanLab meter are similar, but pH values measured in the field are up to 1.2 pH value higher (Figs. 2 and 3). The lab pH profiles are spiky (Fig. 2 to 5, Table 3 to 6) suggesting that differential chemical changes occur rapidly upon peat exposure and alter the pH. Different factors are assumed to influence these changes, i.e. organic constituents and mineral

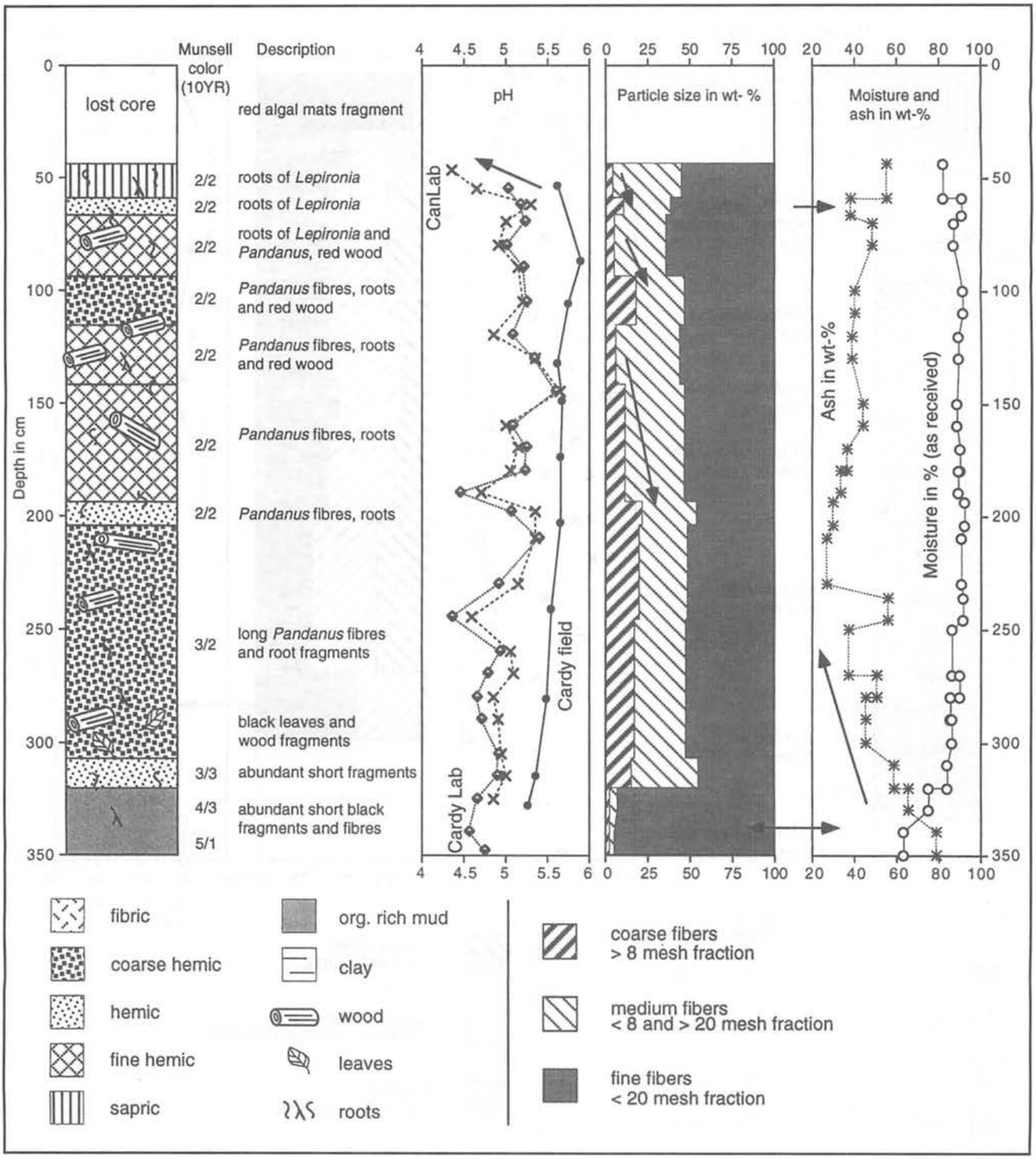

Figure 2. Core B51 in *Lepironia articulata* environment (3°08.592'N, 102°36.106'E).

matter composition, degree of organic matter decomposition, nutrient and base status (Sumner, 1994).

The pH values of profile B51 measured in the field decrease from the top to the bottom from 5.61 (54 cm) to 5.26 (328 cm). The lab measurements show a similar trend. The lowest values were obtained at 47 cm (4.35, CanLab), 190 cm (4.45, Cardy) and 245 cm (4.36, Cardy). The top part of the recovered profile is acidic (pH < 5) with a pH value of 4.35 at 47 cm and 4.65 at 55 cm depth (CanLab), respectively 5.01 (Cardy). The profile B63 (Fig. 3, Table 4) has a field pH minimum of 4.69 at a depth of 6 cm, a rapid increase to 4.96 at 14 cm and then a steady increase to slightly acidic (pH from 5 to 7) with 5.10 at 93 cm and 5.21 at 162 cm. In profile B63, all values but one measurement in the organic-rich mud at 170 cm, are in the acid

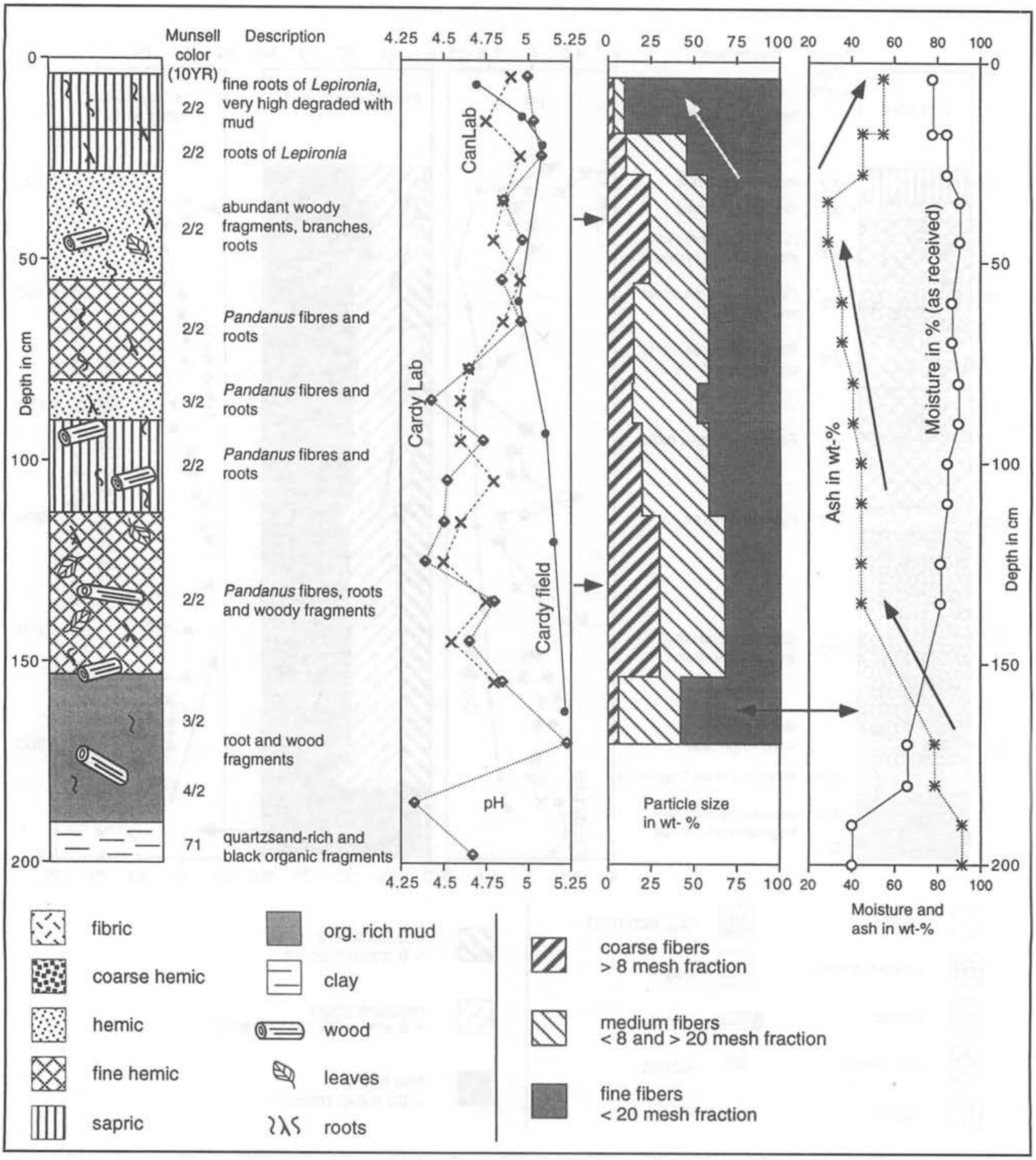

Figure 3. Core B63 in *Lepironia articulata* environment (3°02.498'N, 102°39.071'E).

range (pH < 5). The lower lab values in the middle and lower soil profile is considered to represent an accelerated organic matter decomposition upon air exposure and generation of acids. Similar interpretation might explain the pH ranges in B51 (Fig. 2, Table 3). The pH results of B103 (Fig. 4, Table 5) show similar trends as B63 and B51. The lowest value (4.35 at 210 cm depth) corresponds to zones of high degradation of organic matter and low abundance of coarse fibers. In the subsurface of B103, from 230 to 300 cm, increase and decrease of pH correlates with mineral matter and particle size distribution: the higher amount of coarse and medium fibers (270 to 292 cm) coincides with lower lab determined pH values.

In the swamp forest profile, B89 (Fig. 5, Table 6), an opposite trend of the epipedon pH can be recognized although it shows a much higher ash

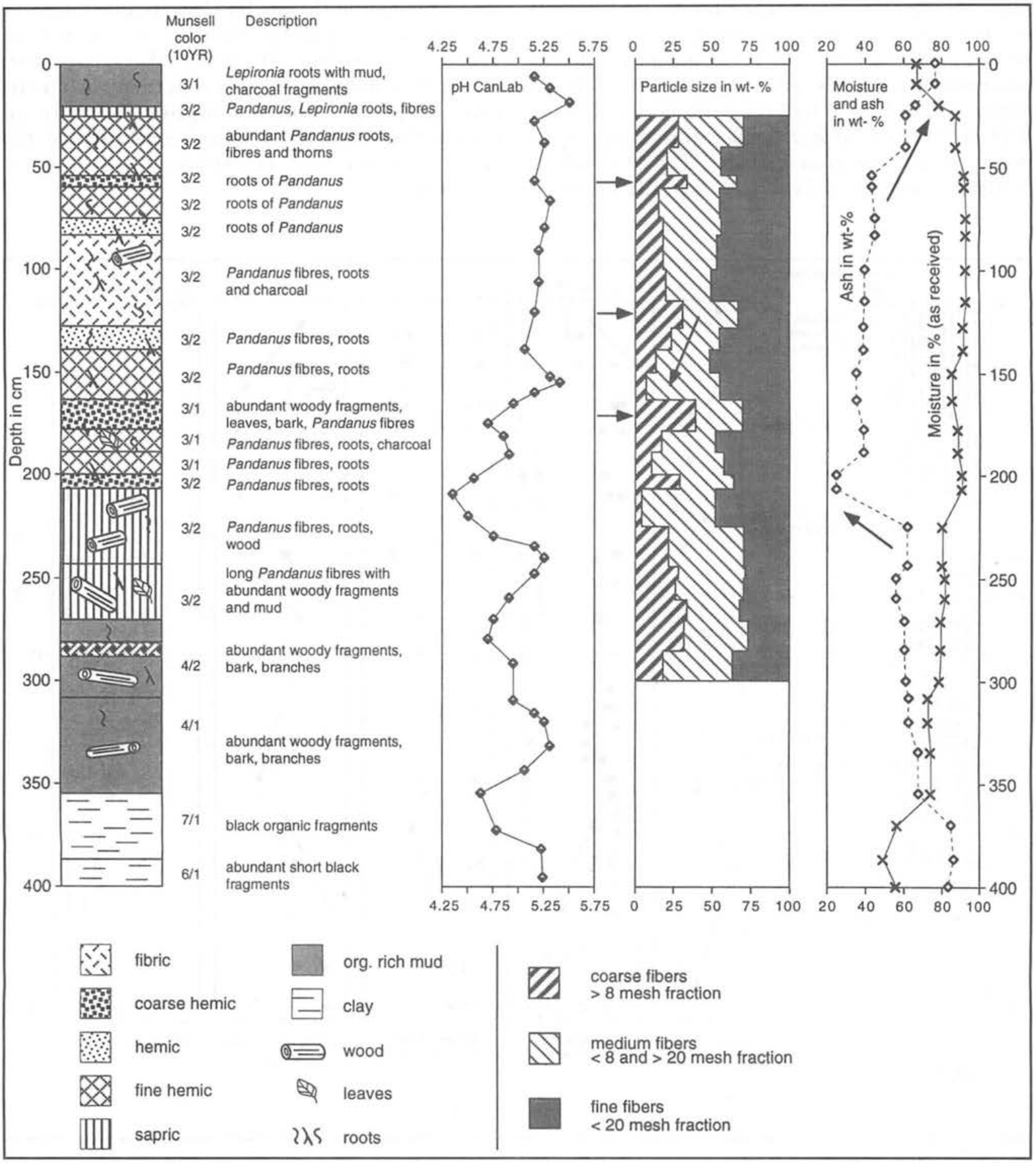

Figure 4. Core B103 in *Lepironia articulata* environment (3°05.472'N, 102°36.834'E).

content than the subsurface layers. In general, the mud and clay-rich deposits underlying the organic rich deposits have the lowest pH values (4.25 to 4.5). This profile shows the narrowest pH range measured in the lab (4.25–4.7).

Dissolved oxygen content

DOC analysis at the core site of B103 (Fig. 8) indicates an oxygen saturation in the top 25 cm of more than 20% because of the low water level (19 cm below surface). Below 25 cm, oxygen saturation drops rapidly to less than 4% at a depth of 35 cm and reaches the lowest saturation of 1.3% at 50 cm depth. The values of BF2 range from 2.49 (33%) to 1.78 mg/l (23%). Water temperature range at all sites was between 27 and 30.5°C. The DOC values in BF11 vary from 1.63 to 0.06 mg/l (21 to 0.9%). BF2 has a higher dissolved oxygen content than B103 and BF11 which might reflect a higher oxygen influx due to groundwater flow. B103 and BF11 are close to the main water channel, located in thick peat deposits and represented more likely the "typical" low dissolved oxygen concentrations of peat deposits (below water level). Dissolved oxygen fluctuation in the epipedon is assumed to occur throughout the year and governed by water level (i.e. aeration) of the swamp system. The measurements at the site B103 shows that dissolved oxygen content rapidly increases at the surface upon water level drop. The dissolved oxygen content at all sites indicates anoxic condition within the peat deposits which implies a reduced microbiological activity and degradation of the organic matter that is necessary for peat net accumulation.

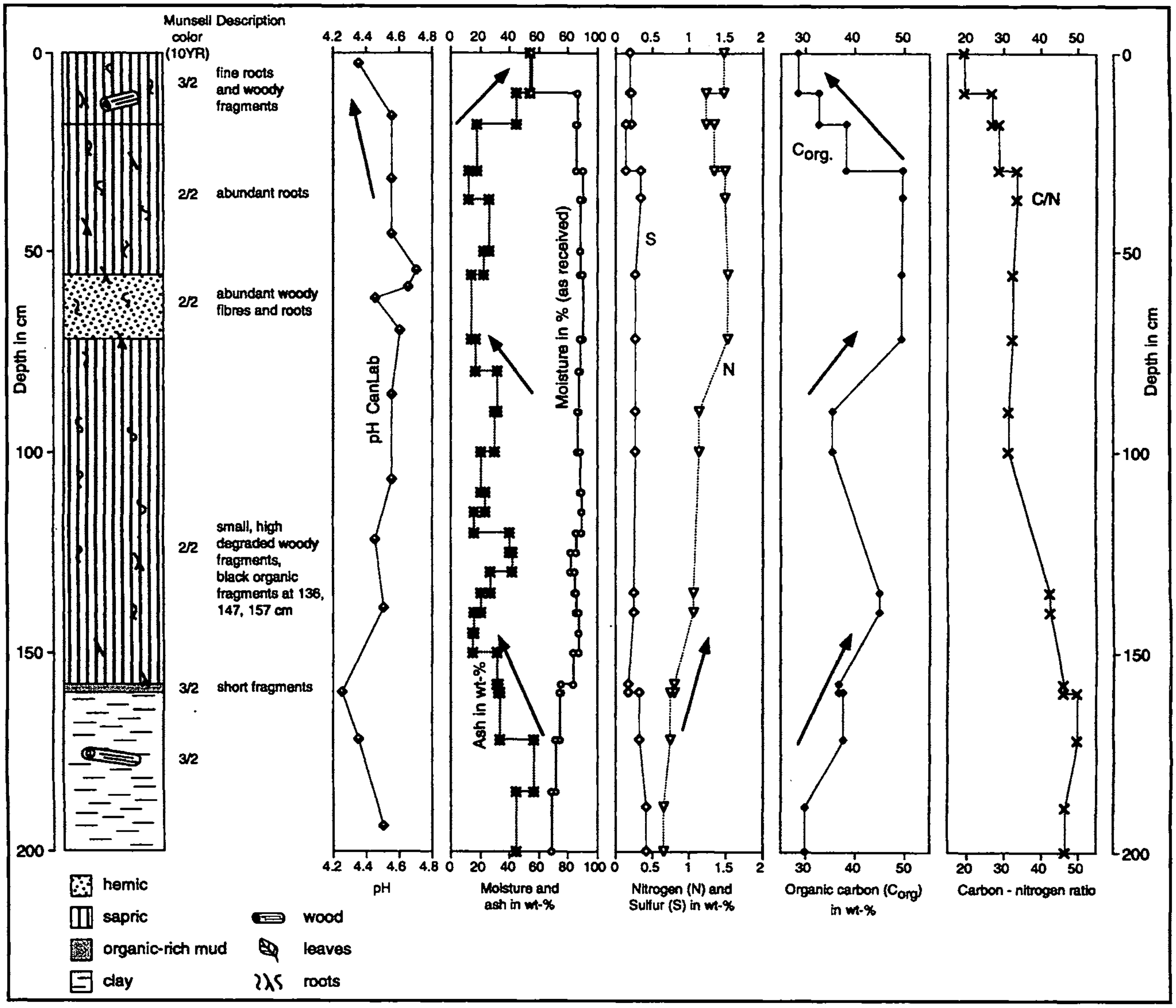

Figure 5. Core B89 in swamp forest environment with *Eugenia* sp., *Thoracostyachyum* sp. and *Pandanus* sp., Paya Belinau (2°57.755'N, 102°39.892'E).

Table 3. pH, particle size, moisture and ash results of core B51.

B51	pH			Particle size in wt %					Moisture and ash in wt %			
				Depth					Depth			
Depth	Cardy field	Cardy lab	CanLab lab	from	to	coarse	medium	fine	from	to	Moisture as received	Ash wt %
47			4.35	44	59	3.7	40.3	56.0	44	59	81.62	55.11
54	5.61			59	67	10.2	27.7	62.1	59	67	90.18	37.43
55		5.01	4.65	67	94	4.9	30.2	64.9	70	80	86.91	47.88
62		5.16	5.30	94	115	17.9	28.8	53.4	100	110	90.95	40.35
70		5.22	5.00	115	142	5.4	38.4	56.1	120	130	88.80	38.59
80		5.00	4.90	142	194	11.3	35.3	53.4	150	160	88.13	43.35
87	5.88			194	204	21.7	32.2	46.1	170	180	89.32	36.66
90		5.21	5.15	204	246	19.7	28.8	51.5	180	190	89.12	33.18
105		5.24	5.20	246	307	16.4	31.0	52.5	194	204	91.85	29.46
106	5.74			307	320	14.8	40.1	45.0	210	230	90.50	26.83
120		5.07	4.85	320	330	1.7	5.2	93.1	236	246	90.78	55.60
130		5.33	5.35	340	350	1.9	2.3	95.8	250	270	86.06	37.33
132	5.61								270	280	89.56	50.26
145		5.60	5.65						280	290	85.45	45.00
149	5.66								290	300	85.96	44.99
160		5.08	5.00						310	320	84.02	58.65
170		5.24	5.15						320	330	74.84	65.09
174	5.64								340	350	62.94	78.79
180		5.23	5.05									
190		4.45	4.70									
198		5.05	5.35									
203	5.64											
210		5.39	5.35									
230		4.91	5.15									
241	5.53											
245		4.36	4.60									
260		4.93	5.05									
270		4.77	5.10									
280		4.64	4.85									
281	5.49											
290		4.71	4.90									
305		4.91	4.95									
315	5.35	4.89	5.00									
325		4.65	4.85									
328	5.26											
340		4.56										
348		4.74										

Particle size

In core B51 (Fig. 2) the fine fiber content exceeds 50% over the whole profile. This fraction contains abundant short, degraded pandan roots and fibres. The coarse hemic horizon has a higher coarse fiber content. Changes from sapric to hemic (from 44 to 67 cm) or fine hemic to coarse hemic (from 67 to 115) corresponding to changes in particle size (see arrows Fig. 2). The underlying organic rich mud shows a > 95% fine fiber component.

Core B63 (Fig. 3) is similar to core B51. Changes in peat composition described in the field are reflected in the particle size analyses of the coarse and medium fraction (see arrows Fig. 3). Hemic peat in the low ash section (25–80 cm) is composed of a higher amount of coarse fragments. The bottom fine hemic part (120–155 cm) has a high coarse and relative low matrix particle content. The uppermost sapric peat and the peat underlying organic-rich mud have a higher mineral content.

Core B103 (Fig. 4) was selected for the most detailed particle size analysis. The fine particle size fraction (< –20 mesh) is most abundant. The fibric peat horizon has a high fine fiber content and also contains the highest amount of large fibers. The matrix of the fibric horizon is highly degraded or sapric. Most of the long organic constituents (>

Table 4. pH, particle size, moisture and ash results of core B63.

B63 Depth	pH			Particle size in wt %					Moisture and ash in wt %			
	Cardy field	Cardy lab	CanLab lab	Depth from	Depth to	coarse	medium	fine	Depth from	Depth to	Moisture as received	Ash wt %
4		4.99	4.90	4	18	2.6	7.1	90.3	4	18	77.56	55.17
6	4.69			18	28	10.0	35.2	54.7	18	28	84.25	45.09
14	4.96			28	55	24.2	33.4	42.3	35	45	90.42	28.80
15		5.03	4.75	55	80	14.7	43.9	41.4	60	70	86.86	35.24
21	5.08			80	90	13.8	37.8	48.4	80	90	89.82	40.68
24		5.07	4.95	90	113	19.1	39.1	41.8	100	110	84.46	44.68
35		4.85	4.85	113	153	29.2	38.7	32.1	125	135	81.36	44.51
45		4.96	4.80	153	170	5.8	36.0	58.2	170	180	66.12	78.69
55		4.84	4.95						190	200	39.85	91.19
60	4.94											
65		4.95	4.85									
77		4.65	4.65									
85		4.43	4.60									
93	5.10											
95		4.73	4.60									
105		4.52	4.80									
115		4.50	4.60									
120	5.15											
125		4.39	4.50									
135		4.80	4.75									
145		4.65	4.55									
155		4.84	4.80									
162	5.21											
170		5.22										
185		4.32										
198		4.67										

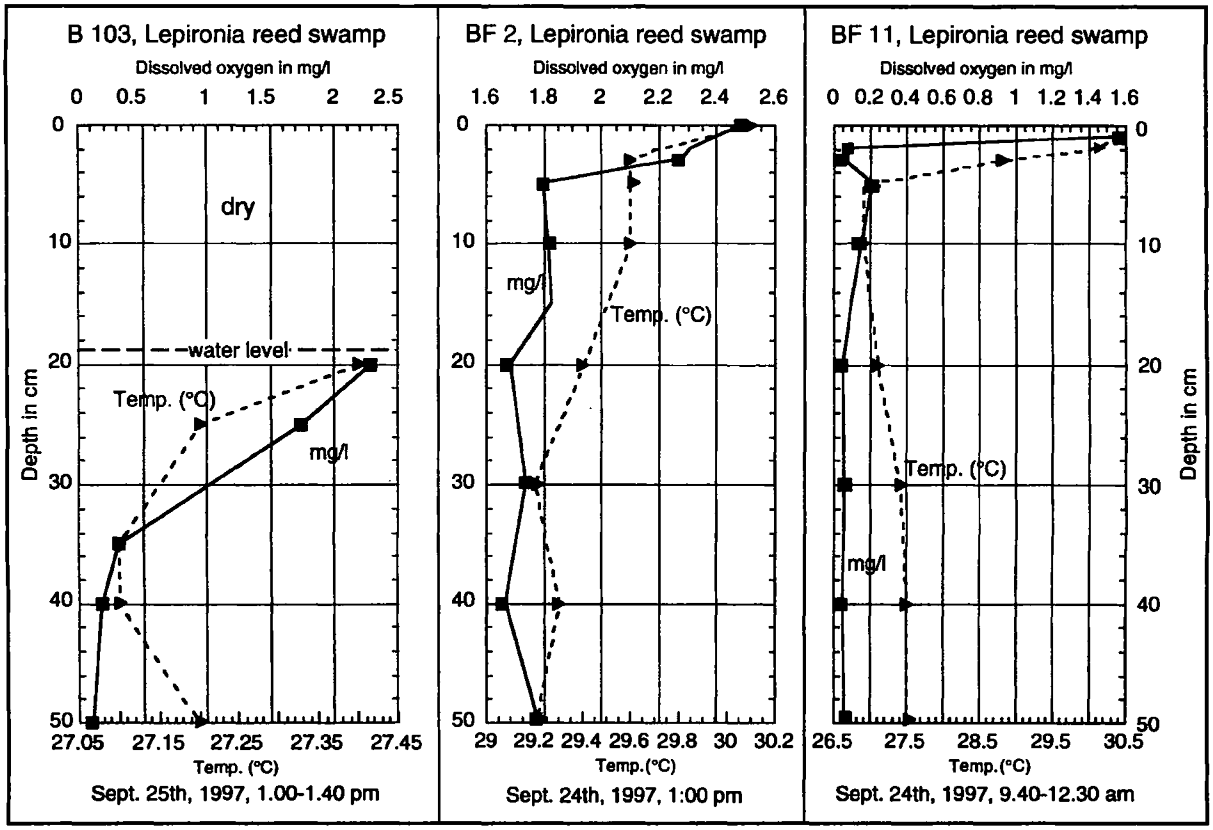

Figure 6. Dissolved oxygen measurements along the transect BF (3°04.500'N).

Table 5. pH, particle size, moisture and ash results of core B103.

B103	pH	Particle size in wt %					Moisture and ash in wt %			
Depth	CanLab lab	Depth from	Depth to	coarse	medium	fine	Depth from	Depth to	Moisture as received	Ash wt %
6	5.15	0	10				0	10	66.64	76.18
12	5.30	10	20				10	20	72.70	74.98
19	5.50	20	25				20	25	78.31	66.11
28	5.15	25	40	28.2	42.3	29.4	25	40	87.70	60.92
38	5.25	40	54	20.0	35.8	44.2	40	54	90.91	42.73
57	5.15	54	60	32.9	32.9	34.1	54	60	92.14	43.25
67	5.30	60	75	15.2	39.4	45.5	60	75	89.61	48.92
80	5.25	75	83	17.3	38.4	44.3	75	83	92.38	44.26
91	5.20	83	100	17.2	35.7	47.1	83	100	91.98	21.28
106	5.20	100	115	19.9	29.5	50.6	100	115	92.51	39.01
121	5.15	115	128	30.1	36.2	33.7	115	128	92.38	37.92
139	5.05	128	139	23.6	31.1	45.3	128	139	91.42	38.61
152	5.30	139	150	13.2	35.1	51.7	139	150	89.96	45.88
155	5.40	150	163	6.5	47.7	45.9	150	163	85.28	47.82
160	5.15	163	178	39.1	30.2	30.7	163	178	90.19	22.60
165	4.95	178	189	16.5	35.6	47.9	178	189	87.78	38.18
175	4.70	189	200	10.0	47.7	42.2	189	200	87.53	51.36
181	4.85	200	207	28.6	35.7	35.7	200	207	90.23	24.08
190	4.90	207	225	3.9	48.0	48.1	207	225	83.81	58.14
202	4.55	225	244	21.1	49.4	29.5	225	244	80.30	69.56
210	4.35	244	250	27.7	43.5	28.8	244	250	85.32	41.34
220	4.50	250	260	25.8	44.7	29.5	250	260	81.63	61.39
230	4.75	260	271	33.4	34.4	32.1	260	271	85.25	57.06
235	5.15	271	285	31.6	41.7	26.7	271	285	79.35	60.00
240	5.25	285	300	17.4	45.7	36.9	285	300	83.61	62.13
248	5.15						300	308	78.78	61.11
260	4.90						308	320	72.61	61.87
270	4.75						320	335	66.67	75.52
280	4.70						335	355	74.02	67.60
292	4.95						355	370	55.93	84.67
310	4.95						370	387	48.75	86.26
316	5.15						387	400	55.41	82.76
320	5.25									
332	5.30									
344	5.05									
355	4.62									
373	4.78									
382	5.22									
396	5.23									

2 cm) of this fraction consist of pandan roots, which are hollow and therefore have a low bulk density.

Moisture and ash

The moisture content reflects the typical high water retention of organic soil deposits. Moisture contents > 90% are common (Figs. 2–5). In all cores analyzed, the following relationship can be observed: the higher the ash content (mineral matter), the lower the moisture content and vice versa. B103 (Fig. 4) is a typical profile from the littoral part of the study area and fluctuation of the mineral matter reflects changing moisture content. The ash content of the peats (Figs. 2–5) ranges from 10 to about 60%, the ash content of the organic rich mud and underclay is up to > 90%. The mineralogical composition of the ash is dominated by clay minerals, particularly kaolinite with a small amount of illite and vermiculite.

CNS analysis

All analyzed samples from Tasik Bera area have very low sulfur contents (0.14 to 0.40%), nitrogen (0.64 to 1.5%) and high carbon (up to 50%)

Table 6. pH, moisture, ash and CNS analysis of core B89.

B89	pH	Moisture and ash in wt %				Carbon, Nitrogen and Sulfur Analysis (%), C/N-ratio				
Depth	CanLab lab	Depth from	Depth to	Moisture as received	Ash wt %	Depth	C	N	S	C/N
3	4.35	0	10	54.78	54.04	0	28.406	1.457	0.188	19.496
16	4.55	10	18	85.65	44.71	10	28.406	1.457	0.188	19.496
32	4.55	18	30	85.16	17.41	10	32.526	1.218	0.209	26.704
46	4.55	30	37	90.02	12.28	18	32.526	1.218	0.209	26.704
55	4.70	37	50	88.38	26.12	18	38.107	1.330	0.138	28.652
59	4.65	50	56	87.95	22.20	30	38.107	1.330	0.138	28.652
62	4.45	56	72	89.87	14.15	30	49.576	1.487	0.334	33.340
70	4.60	72	80	88.38	16.61	37	49.576	1.487	0.334	33.340
86	4.55	80	90	87.18	31.39	56	49.262	1.513	0.267	32.559
107	4.55	90	100	86.06	30.07	72	49.262	1.513	0.267	32.559
122	4.45	100	110	88.25	20.61	90	35.141	1.126	0.267	31.209
139	4.50	110	115	88.68	22.76	100	35.141	1.126	0.267	31.209
160	4.25	115	120	88.97	15.38	135	44.832	1.056	0.235	42.455
172	4.35	120	125	85.27	39.36	140	44.832	1.056	0.235	42.455
194	4.50	125	130	81.30	41.91	158	36.720	0.794	0.161	46.247
		130	135	84.27	26.58	160	36.720	0.794	0.161	46.247
		135	140	84.88	20.72	160	37.443	0.749	0.312	49.991
		140	145	86.71	15.94	172	37.443	0.749	0.312	49.991
		145	150	87.29	14.54	189	29.791	0.639	0.404	46.621
		150	158	83.26	31.02	200	29.791	0.639	0.404	46.621
		158	160	74.62	32.34					
		160	172	73.62	33.19					
		172	185	71.71	56.50					
		185	200	68.89	43.99					

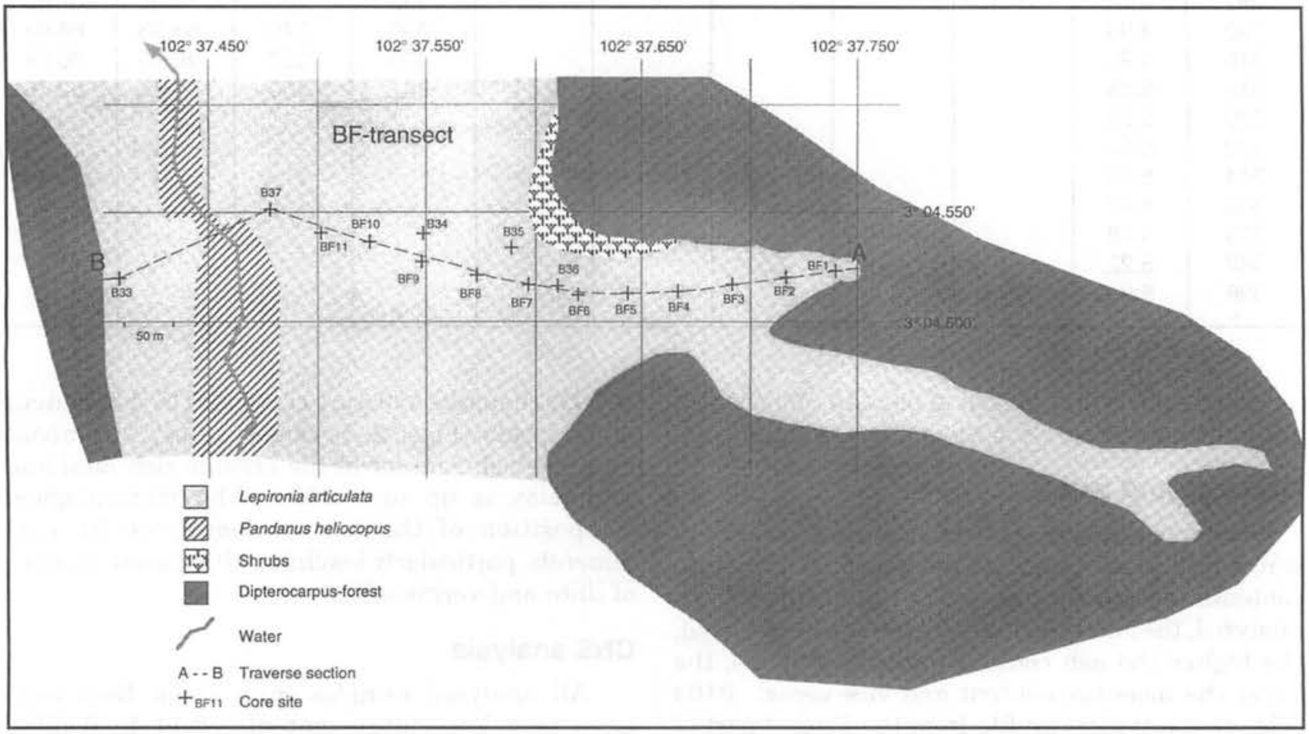

Figure 7. Sample sites and vegetation pattern in the vicinity of the transects BF at about 3°04.500'N.

contents. Carbon and nitrogen contents of the subsoil strata show similar trends in core B89 (Fig. 5, Table 6). Carbon and nitrogen contents increase from the clays to the overlying sapric and hemic peat. A major decrease of carbon in the epipedon (from 49% to 28%, 30–0 cm) is accompanied by an increase of nitrogen (1.21 to 1.45%) and ash content. Both carbon and nitrogen contents are enriched at a depth of 30–80 cm, which could reflect accumulation of organic matter (reduced degradation) in the catotelm due to root growth. The sulfur content is higher (0.40%) in the underclay than in organic deposits (0.14–0.33%).

Transects and spatial organic matter distribution in the littoral swamp basin

Transect BF (Figs. 7, 8) lies in the narrower southern littoral swamp area. The vegetation is primarily *Lepironia articulata*. *Pandanus heliocopus* is restricted to "open" areas of flowing water along the channel. Influence from the southeastern interfluve may have limited organic deposition at the site of BF3 and have led to prolonged mineral matter sedimentation. Before the onset of organic matter accumulation, the main channel was wider and may have been flooded, which led to the deposition of organic rich mud. Thick peat deposits are restricted to the channel. Terrestrialization reduced the original main channel width and paludification resulted in medium thick peat deposits (1 to 1.5 m) in the riparian area. In the second traverse (BB, Figs. 9, 10), vegetation is primarily *Lepironia articulata* with *Pandanus heliocopus* restricted to flowing or stagnant water adjacent channels or the lake. Shrubs occur along the dipterocarp forest edges. The thickest peat deposits are also restricted to open water and channels, e.g. B13, B17, BB17, B53, BB18 or B92. Medium thick peat (1–2 m) has accumulated in the littoral environment, e.g. BB29 to BB24.

The subsurface modeling of both traverses BF and BB shows that the topography prior to organic matter accumulation was irregular and that ponds, lakes and rivers dominated the geomorphology of Tasik Bera. This paleotopography strongly influenced character, accumulation rate and distribution of later deposited organic matter. Terrestrialization in the areas with a high water table (e.g. lakes, channels), by certain pioneer plant species with large subaqueous biomasses (e.g. *Pandanus spp.*), led to prolific peat accumulation.

DISCUSSION AND CONCLUSION

The results of the field and laboratory analyses of this preliminary study confirm that rheotrophic peat deposits are strongly heterogenous in stratigraphic composition, lateral continuity and biochemical character. Peat stratigraphy, pH, ash content and particle size analyses show that external factors mainly dictate the sedimentation of the organic and inorganic matter. Factors such as precipitation, topography, vegetation, groundwater level, inundation or detrital input locally influence peat composition and accumulation in Tasik Bera. The peat deposits have a rheotrophic character, are high in ash and have a high amount of fine particles (fine fiber content) indicating

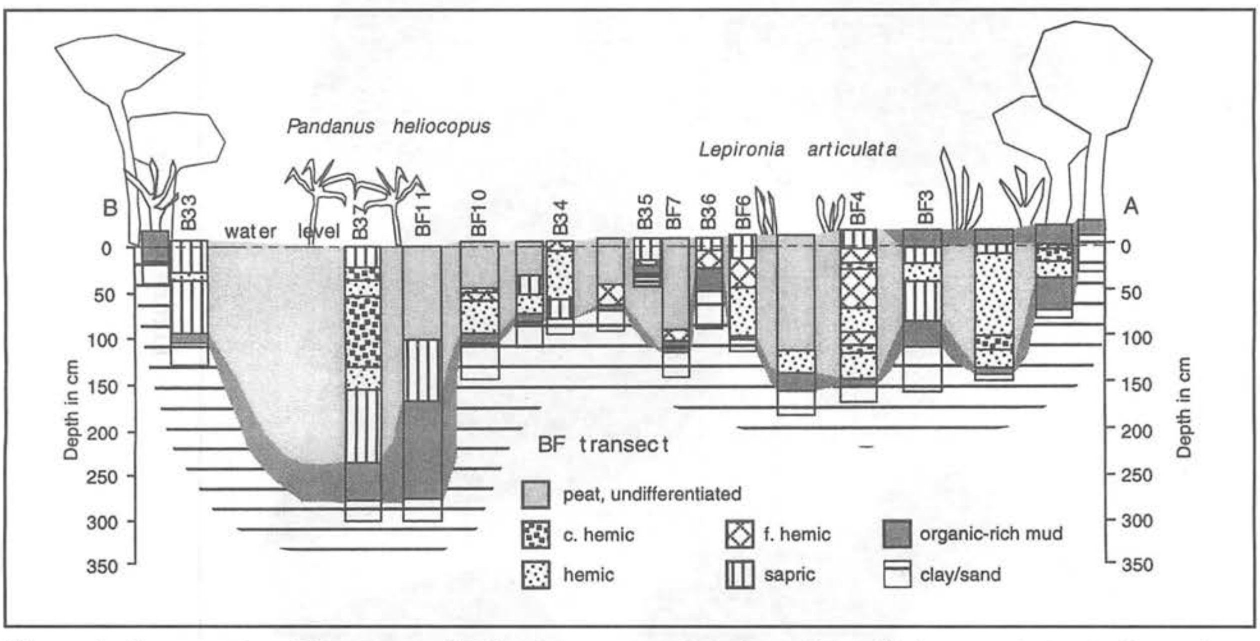

Figure 8. Cross-section of the traverse BF showing peat stratigraphy and peat thickness variation in the southern littoral part of Tasik Bera. The distance A to B is 1,000 m.

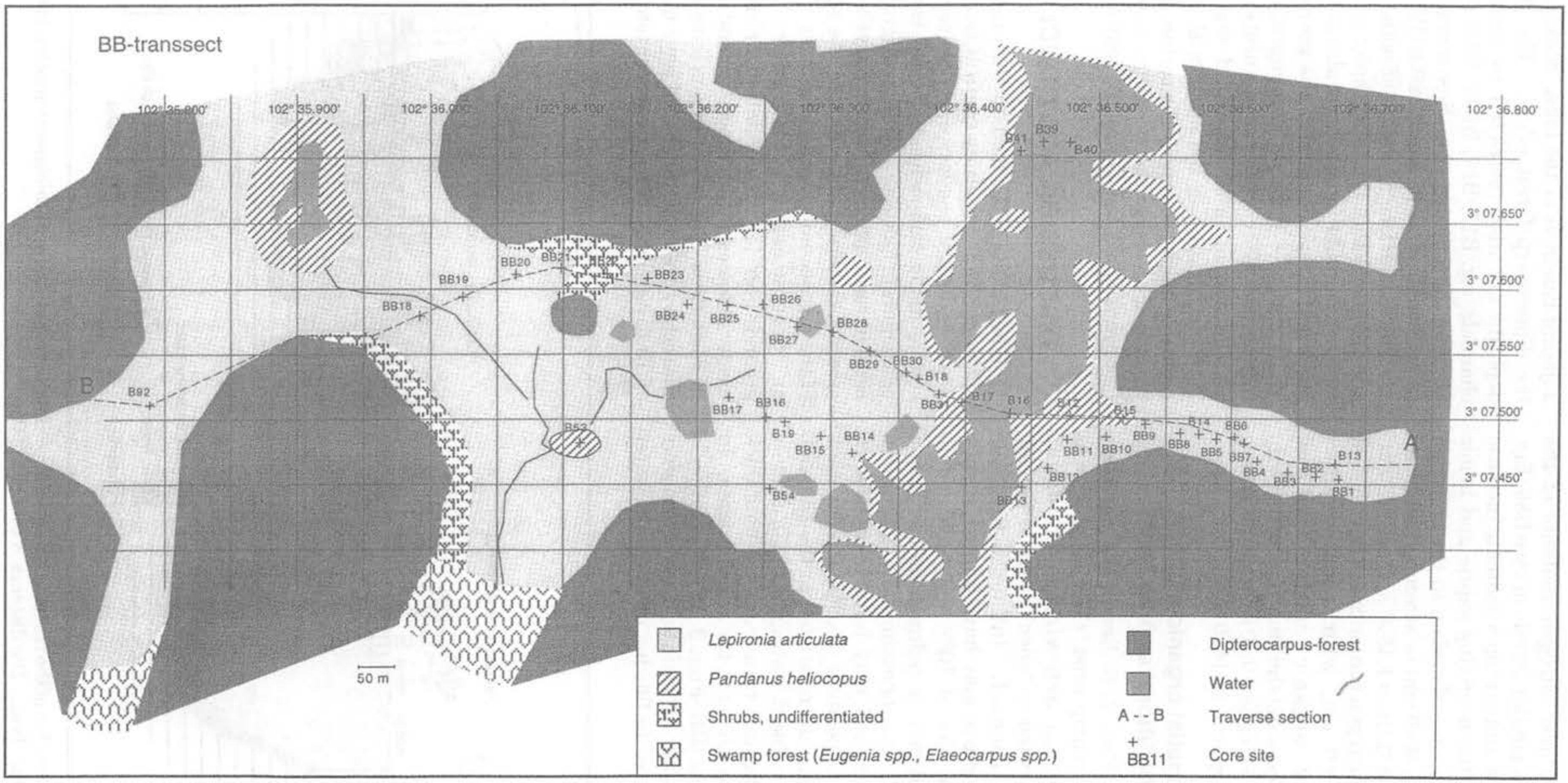

Figure 9. Sample sites and vegetation pattern in the vicinity of the transects BB at about 3°07.500'N.

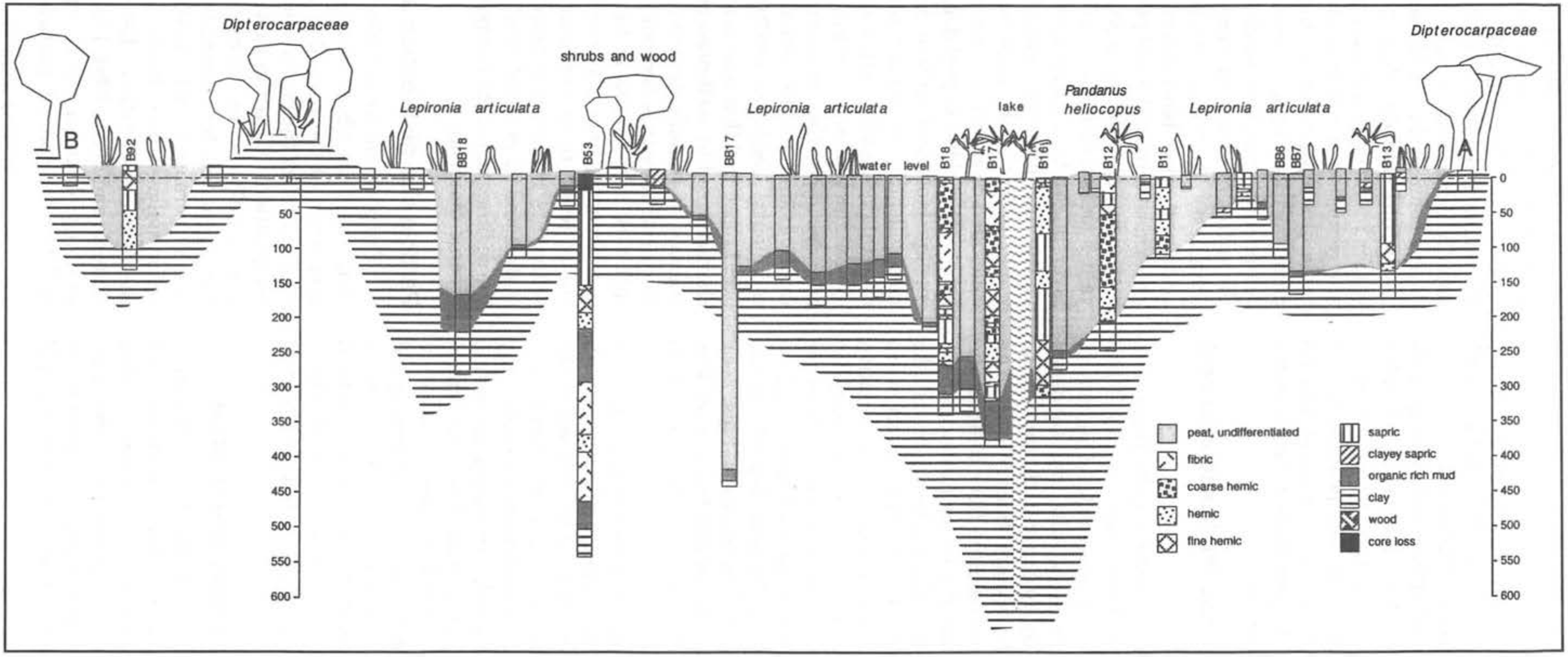

Figure 10. Cross-section of the traverse BB showing peat stratigraphy and peat thickness variation in the northern littoral part of Tasik Bera. The distance A to B is 3,000 m.

enhanced decomposition of plant constituents. All profiles show that the epipedon is enriched in mineral matter. The transition to clay-rich peat is regarded to be a result of rain forest conversion around the lake system which, together with climatic change (El-Niño events) may have led to a higher degree of humification and consequently organic matter decomposition. Further clastic influx could minimize organic matter accumulation or promote faster degradation of older peat sediments. On the other hand, a high clastic input of mineral matter could preserve the peat deposits accumulated during the last 4,500 years.

Depositional history and implications to peat composition

Organic matter accumulation in the Tasik Bera basin started some 4,500 years ago (Morley, 1982) in response to the mid-Holocene sea level highstand. Lacustrine and limnic clays, silt- and sand-rich clays are overlain by organic rich mud with abundant leaves and woody fragments. The macroscopic, coarse and medium fiber composition of these deposits is attributed to authochtonous forest swamp more likely than allochthonous lake sedimentation. Initially, limited areas were colonized by *Pandanus* and *Lepironia*. Inundation of the low-lying riparian areas was necessary for the following paludification and set the base for floral changes from forest to reed moor. These changes are reflected in the peat deposits of the littoral environment are fibric to sapric (Figs. 2–4). The peat deposits from the swamp forest area (Fig. 5) are sapric to fine hemic and reflect very high plant decomposition.

The transition from sapric/fine hemic peat with woody fragments to sapric/hemic/fibric peat with abundant pandan roots (Fig. 2 to 4) denotes the shift from arborescent forest to woody shrubs and *Cyperaceae* communities, probably contemporarily with a rise in water level. In marginal swamp areas, cycling shifts occur from forest to littoral environment (Fig. 3). Similar observations were made by Morley (1982) based on palynological investigations. A gradual evolution from a primary swamp forest environment to an expanded littoral environment with Cyperaceae and other hydrophytic plant communities, like *Utricularia sp.*, took place.

Acidity and organic matter preservation

Acidity in peat deposits influences microbiological life and hence structural and chemical decomposition of plant constituents (Stach *et al.*, 1982). In peat bog porewaters, the main source of H^+ are dissolved humic substances and carbonic acids, both which control the pH (Steinmann an Shotyk, 1997). Analysis of peat profiles in the field and in the lab reveals that pH changes resulted in an acidity drop upon peat exposure. This supports the observations of Farnham and Finney (1965) that pH values are usually depressed in various amounts upon air-drying compared to field conditions.

In B51 and 63 (Figs. 2 and 3), low field pH values in the epipedon may be related to oxidation and reduction of sulfur species in the zone of water table fluctuation or to higher organic matter decomposition (hence presence of abundant acid compounds (humic or fulvic acids) at and close to the sediment-water interface where oxygen supply is highest). The "concentration" of humic and fulvic acids and other biochemical acid products in the uppermost part of the soil profile may also indicate higher mineral matter deposition. The higher pH values measured in the lab for B103 in the surface layer might be related to dissolution of mineral matter due to the presence of various acids, which would buffer the pH. Steinmann and Shotyk (1997) concluded that various reactions may buffer the pore water acidity in peat deposits. These processes include biological sulfate and nitrate reduction, mineralisation of organic nitrogen compounds or mineral dissolution. pH, water level and dissolved oxygen fluctuations strongly influence degradation and decomposition of organic matter and have implications for humification of the organic sediments. Cecil *et al.* (1979) and Renton and Bird (1991) observed that acid peat deposits (pH < 4) are characterized by well-preserved plant matter, low degrees of humification and low sulfur content. Bacterial activity is favored in more neutral milieu (pH 4–8) and results in higher humified organic constituents, hence, preservation is poorer and sulfur tends to be concentrated. Acidity of the sediments reflects the trophic state of the mire system and its available buffers in the water and of the sediments, i.e. the composition of inorganic and organic material.

Particle size distribution and ash content

The particle size distribution of the cores shows that the fine fiber content comprises a large proportion of the peat, due to both typically high degradation of the organic matter and clay mineral composition. With the same ash content, particle size analysis in general reveals a close correspondence between an increase in humification and a decrease in pH measured in the lab. In all cores analyzed, particle size does not properly reflect the field classification. Esterle (1990) and others (Esterle and Ferm, 1994; Phillips and Bustin, 1996) similarly observed a low correlation between field and lab determined particle size distribution as determined by point-counting or sieving.

The rheotrophic organic-rich deposits of Tasik Bera have a higher ash content than the ombrotrophic peat deposits described in the literature (Casagrande *et al.*, 1977; Anderson, 1983; Moore, 1984; Esterle, 1990; Shotyk *et al.*, 1992; Phillips and Bustin, 1996; Steinmann and Shotyk, 1997). The carbonaceous sediments of Tasik Bera, with 25 to 60% mineral matter, are concentrated in the littoral environment (Fig. 2 to 4). In Tasik Bera, low ash peat is mainly restricted to the swamp forest. All cores record cycles of deposition of higher amounts of mineral matter. Precipitation changes in the Tasik Bera area has an impact on weathering, runoff and hence mineral matter input into the swamp system. An increase in runoff and a consequent inundation of the swamp system favors mineral matter distribution onto the peat deposits. Present fluctuations in runoff are often locally restricted and rarely consistent in the Tasik Bera basin (see Table 1) which make interpretations difficult; each area has to be considered individually within its own geographical and ecological settings. In the Tasik Bera area, vegetation has a major influence on water level and hydrological settings and therefore on genesis of the peat deposit.

Carbon, nitrogen and sulfur content

In addition to pH, mineral matter and oxygen content, a high amount of nitrogen is favorable for bacterial activity and therefore degradation (Stach *et al.*, 1982). In core B89, pH, ash, DOC and nitrogen content reflects the condition for a prolific bacterial community in the acrotelm (Fig. 5). In addition, the small C/N ratio of the acrotelm also indicates bacterial growth and eutrophic condition of the Tasik Bera swamp (Stach *et al.*, 1982). The increased sulfur content in the lower part of the pedon might be due to inorganic sulfur concentration. Sulfur content seriously affects the coal quality for coke production for the steel industry (Bustin *et al.*, 1983). The freshwater peat deposits in Tasik Bera have much lower sulfur contents (< 1%) than their counterparts in marine settings and coastal environments (> 1%, Casagrande *et al.*, 1977; Cohen, 1984; Cohen *et al.*, 1989).

Spatial peat occurrence in the intermontane basin of Tasik Bera

The spatial distribution of telmatic and limnic peat deposits reflects locally changing vegetation and nature of the substratum that restricted lateral peat accumulation to ponds and channel environments. The two traverses (BF and BB) show that terrestrialization of the main channels and occurred whereas the low-lying riparian environment underwent paludification during the last 4,500 years. Less degradation in depressions and along river channels due to the high water level, led to terrestrialization of the initial wider channel system and in the open water areas. Peat accumulation is thickest where water was stagnant or flowing and decreases towards the swamp edge. Hummocky areas show shallow and higher degraded peat deposits with a higher detritial component than their counterparts deposited along the channels and in water-filled hollows or lakes. Peat composition varies frequently vertically and laterally and reflects local changes in vegetation through time (Figs. 7 and 9). The peat deposits have a complex and variable internal composition. Stratigraphic correlation of these soligenous deposits are more complex then the correlation of ombrotrophic deposits described in the literature (Esterle, 1990; Anderson, 1964, 1983). Climatic changes have a direct impact on these organic-rich, rheotrophic deposits.

Implication for coal formation

The comparison between peat and coal is difficult. Studying modern peat accumulation provides an understanding of certain variables such as climate changes, plant association or spatial distribution of organic matter. The dendritic drainage basin of Tasik Bera represents deposition of limnic, rheotrophic peat and organic-rich sediments. Thick peat deposits and various ecological environments within the low-lying riparian mire area therefore serve as an excellent analogue for intermontane coal deposition. Although the organic–rich deposits in the Tasik Bera basin belong to the class of organic soils (soils with > 20–30% organic matter or > 17% organic carbon and at least 12 cm thick, Farnham and Finney, 1965), most peat horizons from Tasik Bera fall outside the strict definition of an analogue for good quality coal deposits (< 25% mineral matter).

Humification of the surface peat deposits in the dendritic Tasik Bera basin is promoted by year-round high temperatures, high oxygen supply and the slightly acidic to acidic environments. The littoral deposits, dominated by sedges (*Lepironia articulata*) and woody shrubs (*Pandanus heliocopus*) with large subaqueous biomass, show very low sulfur (0.14–0.40%) and ash contents (between 20% and 60%). Such peats form lighter colored (reed moors) overlying duller colored (forest swamps), low-sulfur, high ash coal and carbonaceous shale (carbargilite). The thick hemic to fibric peat deposits close to channel and open water areas could result in bright banded, laterally restricted humic coal deposits with a medium ash content. The swamp forest, which occupies most of the mire system (Furtado and Mori, 1982), contributes hemic to sapric peat with much lower mineral matter contents which would result in low-sulfur, intermediate to high ash humic coal. The thick (> 150 cm) forest peat is laterally more consistent and would result in 200–700 m wide and up to 50 cm thin dull coals along trunk river systems. At the swamp margins, humic coal and carbonaceous shale thickness would be reduced and these facies would interfinger with clay and sand-rich clay deposits. This organic matter layers with a high detrital mineral content (dry weight) will result in stony coal seams with lower economic value. The apparent modern increase in sediment load supply to the swamp area may promote burial and preservation of the peat deposits.

A preliminary evolution history of the telmatic and limnic peat deposits at Tasik Bera

The general depositional evolution of the Tasik Bera peat deposits can be summarized as follows:

1. Deposition of fine grained, highly weathered mineral matter in the basin. These sediments consist of kaolinite-rich clay and form the low permeability layer that reduces vertical water discharge. These deposits are essential for the formation of a "lake"-system such as the one in the northern part of Tasik Bera. A slower water drainage and the formation of the lake system, is assumed to be initiated by sediment loads transported by the Sungai Bera and deposited at the northern part of the basinal outflow because of water velocity and slope decreases. Plants with dense, interwoven subaereal roots such as *Pandanaceae* with stilt roots supported the initial damming of the drainage basin.
2. Accumulation of mud and organic matter, with abundant wood fragments, indicate an initial swamp forest environment throughout the Tasik Bera basin. During damming, the wide channels were flooded and terrestrialization of the channels and lake area began.
3. Deposition of various peat sediments. Vegetation changes through time reflect alternation between swamp forest and littoral vegetation (*Pandanaceae* and sedges). *Pandanaceae* are prolific producers of catotelm organic matter deposits due to their extensive subaqueous rooting system. Sedges are restricted peat producers of the acrotelm layer with a shallow, intertwined rooting system. During the last few hundred years, the littoral vegetation has progressively displaced the swamp forest. Assuming that ecological habitats of plants in tropical Tasik Bera have not changed over the last 4,000 years, peat composition (macroscopic and microscopic analyses) may be used for further investigations of the vegetation change.
4. An epipedon enriched in clay minerals formed in response to the disturbance of the wetland environment during the last four decades due to human influence, in the form of rubber and oil palm plantations encroachment of the Tasik Bera watershed. This may result in a dying swamp system and a beginning of the burial of the accumulated organic matter.

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