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Cenozoic ecological history of South East Asian peat mires based on the comparison of coals with present day and Late Quaternary peats

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ABSTRACT

Tropical peat swamps are more widespread in Sundaland than in any other equatorial region. Also, Cenozoic deposits from the area are rich in coals. The developmental pattern of present day peat swamps from the region has often been used to help clarify that of coals in the geological record. This paper initially reviews the ecology of present day ombrotrophic, rheotrophic and brackish mangrove peat swamps, and their pattern and timing of development during the Holocene and latest Pleistocene based on palynological studies. Then, it attempts to examine the developmental pattern of the peats which led to the formation of Cenozoic coals across the region, based on both published and unpublished datasets generated during the course of hydrocarbon exploration programmes. It is concluded that Cenozoic coals reflect a greater variety of peat forming settings than occurs in the region today. Extensive brackish water peats formed during the Middle and Late Eocene and Middle and Late Miocene, these often being laterally very extensive. Rheotrophic peats also formed widely through most of the Cenozoic. Ombrotrophic kerapah *type peats are first recognised in the Late Oligocene, based on their content of common* Casuarina *type and* Dacrydium *pollen, and were particularly common during the Early and Late Miocene in the Sunda shelf region.* Kerapah *peats sometimes developed great thickness. Basinal peats, on the other hand, increased in representation during the course of the Miocene. No convincing evidence for doming in Cenozoic peats has yet been noted, but on the other hand, no really thick coals, which may have been formed from basinal peats, have so far been studied. As a consequence, examples of doming in the rock record from this area are probably yet to be found.*

Key words: ombrotrophic kerapah *mires, basinal peat mires, rheotrophic peats, Southeast Asia, Cenozoic coals.*

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INTRODUCTION

The occurrence of widespread peat swamps along the east coast of Sumatra was brought to attention by Koorders (1895). Koorders considered these swamps to be present day analogues of the peat swamps which led to the formation of carboniferous coals. Geomorphological and ecological studies from Sumatra by Polak (1933, 1950) and from Sarawak/Brunei by Anderson (1963, 1964) subsequently demonstrated that many peat swamps were dome-shaped, and hence ombrotrophic (*i.e.* they receive their water and nutrients from precipitation only). The doming is also clearly reflected in their vegetation, which is generally organised into concentric zones, characterised both floristically and physiognomically, with vegetation attaining smaller stature and reduced diversity, which are thought to reflect a gradient of increasing oligotrophication and reduced nutrient availability from the margins to the centre of each dome. These catenas were demonstrated to reflect true temporal successions from palynological studies (Anderson and Muller, 1975), with Sarawak peats accumulating mostly since sea levels became stabilised during the mid-Holocene, about 5000 years ago.

The analogy between these peats and the peats which formed the Carboniferous coal measures has since been strengthened through the demonstration that the vegetation which formed Carboniferous peats also exhibited a temporal vegetation succession, which is reflected by palaeobotanical data (Eble and Gaudy, 1990; Pierce *et al.*, 1991; Rupert *et al.*, 1991) and in successional variations of coal macerals (Gaudy and Eble, 1990).

The Southeast Asian region is rich in coal deposits of Cenozoic age, and a logical progression was to examine such coals for analogous temporal successions. Initial studies from Brunei by Anderson and Muller (1975) clearly demonstrated that a peat which formed a Miocene coal bore a vegetation which was floristically and ecologically very similar to that observed in the initial stage of the succession within present day Sarawak peat swamps, but up to now, no convincing evidence for the concentric zoning, or of temporal successions comparable to that seen either in present day peat swamp vegetation, or in Holocene peats, has been brought to attention with respect to Cenozoic coals.

It has been suggested that ombrotrophic peats are the main source of coals in the geological record (Clymo, 1987). However, this review suggests that coals may have formed from ombrotrophic and rheotrophic (*i.e.* receiving water and nutrients mainly from groundwater or rivers) freshwater and brackish water peats.

Our present day knowledge of peat-forming vegetation in Southeast Asia shows that there are many regional differences, and also that peats form in a variety of geomorphological settings, depending on topography, soils, salinity and climate. This review initially compares the different types of peat-forming vegetation which are recorded from Southeast Asia, and pays particular attention to evidence for temporal successions within such vegetation types, which can be supported from palynological studies. The second part of the review examines palynological evidence for the nature of Cenozoic peat swamp vegetation from the palynological study of coals, and pays attention on the one hand to the changing character of peat-forming vegetation through time, and on the other hand, to evidence for temporal vegetational successions within coals which might reflect the concentric zoning or doming recorded within some present day peat mires.

METHODS

The first part of this review is based on published ecological studies of southeast Asian peat swamps, and Quaternary palynological records, whereas the second part utilises palynological studies of coals, using partly published and partly unpublished data generated during the course of petroleum exploration, based on analysis of conventional cores and cuttings from petroleum exploration wells. Palynological data from Cenozoic deposits have been examined using the same methods as for Quaternary peats, allowing judgments to be made as to whether Cenozoic peat forming environments were similar or different to those of the Quaternary.

PRESENT DAY AND HOLOCENE PEAT-FORMING VEGETATION IN SOUTHEAST ASIA

Peat formation in Southeast Asia may occur in areas of high rainfall, with the absence of a dry season (Morley, 1981a, 1981b), either in the form of ombrotrophic blanket bog type mires, which are maintained wholly by rainfall, and are believed to be highly oligotrophic, and covered by dense forests, or in rheotrophic, topogenous mires, with topographic factors retarding drainage, in which case they may be either oligotrophic or eutrophic and bear either forest, or herbaceous marsh (Fig. 1). Ombrotrophic peat-forming mires are particularly widespread in coastal regions, where they often attain large size, but also occur widely inland, and also form locally in mountainous regions. Rheotrophic mires have been much less studied and are little-understood. Some are very extensive, such as the Berbak swamp in Sumatra; however, most are of limited

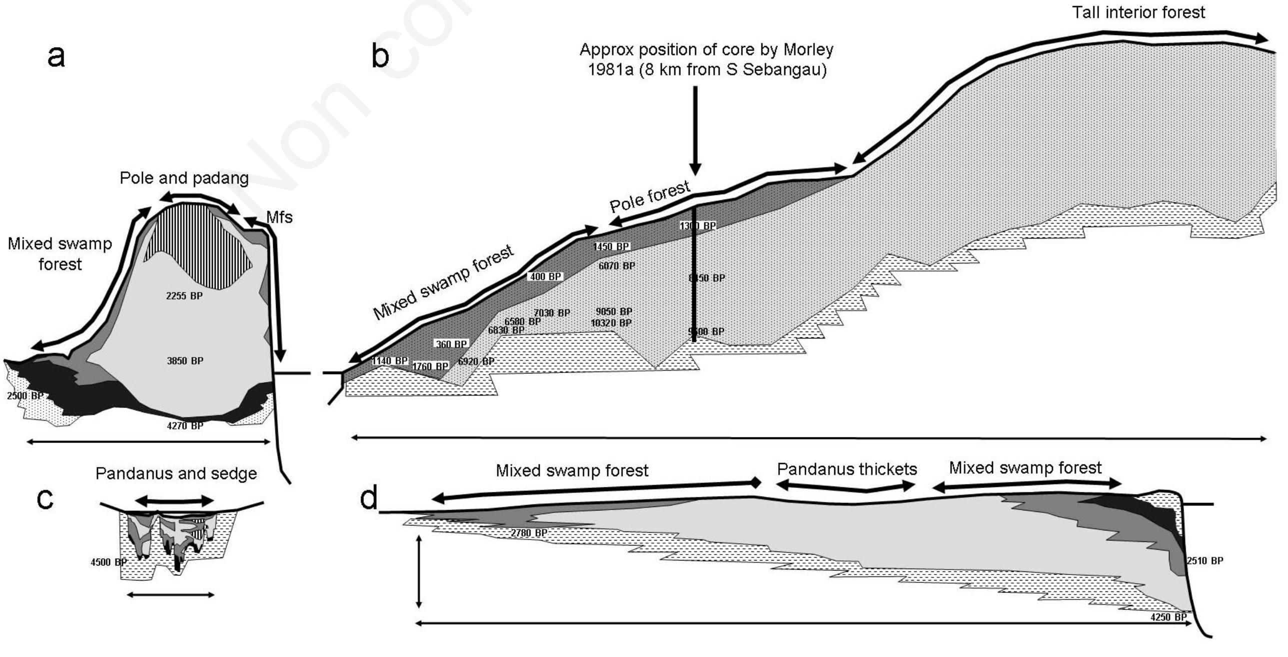

Fig. 1. Peatswamp profiles at the same scale. Ombrotrophic: a) Marudi, Sarawak; b) Sebangau, Kalimantan Tengah. Rheotrophic: c) Tasek Bera, West Malaysia; d) Berbak swamp Jambi, Sumatra. a,d) Peat profiles from Esterle and Ferm (1994); b) from Page *et al.* (2006); c) from Bastin and Wurst (2002). The Sebangau profile is 25 km long.

geographical extent. They are also common in mountainous regions. As will be clear from the following text, peats may form in settings which are intermediate between the rheotrophic and oligotrophic extremes. Peats also sometimes form within coastal mangroves.

Ombrotrophic swamp vegetation

There are two main types of freshwater ombrotrophic peat-forming forest within the lowlands of the Southeast Asian region, and a comparable type within montane regions, each characterised by extreme waterlogging, low levels of mineral nutrient availability and tea-coloured, very acid water, the two divisions first being recognised by Brunig (1974). These are: *basinal* peats, growing behind mangrove swamps [the coastal domed peats were initially studied by Anderson (1963)], and *kerapah* or *watershed* peats (Morley, 2000) which mainly form inland. Brunig (1990) termed the lowland types as *coastal*, or *deltaic* peat swamp forest and *kerapah* forest (the local Sarawak name for such forests), which is the waterlogged variant of *kerangas*, or *heath* forest. Andriesse (1974) suggested the term *basinal* for the former type, which is preferred here, since such peats may not be restricted to deltas, and also *kerangas* peats may occur in coastal locations. Basinal peats are described in detail by Anderson (1963, 1964, 1983). Sieffermann *et al.* (1992) suggested the name *high* peats for inland peats in South Kalimantan, a term which does not capture the wide variation seen in this peat swamp type, and so the term *kerapah/watershed* peat is preferred (Morley, 2000). Brunig (1974, 1990) outlined the main features of *kerapah* peats from Sarawak. The Sarawak *valley* peat swamps of Andriesse (1974) are probably a variant of *kerapah* peats.

Basinal peats

Basinal peat swamp forests (Figs. 1a and 2A) principally develop along relatively stable or subsiding, prograding coastlines in areas previously occupied by mangrove swamps (*e.g.* Caline and Huang, 1992), or extend along lowland river valleys in areas such as South Kalimantan (Sieffermann *et al.*, 1992) and Central and South Sumatra (Supiandi, 1990). These peat swamps developed following stabilisation of sea levels around 6000 years ago (Dommain *et al.*, 2011), and are thus closely tied to the cycle of eustatic sea level change (Morley, 1996). They have yielded basal radiocarbon dates varying from 6000 to 1100 years before the present (bp) (Dommain *et al.*, 2011). These forests are characterised by concentrically zoned vegetation and may grow on deep peat, up to 20 m thick. Basinal peats are widely developed in Sarawak/Brunei, West Sumatra, West and South Kalimantan. The manner in which peat formation commences has been variously discussed (Anderson, 1964; Esterle and Ferm, 1994), but Gastaldo (2010) demonstrated that peat formation is determined mainly by the mineralogy of the substrate, with peats forming when the underlying clays consist of mixed layer and expandable clays, restricting pore water flow in the tidal and overbank deposits, and forming an aquiclude, above which paludal conditions develop, promoting accumulation of organic matter.

Although the character of both basinal peat swamp and *kerapah* forests in Sarawak and Brunei has been known for some time, the extent to which these are representative of peat-forming swamps on a more regional basis, and the timing of peat formation, is only just becoming clear. Anderson (1963, 1964) differentiated the basinal peat swamps in Sarawak/Brunei into six phasic communities, along a gradient, or catena, of decreasing soil fertility and increasing waterlogging, from the periphery to the centre of mires. The structure of Sarawak swamps and representation of phasic communities is strongly influenced by the presence of one dominant species, *Shorea albida* (Dipterocarpaceae), which is absent from swamps outside Sarawak, western Brunei and northwest Kalimantan. The importance of this species in phasic community characterisation in Sarawak needs to be given close attention when making comparisons to areas outside the range of *S. albida*.

With respect to mixed swamp forest from Sarawak/Brunei, phasic community (ph.) 1 (Figs. 2A and 3a) occurs around the perimeter of mires, and according to Anderson (1983) shows many similarities with lowland rain forest in terms of physiognomy, being floristically diverse, structurally complex, multistoreyed, mesophyllous forest, and floristically with some *kerangas* communities (Brunig, 1990); the dominant species are *Gonystylus bancanus* (Gonystylaceae), *Copaifera palustris* (Leguminosae), *Dactylocladus stenostachys* (Crypteroniaceae) and some dipterocarps, such as *Shorea uliginosa* and *Dryobalanops rappa* (but excluding *S. albida*). Ph. 2 shows many similarities to ph. 1, but is of reduced diversity, with *Shorea albida* well represented among the canopy and emergent trees, and with *Stemonurus secundiflorus* (Icacinaceae) and *Gonystylus bancanus* characteristic of the canopy and understorey, whereas ph. 3 is composed almost exclusively of very large specimens of *Shorea albida*, with very poor development of the understorey (Figs. 2A, 3b and 4a). The leaf-size spectrum of the canopy changes within ph. 3 from mesophyll to mesophyll/notophyll, and with leaves becoming more sclerophyllous and xeromorphic. Ph. 4 and 5 lack emergent size trees, and consist of very dense notophyll-leaved pole forests (Figs. 2A and 3c). Dominants are *Tristania* spp. (Myrtaceae), *Parastemon spicatum* (Rosaceae), *Palaquium cochlearifolium* (Sapotaceae) and *Combretocarpus rotundatus* (Rhizophoraceae) with *Shorea albida* present only in ph. 4. Within the notophyllous to microphyllous open woodland or *savanna* of ph. 6 (Figs. 2A and 3d), *Combretocarpus rotundatus* is the only significant tree species, but shrubs (mainly of species which attain tree status in other phasic communities), and herbs are common (especially myrmecophytes and insectivorous plants).

Palynological studies by Anderson and Muller (1975) demonstrated that the succession seen in the catena is a true temporal succession, developing over the last 5000 years, since sea levels stabilised during the mid Holocene (Fig. 5), although they experienced difficulties in differentiating ph. 2 from 3, and 5 from 6. The earlier phases (1 and 2) were clearly differentiated by the presence of regular pollen of the trees *Blumeodendron* (Euphorbiaceae), *Campnosperma* (Anacardiaceae), *Gonystylus, Lophopetalum multinervium* (Celastraceae), *Stemonurus,* and common spores of the fern *Stenochlaena palustris* (Blechnaceae), whereas the more advanced phases (ph. 4-6) were characterised by the presence of common *Combretocarpus rotundatus, Parastemon, Dactyocladus*, and herbs, such as Cyperaceae and *Nepenthes* (Nepenthaceae). They note rare specimens (less than 1%) of mangrove pollen, and *Dacrydium* (Podocarpaceae) and *Casuarina* (Casuarinaceae) within several samples, but they interpret these as being blown in from outside the swamp.

Outside Sarawak and Brunei, in areas without *Shorea albida*, the catena is simpler, with ph. 2, 3 and 4 being absent, although substantial interstand variation may occur within the same phasic community. Evidence for concentric zoning is clear in Sumatran, South Kalimantan and some West Malaysian swamps (Anderson, 1976, 1983; Esterle and Ferm, 1994), and in these areas, two, or pos-

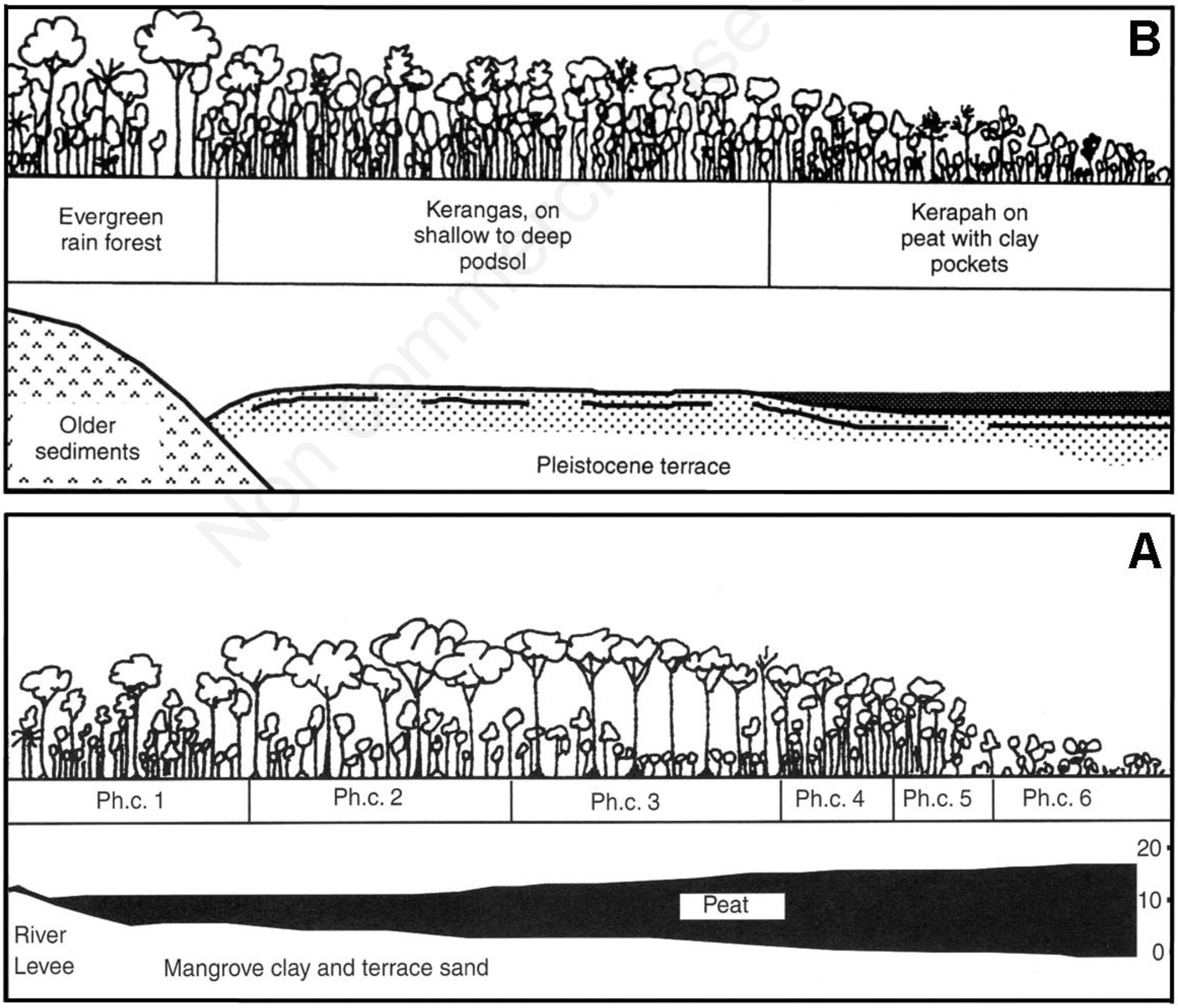

Fig. 2. Basinal (A) and *kerapah* (B) peat swamp catena compared [from Morley (2000)].

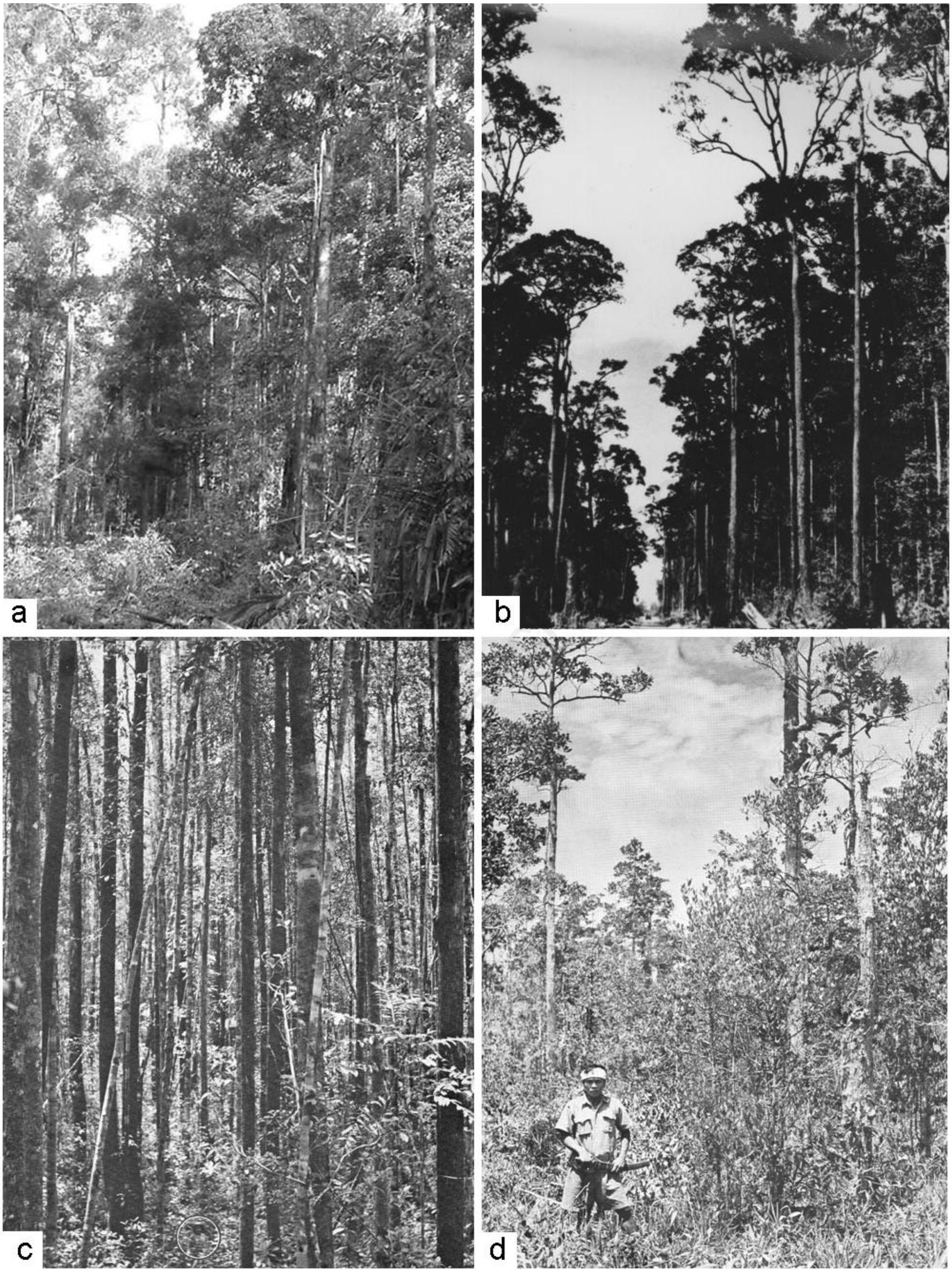

Fig. 3. Photographs of basinal peat swamp forests: a) mixed swamp forest (ph. 1), Pekan, West Malaysia, with *Gonystylus bancanus* and *Calophyllum* spp. dominant; b) Alan Bunga forest (ph. 3), with *Shorea albida* dominant, Brunei (photo by P.S. Ashton); c) *Padang* Alan, pole forest (ph. 4), Sarawak, *Shorea albida* dominant [from Whitmore (1975) (courtesy of J.A.R. Anderson)]; d) *Padang* Keruntum (ph. 6), Sarawak, *Combretocarpus rotundatus* dominant [from Whitmore (1975) (courtesy of J.A.R. Anderson)].

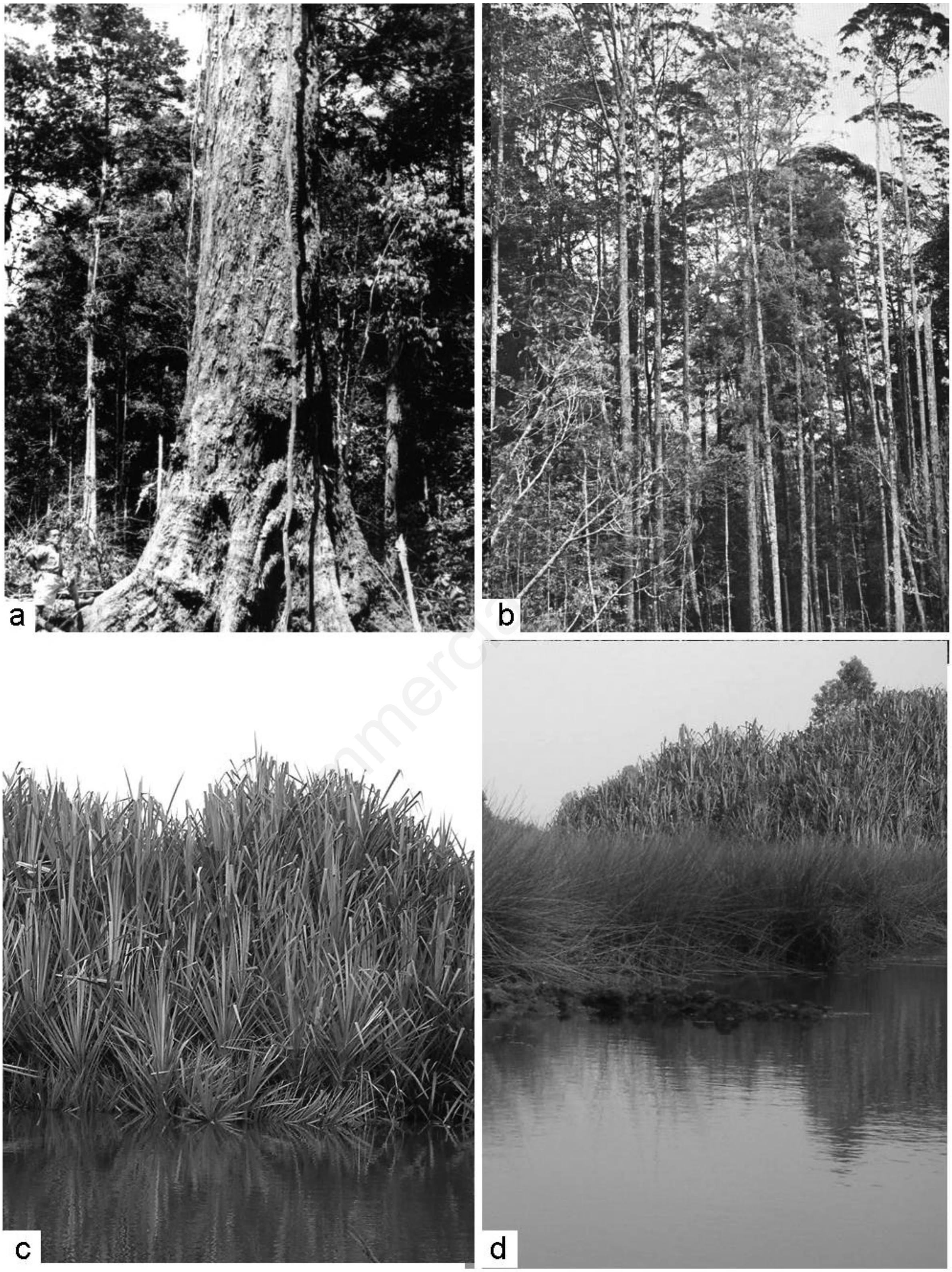

Fig. 4. a) Basinal peat swamp forest, large bole of *Shorea albida* (photo by P.S. Ashton); b) *kerapah* forest, Lawas, Brunei, with *Gymnostoma nobilis* (umberella shaped crown) and *Dacrydium beccarii* (feathery crown) dominant [from Whitmore (1975) (courtesy of J.A.R. Anderson)]; c,d) rheotrophic peat swamp, Tasek Bera, West Malaysia; c) *Pandanus helicopus* dominant; d) Tasek Bera, *Lepironia articulata* in foreground.

sibly three phasic communities are present: mesophyllous mixed swamp forest (ph. 1) around the margins of mires; notophyllous pole forest (ph. 5), which is often termed *Padang*, in central areas; and open microphyllous/notophyllous woodland comparable to ph. 6 may occur in very mature swamps.

Mixed swamp forest from Riau province were dominated by *Durio carinatus*, with *Palaquium* spp., *Dyera lowii* (Apocynaceae)*, Gonystylus bancanus, Strombosia javanica* (Olacaceae) and *Shorea* spp. present in the upper canopy (Anderson, 1976), whereas from Sebangau in South Kalimantan, *Calophyllum* spp. (Guttiferae) were overwhelmingly dominant with widespread *Gonystylus bancanus*. *Padang* forest from Riau was dominated by *Palaquium* spp. *Parastemon urophyllum* and *Alstonia pneumatophora*, whereas from South Kalimantan (Sebangau), *Palaquium* spp., *Calophyllum retusum* and *Diopyros evena* (Ebenaceae) were dominant elements (Anderson, 1976).

The more advanced phasic communities of basinal peat swamps are clearly related, both floristically and physiognomically, to *kerangas* forests, which are *stunted*, notophyllous, open-canopied forests of white podsolic sands which occur widely in Sarawak (Brunig, 1974), Central Kalimantan and elsewhere (Whitmore, 1984). Brunig (1990) considers all the phasic communities of basinal peat swamp forests to be closely related to *kerangas* forests, for there are more species in common with *kerangas* forests than mixed dipterocarp forests. Within ph. 1 and 2, 75-85% of peat swamp species also occur in *kerangas*, whereas within ph. 5 and 6, this increases to 100% (Brunig, 1990), and Anderson (1983) notes that there are no species *confined* to basinal peat swamp forests. Brunig (1990) suggests that *kerangas/kerapah* has been, and still is, a stepping stone for *dryland forest* species to adapt for invasion and occupation of basinal peat swamps.

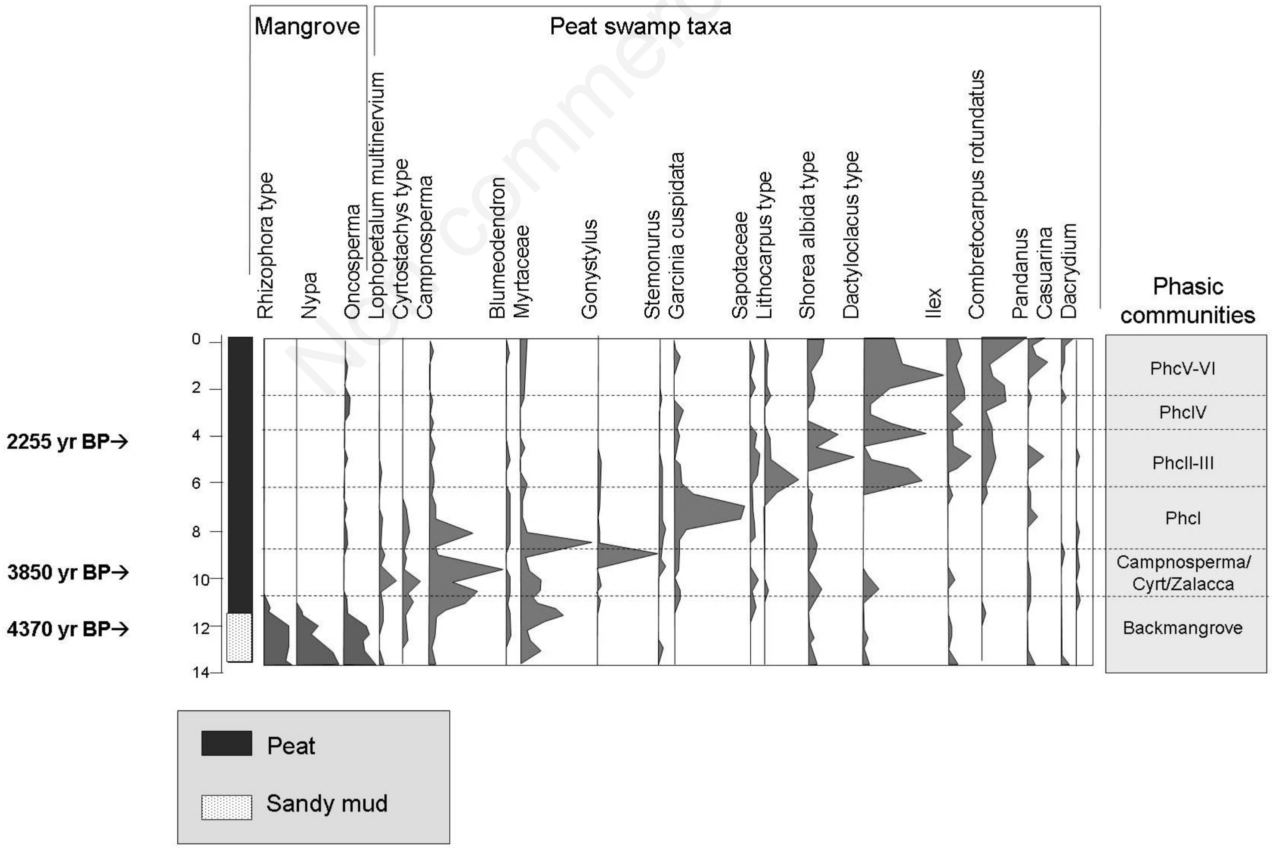

Fig. 5. Summary of pollen diagram from Marudi, Sarawak [summarised from Anderson and Muller (1975)]. Selected taxa are shown only. Phc=phasic community. Pollen sum *total arboreal pollen*.

Kerapah *peats*

Kerapah forests, first studied in detail in Sarawak by Brunig (1974, 1990) occur there on thin peats, up to just 2 m thick (Fig. 2B). However, *kerapah* peats may attain substantial thicknesses of up to 12 m in inland localities in South Kalimantan (Fig. 1b) (Seiffermann *et al.*, 1992), and possibly up to 16 m in the Kutei lakes area in East Kalimantan (Hope *et al.*, 2005). *Kerapah* peats develop in areas of podsolic soils where drainage is impeded through the development of an iron or humic pan (Brunig, 1974, 1990), and the term *watershed peats* applies to such swamps occurring on low lying interfluves. Thus, they are particularly widespread as drapes on low-lying, lowland watersheds in areas of podsolic soils (Sieffermann *et al.*, 1992), but also occur adjacent to freshwater lakes (*e.g.* lake Sentarum, West Kalimantan (Anshari *et al.*, 2001), in Kutei, and on low plateaus within the upper limits of the lowland rain forest formation, in areas of impeded drainage, such as on Gunung Panti in southern Malay peninsula, and the Merurong plateau in Sarawak (Brunig, 1974; Corner, 1978). Montane peat-forming forests drape watershed areas at very high altitudes within the upper montane rain forest formation (Whitmore and Burnham, 1969; Flenley *et al.*, 1972). Since upland peats are rarely preserved in the geological record, this account deals only with lowland peat-forming vegetation, occurring below 1000 m asl.

Kerapah peats develop over quite different timescales to basinal peats, their formation depending primarily on climate and secondarily on drainage factors, and unlike basinal peats need not to be directly connected to the cycle of sea level change. The oldest peats are from inland sites, such as lake Sentarum in the Kapuas lakes area and Sebangau in Kalimantan (see below) dating from 28 and 35 thousand years (ka) ago, respectively. They have been studied most intensively in the Sebangau region of Kalimantan (Fig. 6) by Morley (1981a), Sieffermann *et al.* (1992), Page *et al.* (1999, 2006), Rieley and Page (1997)

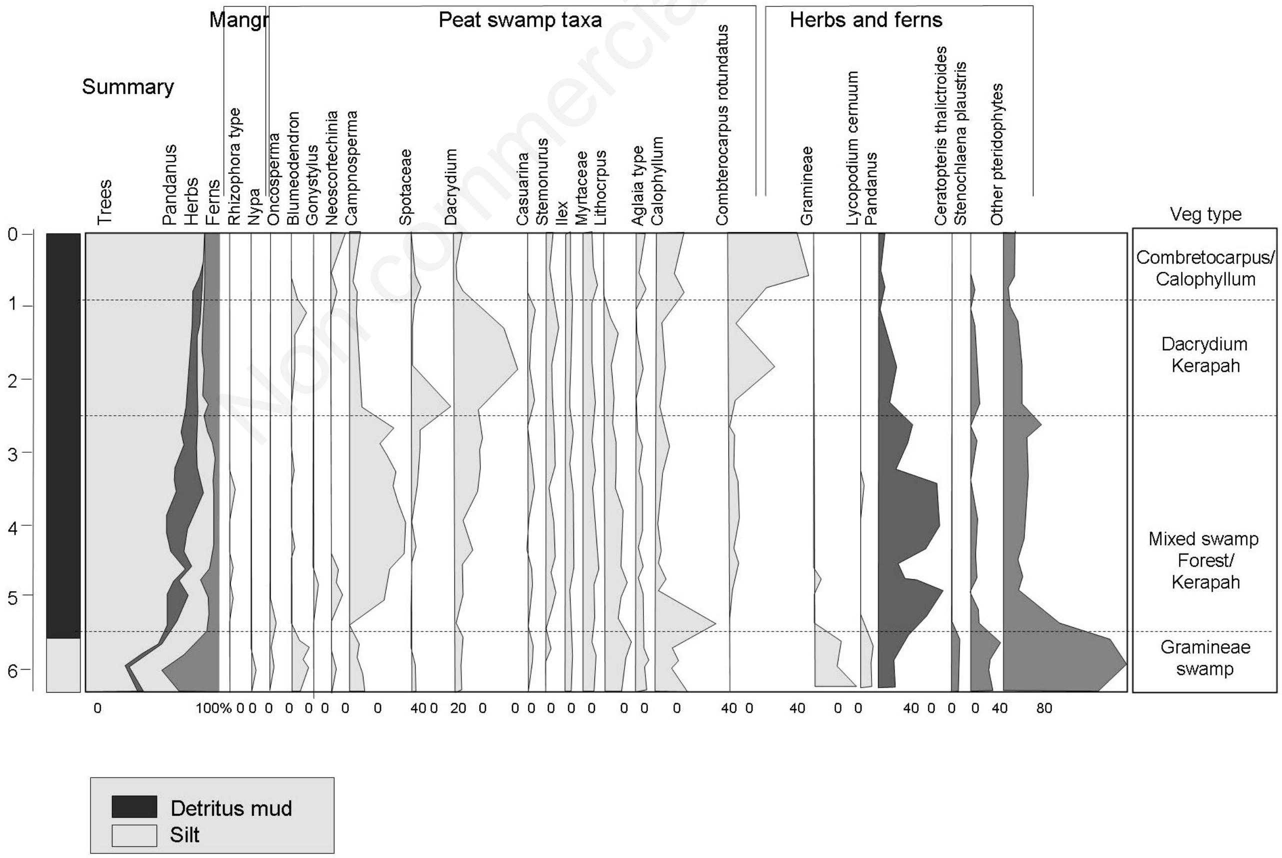

Fig. 6. Summary of palynological analysis through peat at Sungei Sebangau, Kalimantan Tengah [summarised from Morley (1981a)]. Selected taxa are shown only. Pollen sum *total arboreal pollen* except for *herbs+pteridophytes* which are presented in terms of *total pollen* and *total pollen and spores*, respectively.

and Kershaw *et al.* (2000), although an integrated overview is still wanting. The peat swamp succession in Sebangau is complex and requires detailed explanation, since basinal and *kerapah* peats occur in association. The peats from this area formed as drapes on an old watershed about 20 m asl and the oldest are dated from 35-20 ka, prior to the last glacial maximum (LGM). The peat is characterised by abundant fern spores and Cyperaceae pollen (Wurst *et al*., 2007) and most likely formed within a rheotrophic herbaceous marsh, the *Gramineae swamp* of Morley (1981a, 1981b). No peat formation took place during the LGM, because during this time it is thought that the climate was too dry for peats to form (Page *et al.*, 1999; Morley, 2012). Peat formation recommenced after the LGM, initially within a herbaceous marsh setting, but subsequently, after about 10 ka, and possibly as early as 13 ka, within an ombrotrophic setting with the development of peat swamp forests. Ombrotrophic peat formation thus began when the sea level was from 40 to 90 m below the levels of the mid Holocene. It is suggested that peat initiation commenced after a change to a wetter climate, probably associated with the sudden sea level rise after about 13 ka (Morley, 2012). Peat formation within a *kerapah* setting continued in this area until about 6 ka (Page *et al.*, 1999), after which time peat formation ceased, possibly due to a change to a more seasonal climate. The peat at this location is much drier than actively growing peats from the same area (Sieffermann *et al.*, 1992; Page *et al.*, 1999), no doubt due to a long period without growth, and possibly also with deflation. Sometime after 2000 bp, peat formation recommenced in the same area, following the growth of basinal peats along the Sebangau river (Fig. 1b), and most likely has been continuing up to the present day. The vegetation growing on the basinal peat exhibits some degree of concentric zoning as noted above (Anderson, 1976; Page *et al.*, 1999).

It is suggested that peat swamps in the Kutei lakes area, studied by Hope *et al*. (2005) are also of the *kerapah* type; these started to form as sea levels continued to rise during the early Holocene, but before the development of widespread basinal peats along coastlines. They probably started to form as the Mahakam delta began to build out from its present position during the latter period of sea level rise, following infill of the Mahakam incised valley, resulting in the development of paludal conditions in the Kutei lakes area.

Kerapah forest composition has been studied in detail only in Sarawak and Brunei by Brunig (1968, 1974, 1990), and is floristically similar to *kerangas*. Although Brunig (1990) noted structural trends and concentric zoning within *kerapah* peat swamps which bear some similarities with those seen in basinal swamps (Fig. 2), he was not able to identify consistent trends between forests on different mires, in the manner of the coastal/delta peat swamps studied by Anderson. He attributed this to the much greater inter- and intra-stand floristic variation within *kerapah* compared to basinal peat swamp forests, and this reflects the much higher floristic diversity of *kerangas* vegetation (948 species recorded in Sarawak *kerangas/kerapah* forests, as opposed to 242 species in basinal peat swamps). Greater diversity of *kerapah* peats may be a reflection of their greater geological age (see below). Two important *kerapah* genera which are generally absent from basinal peat swamps, and which deserve special mention are *Dacrydium* (Podocarpaceae) and *Gymnostoma* (Casuarinaceae), since they often occur together and achieve single species dominance (Brunig, 1990). *Gymnostoma* and/or *Dacrydium* seem to have been important elements of most of the *kerapah* swamps studied, and their presence seems to be a good indicator of *kerapah* swamps. Brunig (1990) also suggests that their tannin-rich leaves prevent litter decomposition, and increase peat-forming tendencies. Other *kerapah* elements are *Falcifoliatum* and *Podocarpus* (Podocarpaceae), and *Tristania* (Brunig, 1990).

The canopy of *kerapah* forests at Sebangau, summarised by Page *et al.* (1999), included *Agathis dammara* (Araucariaceae)*, Calophyllum* spp., *Dactylocladus stenostachys, Dipterocarpus coriaceus, Gonystylus bancanus, Gymnostoma sumatrana, Palaquium* spp.*, Vatica mangachopei* (Dipterocarpaceae)*, Xylopia* spp. (Anonaceae), Leguminosae and Myrtaceae. However, this forest is growing on old peat, and may thus not reflect a true successional stage. A very low canopied forest from waterlogged areas in the same locality was characterised by *Calophyllum* spp., *Combretocapus rotundatus, Cratoxylum* spp. (Guttiferae)*, Dactylocladus stenostachys, Litsea* spp. (Lauraceae)*, Plioarium alternifolium* (Theaceae) and *Tristania* spp. (Page *et al*., 1999).

Palynological studies of both lowland and upland *kerapah* peats from Sarawak have been performed by Muller (1963), with pollen diagrams presented here in Fig. 7, and published by Brunig (1974). Although the diagrams show some minor temporal trends, these are difficult to interpret. The most distinctive feature of the diagrams is their characterisation by common to abundant *Dacrydium* and *Casuarina* type pollen, which, as noted above, are thought to provide evidence for differentiating *kerapah* from basinal swamps.

Muller (1963) also made some brief comments on palynological analyses on a peat profile from an *anomalous* lowland peat swamp at Lawas, in Brunei (Anderson, 1963), which is dominated by *Gymnostoma nobilis* and *Dacrydium elatum* (Fig. 4b). Brunig (1990) proposed that this swamp should be classified as *kerapah*, rather than a basinal peat swamp, despite its coastal locality. The detailed palynological analysis of Lawas (Fig. 8) (Muller, unpublished data; Morley *et al.*, 2011) clearly shows that

Dacrydium colonised directly over mangrove muds, a *kerapah* swamp forming presumably because of the proximity of *kerangas* vegetation on adjacent podsolic soils. The continued dominance of *Dacrydium,* and later *Gymnostoma* (from the presence of *Casuarina* type pollen), throughout the peat profile, supports the suggestion of Brunig (1990) that *Dacrydium* and *Gymnostoma* leaf litter may have an allelopathic capacity, retarding the regeneration of other taxa.

Palynological profiles through the Sebangau peat swamp adjacent to the Sebangau river, show an initial development of mixed swamp forest (ph. 1) with common *Pandanus* and *Campnosperma*, over alluvial swamp (Morley, 1981a), probably dating from ~10 ka. Yet, they also show that subsequently the vegetation became dominated by *Dacrydium* (Fig. 6), thus suggesting a *kerapah* swamp, which probably continued to build up until about 6 ka. The youngest peats however, forming after ~2000 bp are dominated by *Calophyllum* and *Combretocarpus* and these are thought to reflect the *Padang* stage of basinal peat swamp. The succession until the end of the *kerapah* phase is very similar to that recorded from the Kutei lakes by Hope *et al.* (2005), with an initial succession with common *Pandanus*, followed by a vegetation with common *Campnosperma*, and subsequently with common to abundant *Casuarina* type (probably from *Gymnostoma*) and *Dacrydium.* The Kapuas lakes succession, analysed by Anshari *et al.* (2001), showed a similar succession, with an initial stage dominated by Anacardiaceae and Sapotaceae, followed by a later stage with *Calophyllum* and *Gymnostoma*.

Because *kerapah* peats are less common than basinal peats, and because there is clear evidence for their decay, it is very likely that *kerapah* peat swamp vegetation was formerly more extensive. It is noteworthy that no peats older than 30 ka have been reported from inland localities in Borneo, suggesting that older peats in interfluve areas were mostly destroyed by oxidation during periods of drier climate such as during the LGM, older peats being preserved mainly in coastal locations where there was subsidence. It was also suggested that *kerapah* swamps may have been widespread across the Sunda shelf in areas which were exposed when sea levels were 50 m below present levels (Slik *et al.*, 2011).

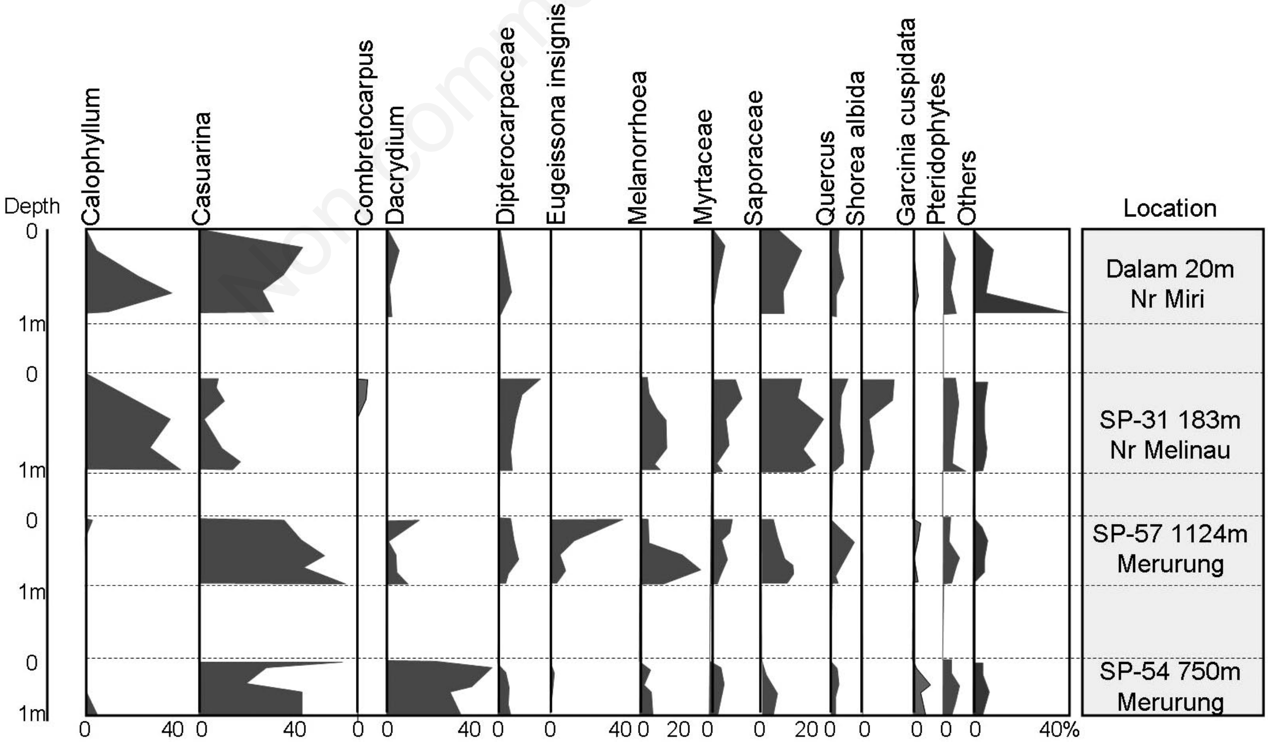

Fig. 7. Palynological successions through four modern *kerapah* peats (Brunig, 1974). Rare taxa excluded, pollen sum *total arboreal pollen*. Dalam, 20 m asl, coastal locality near Miri, Sarawak; SP-31, inland locality at 183 m asl, near Melinau, Brunei; SP-54 and SP-57, inland locality on Merurong plateau, at 1124 and 730 m asl, respectively.

Rheotrophic swamps

Rheotrophic swamps occur widely throughout Southeast Asia, although few have been studied in detail. They vary from large swamps within tectonically controlled depressions (*e.g.* Air Batang Toro swamp in the Semangko rift valley of Sumatra and Tasek Bera in West Malaysia) to infilled volcanic craters (*e.g.* Rawa Danau in West Java), infilled oxbow lakes, and many others. The extensive Berbak swamp in Jambi province, South Sumatra is also likely to be mainly rheotrophic, as it shows a planar, rather than domed succession (Esterle and Ferm, 1994). It is thought that this swamp differs from others due to rapid subsidence in this area, as the oldest peats, dated to just 4250 bp, are now over 5 m below present sea level. Although many rheotrophic swamp settings may rapidly infill with sediment, they may not necessarily all be peat-forming; this discussion will be confined to those swamp vegetation types which are known to develop peats, or detritus muds, and other vegetation types which, it is believed from the fossil record, may have been important in

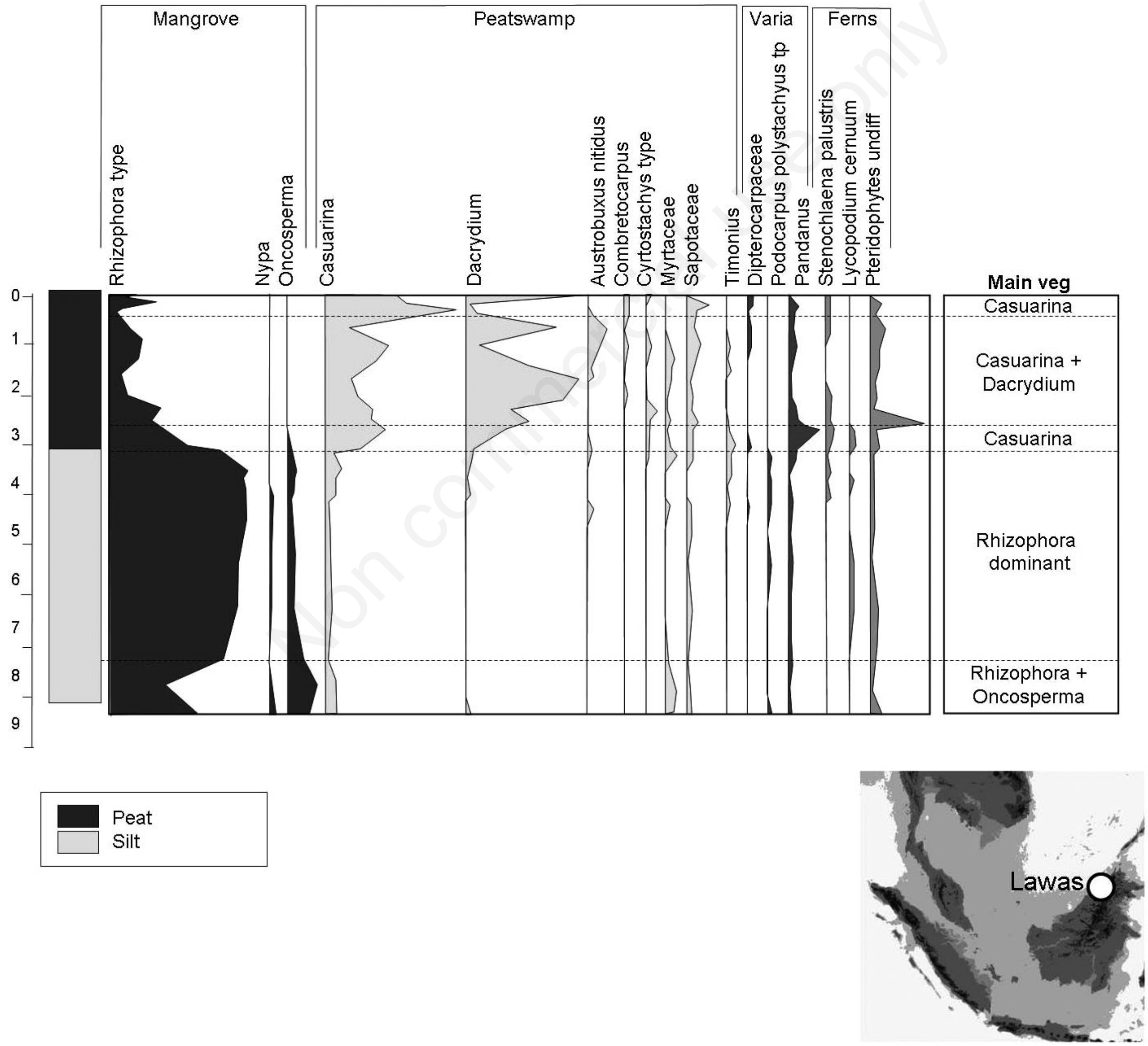

Fig. 8. Palynological analysis through peat and underlying muds at Lawas, Brunei (Muller, unpublished data). Selected taxa are shown only. Pollen sum *total arboreal pollen* except for fern spores which are presented in terms of *total pollen and spores*. Dominant palynological components are indicated on the right.

forming peats during the Tertiary. Alluvial or freshwater swamps are excluded from consideration, since these associations are not peat-forming.

Palm-dominated swamps

The vegetation of the extensive Berbak swamp forest in South Sumatra (Fig. 1d), briefly described by Dransfield (1974), is dominated by rattans (Palmae), including *Calamus, Daemonorops* and *Korthalsia,* together with other palms, such as *Pinanga, Licuala* and *Pholidocarpus.* This is the only known large swamp characterised by common palms. This swamp lies in a coastal setting, behind a wide swathe of *Pandanus helicopus* (Pandanaceae)*,* with *Oncosperma* and *Nypa* occurring (both Palmae) extensively in brackish, coastal regions. The dominance of palms in coastal swamps may therefore be indicative of rheotrophic swamps. Esterle and Ferm (1994) also note extensive areas with mixed swamp forest indicating minor doming, and thus it is possible that in places this swamp is developing into a basinal type ombrotrophic swamp.

Rattans are also mentioned as being important components of vegetation in swamps on the Citarum delta, Java (Van Steenis and Schippers-Lamertse, 1965), in the Rawa Lakbok, in Central Java (Polak, 1950), and in the Opa swamp in South East (SE) Sulawesi (Jacobs *et al*., unpublished report, and rattan *brakes* are recorded in poorly drained areas in Myanmar (Dudley-Stamp, 1925). It is noteworthy that a number of these sites occur in areas with a distinct seasonal climate. Since there are no palynological studies in any of these localities, it is not possible to comment on their contribution to swamp vegetation through time.

Pandanus *swamps*

Pandanus spp. form extensive swamps within blackwater lakes in the Malay peninsula, such as Tasek Bera, and Tasek Chini in Pahang. Tasek Bera is a drowned river valley which began to infill with detritus muds some time after 4500 years ago, (Morley, 1981b, 1982b; Wüst and Bustin, 2004). The lake is acid, although less so than basinal or watershed peats, and has a pH of about 5.5 (Furtado and Mori, 1982). The major part of the area is vegetated

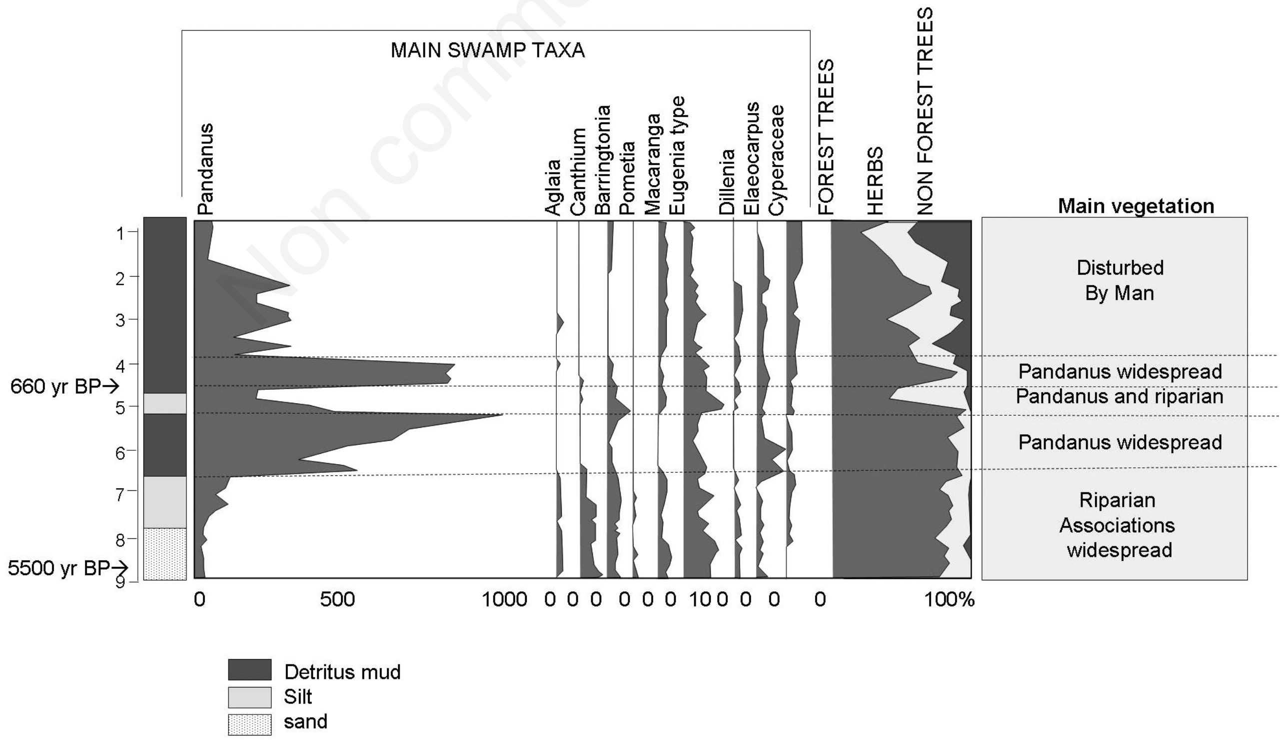

Fig. 9. Summary of palynological analysis at Tasek Bera, Pahang, Malaysia [summarised from Morley (1982a)]. Selected taxa are shown only. Pollen sum *total pollen* excluding *Pandanus*, which is calculated *outside* the sum; note different scale for *Pandanus*. *Aglaia, Barringtonia, Canthium, Pometia* and *Macaranga* are probably components of riparian vegetation.

by a consocies of *Pandanus helicopus* (Fig. 4c), and *Lepironia articulata* (Cyperaceae) marsh is also extensive (Fig. 4d). *Pandanus* spp. were widespread in this location since the initial formation of detrital sediments (Fig. 9), and were in fact much more extensive prior to burning of the vegetation by forest-dwelling peoples during the last 600 years. Before the development of *Pandanus* swamps, the river valley bore a typical streamside vegetation with *Canthium* (Rubiaceae), *Barringtonia* (Lecythidaceae), *Macaranga* (Euphorbiaceae), and *Pometia* (Sapindaceae). Intermittently, *Elaeocarpus* (Elaeocarpaceae) formed a significant swamp element (Morley, 1981b).

Pandanus helicopus swamps occur extensively along a number of river courses on the East coast of the Malay peninsula, such as Sungei Sedili and South Kuantan, and in western Sarawak, and as noted above, seaward of the Berbak swamp in South Sumatra. They also possibly occur in Benkalis (Sewanando, 1938). The widespread *Pandanus* swamps are restricted to coastal areas which are affected by tides, but too far inland to receive brackish influence (Corner, 1978; Morley, 2000).

Swamp forests

Forests growing on rheotrophic peat swamps are widespread, but have been very poorly studied. In West Java, the swamp forest at Rawa Danau includes species of *Elaeocarpus littoralis, Alstonia* (Apocynaceae), *Ficus* (Moraceae), *Lagerstroemia* (Lythraceae), *Eugenia, Ilex* (Aquifoliaceae) and *Barringtonia* among its dominants (Endert, 1932). This locality has been studied palynologically by van der Kaars *et al.* (2001) and shows a succession from open grass-dominated swamp prior to 13 ka, to a swamp forest with *Elaeocarpus*, Moraceae, Dipterocarpaceae and Euphorbiaceae for most of the Holocene, but with *Elaeocarpus* becoming dominant during the latest Holocene. Stands of *Elaeocarpus littoralis* have also been noted in freshwater swamps near Jakarta by van Steenis (1934).

An interesting patchwork of swamp forest communities occurs at Danau *Padang*, a small peat-filled lake basin at 950 m asl in Sumatra (Morley, 1982a). The swamp vegetation at this site can be divided into *Ilex* swamp, dominated by *Ilex cymosa*, which occurs in peripheral areas, and *Myrsine* swamp which is characterised by *Myrsine affinis* and *M. avenis* (Mysinaceae) and occurs close to a central open water area which is surrounded by marsh dominated by *Machaerina rubiginosa* (Cyperaceae). Palynological studies reveal a succession of swamp vegetation at this site. Initially, a swamp forest with *Ilex* and Myrtaceae, surrounding an extensive open water area, gave way to a swamp forest dominated by *Elaeocarpus* sp. This in turn was replaced by *Myrsine* spp. and herbaceous swamp. It is likely that the *Myrsine* swamp reflects a trend toward greater oligotrophy, since there is a close association with the pitcher plant *Nepenthes.*

Brackish peats

Only one example of autochthonous peat-forming settings is known within brackish environments from SE Asia at present day; dense stands of *Sonneratia caseolaris* (Sonneratiaceae) were noted growing on *rather acid, peaty soil* on the eastern coat of North Sumatra (Bunning, 1947). Thin peats are associated with beach ridges on the Mahakam delta (Allen *et al.*, 1979; Gastaldo *et al.*, 1993), but these are allochthonous, and are formed mainly of coarse woody debris carried by water. However, a study of coastal sediments by Yulianto *et al.* (2004) from South West (SW) Sulawesi shows the presence of early Holocene peats which were in part dominated by *Rhizophora* pollen, with subordinate *Avicennia* and *Sonneratia*. Also, a study of the Thale Noi peat swamp, near the Sonkla lakes in South Thailand (Horton *et al.*, 2005) indicates that true mangrove peats developed for a very short period immediately following the early Holocene sea level rise, about 6900 years ago, but were replaced after a short time by mixed swamp forest. Clayey peats dated to isotope stage 4 from near Penang, West Malaysia (Kamaludin and Yakzan, 1997) were dominated by mangrove pollen, suggesting formation within a widespread mangrove swamp, perhaps when this area was an isolated island. Mangroves have thus formed peats during the late Quaternary, although none appear to be forming today.

Mangroves growing on peats are, however, widely reported on oceanic islands in areas of everwet climate, forming above carbonates, in the western Pacific (Ellison, 2009). Similar settings occur in the Caribbean (Spackman *et al.*, 1966).

OVERVIEW OF CENOZOIC HISTORY OF PEAT-FORMING VEGETATION IN SOUTHEAST ASIA

Palynomorph names: Cenozoic pollen types are referred to pollen of extant taxa in cases where determinations are unequivocal, and to form taxa in instances where determinations are questionable, or parent taxa are clearly extinct. The suffix *type* is used if a pollen type is identical to pollen of two or more extant taxa.

Paleocene

The oldest coals examined palynologically from the Southeast Asian region are of Paleocene age, and are noted within the Tabyin-Laungshe formation in Myanmar, and the *Pre-Nimbang* formation from the East Java sea (Reimann and Thuang, 1981; Morley, 2000). Palynomorph assemblages from these coals are dominated by an undescribed trichotomosulcate pollen type which is believed to be from an extinct palm and shows closest morphological similarity to pollen of the central American genus *Gastrococcus* (*Tricolpites* types A-C; Reimann and

Thuang, 1981), and due to the dominance of this pollen type, vegetation growing on peats at this time was probably of very low diversity indeed; none of the remaining pollen types recorded within these coals can be referred to extant plant families (Morley, 2000).

Middle and Late Eocene

Middle Eocene coals from the Nanggulan, Bayar and Ngimbang formations of Java, the Mallawa formation of Southwest Sulawesi and the Tanjung formation of Southeast Kalimantan have been studied palynologically to some degree, although most of this work remains unpublished. The ecological development of Middle Eocene coals is best illustrated by reference to studies of a 50 cm thick coal from the Nanggulan formation in Central Java (Barton, unpublished thesis; Morley, 2000) which has been examined in some detail, with results summarised in Fig. 10. As with the Paleocene, assemblages are dominated by palm pollen, but of markedly different composition. The trichotomosulcate form which dominated older coals is absent, and is replaced by *Palmaepollenites* spp. (Palmae), especially *P. kutchensis*, which is thought to have been produced by extinct members of the tribe Iguanurinae (Harley and Morley, 1995). This group of palms, together with many other taxa, is believed to have dispersed to Southeast Asia from India, following the collision of the Indian and Asian plates in the Middle Eocene (Morley, 1998, 2000) and their appearance is thought to relate directly to the extinction of earlier groups. Other characteristic palm pollen types within this coal are *Calamus* type, produced by rattans, and *Nypa*, together with the form-genus *Proxapertites* spp., thought by Muller (1968) and Morley (2000) to be derived from an extinct group of nypoid palms, but by Zetter *et al*. (2001) more likely from an extinct aroid. Whatever its identity, the succession of *Proxapertites* pollen relative to that of *Nypa* and foraminiferal tests in paralic sediments from many localities suggest an origin from a mangrove plant.

Pollen spectra through this coal show a clear ecological succession. The lower part, and the topmost sample contain regular *Nypa* pollen and *Acrostichum* (Pteridaceae) spores, suggesting brackish influence; the curves for *Nypa*, *Acrostichum*, *Florschuetzia trilobata* (Lythraceae/Sonneratiaceae) and cf. *Lagerstroemia* (Lythraceae/Sonneratiaceae) and *Brownlowia* type (Tiliaceae) follow the same trend with two maxima, and it is likely that the parent plants of the latter taxa also grew under brackish conditions. Iguanuroid palm pollen dominates the upper part, which clearly accumulated under wholly freshwater conditions. Bearing in mind the return of pollen of brackish taxa in the topmost sample, it is likely that peat accumulation was terminated by marine transgression.

Samples examined from other Nanggulan coals are

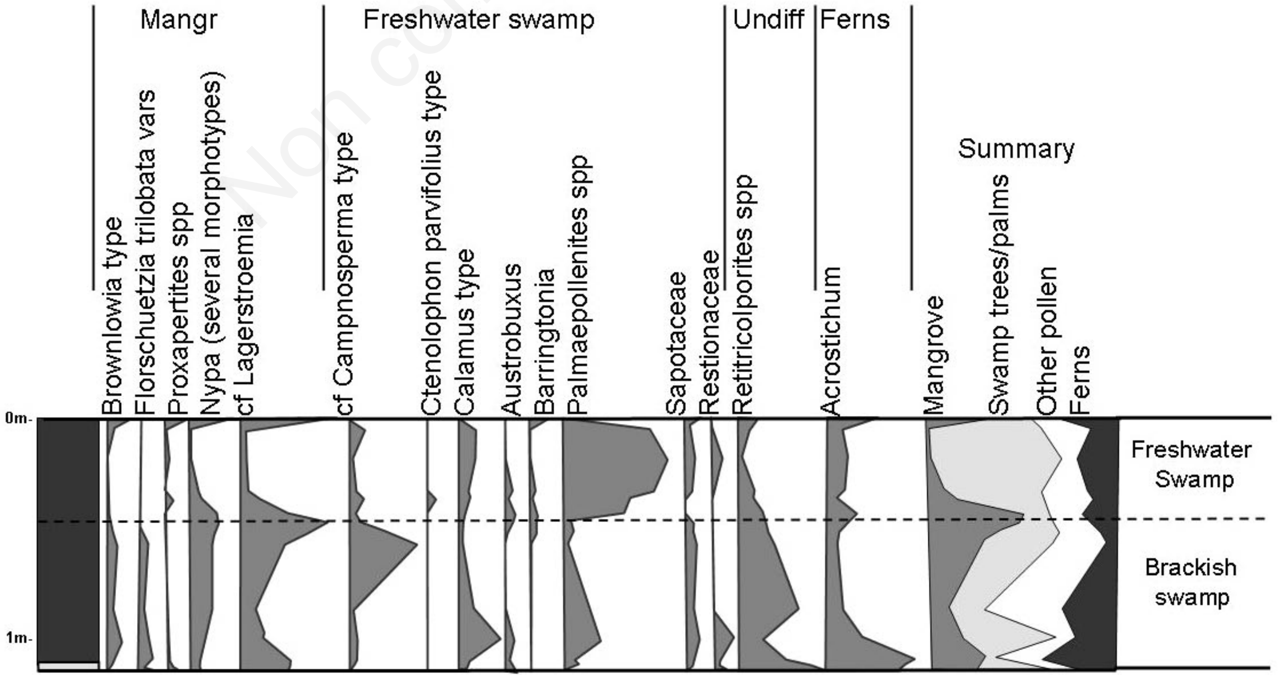

Fig. 10. Palynological analysis of Middle Eocene coal from Nanggulan, Central Java, selected taxa are shown only [from Morley (2000)]. Pollen sum *total miospores*; lithologies are to the left of the diagram.

also rich in pollen of dicotyledonous trees, including a species of Polygalaceae, *Ixonanthes* (Ixonanthaceae), *Ctenolophon parvifolius* (Ctenolophonaceae) and a Sapindaceous tree that produced the pollen type *Cupanieidites flaccidiformis* (closely comarable to some forms of *Mischocarpus*). In general, the diversity of palynomorphs within coals from this formation is considerably less than the diversity of assemblages from adjacent mudstones, suggesting that in the same manner as today, Eocene peat-forming vegetation was less diverse than surrounding dry-land forests. The succession from brackish to freshwater, without evidence for subsequent succession within the freshwater interval that might relate to nutrient availability, is thought to suggest that peat formation occurred in a rheotrophic, rather than ombrotrophic setting.

The palynomorph associations within the above coal are probably typical of most Middle Eocene coals from the southeast margin of Sundaland. For example, thin coals from the Bayar formation in West Java are dominated by pollen of brackish nypoid palms (or extinct aroids), whereas some coal samples from the Mallawa formation in Southwest Sulawesi proved to be dominated by pollen of iguanuroid palms.

Coals of Late Eocene age have been examined from the Tanjung formation in southeast Kalimantan (Dettmann and Playford, unpublished report; Witts *et al.*, 2012), from the latest Eocene of the Mangkalihat peninsula (Morley, 2000), and from the Yaw formation of Myanmar (Potonie, 1960). The Tanjung coal studied by Dettmann and Playford (unpublished report) was 7 m thick, with the seam base accumulating in a wholly freshwater setting, but with brackish influence being present in the upper part, and with peat accumulation presumably ceasing due to marine transgression. The Mangkalihat coals, which are from a number of poorly exposed outcrops of uncertain stratigraphic relationship, are dominated by pteridophyte spores, suggesting a much more open, herbaceous vegetation, with subordinate iguanuroid palms and rattans. *Nypa* pollen and *Proxapertites* occur in low frequencies, suggesting some brackish influence. In addition, these coals contain common *Meyeripollis naharkotensis* (possibly Myrtaceae), which, from its fossil distribution, occurring commonly in association with coaly lithologies, but virtually absence from areas of seasonal palaeoclimate, is believed to have been produced by a swamp-forest tree. Rattan pollen (*Calamus* type) was dominant in the coal sample analysed by Potonie (1960) from the Yaw formation of Myanmar, suggesting an open vegetation with palm thickets. Each of these coals is likely to have formed in a rheotrophic setting.

Oligocene

There was a major change to monsoonal, or seasonal climates at the end of the Eocene, which affected a major part of the region of Southeast Asia (Morley, 1998, 2000, 2012). Coal-forming environments through most of the Oligocene, until the Late Oligocene thermal maximum, were of very restricted occurrence. Extensive Oligocene coals are known only from the Sawahlunto formation (Ombilin basin), where they form part of the initial rift infill sequence (Koesoemadinata and Matasak, 1981) and from the Pematang formation of Jambi province. The Sawahlunto coal grades laterally into lake deposits (Wateley and Jordan, 1989), and is also rich in algal remains, such as *Pediastrum* spp. Therefore, the Sawahlunto coal most likely formed from a rheotropic, eutrophic peat. The limited data obtained from this coal suggests that Iguanurinae and ferns were important members of peat-forming vegetation (Bartram and Nugrahaningsih, 1990), but details of the vegetational succession remain poorly known.

Thin coals are recorded from the early Oligocene Pematang formation in Central Sumatra, and palynological analyses demonstrate that these are characterised by abundant fern spores, in particular, the Schizaeaceous *Cicatricosisporites dorogensis,* and spores of the rooted or floating fern *Ceratopteris* (Parkeriaceae), which occur together with pollen of *Oncosperma*, *Barringtonia* and *Alchornea* (Euphorbiaceae) (Pribatini, unpublished thesis). These thin coals are believed to be the remains of localised rheotrophic peats or lake muds which formed in shallow depressions, perhaps in oxbow lakes at a time when the climate was distinctly seasonal. Similar very thin coals have been noted from well logs through the earliest Miocene of the Malay basin, and cuttings from these horizons also contain common spores of *Ceratopteris*. These also are believed to be rheophytic infill deposits, again possibly reflecting ephemeral oxbow lakes or ponds.

The Eocene palm-dominated swamp flora seems to have largely disappeared through the course of the Oligocene, possibly as a result of extinction following Oligocene climatic change, but equally may be due to habitat loss, since brackish peat mires would have been very poorly represented during the earliest Oligocene since everwet climates were of very restricted occurrence at that time.

Widespread peat formation recommenced at the time of the Late Oligocene thermal maximum, when extensive peats formed along the south coast of Sundaland, represented by coals within the upper part of the Talang Akar formation in South Sumatra, and lateral equivalents recorded in the subsurface of the Sunda and Arjuna basins in the West Java sea area, and also within the *Coaly* Cau formation of the Nam Con Son basin, south of Vietnam (Morley and Swiecicki, 2011) which formed along the eastern coast of Sundaland landmass (Morley, 2012).

The Talang Akar coals are mostly characterised by the presence of common to dominant *Casuarina* type pollen, and also *Dacrydium* pollen. The common occurrence of both *Casuarina* type (probably from *Gymnostoma*) and *Dacrydium* pollen suggests that these coals were probably derived from *kerapah* type peats, which must have been of very extensive occurrence from South Sumatra eastward at this time, and reflect two successive periods of very wet climate, probably as sea levels rose at the time of the Late Oligocene thermal maximum. These coals were thus of the ombrotrophic type. *Kerapah* peat swamp forest with *Gymnostoma* and *Dacrydium* is therefore a very ancient plant community. Studies from marine sediments in East Java (Lelono and Morley, 2011) indicate that these pollen types are associated back to the base of the Oligocene.

In addition to *Dacrydium* and *Casuarina*, Talang Akar coals are also rich in *Calamus* type pollen, suggesting that the swamp vegetation was rich in rattans, and locally, *Pandanus* pollen is common, perhaps reflecting rheotrophic swamps.

The Nam Con Son *coaly* Cau formation coals also formed within a coastal setting, but closer to the palaeo-coastline in reach of brackish influence, and are thought to contain abundant (back) mangrove pollen of the form species *Florschuetrzia trilobata* (ancestral *Sonneratia*). This judgment is not certain, since these coals have been examined only in cuttings, rather than core.

Miocene

A major climatic change occurred through most of the region of Southeast Asia at the beginning of the Early Miocene (Morley, 2006, 2012) with the onset of the East Asian monsoon, at which time everwet climates became much more widespread. Peatlands must have been very extensive because, from the basal Early Miocene onward, coals are widely represented in the sedimentary records of many Southeast Asian basins, especially the West Natuna and Malay basins through the West Natuna Arang and Malay basin *Sand/Coal* formations.

Kerapah *peats*

Kerapah peats were important progenitors of coal throughout the Early Miocene of several Sunda shelf basins, including West Natuna, Penyu and Malay basin. In each of these basins, successive acmes of *Casuarina* type and *Dacrydium* pollen occured through the Early Miocene, associated with the early stages of successive depositional sequences, especially within Malay basin seismic group I and its lateral equivalents (Shamsudin and Morley, 2006), and then, following the mid Miocene thermal maximum, within seismic group E sequences (Morley, unpublished material). These acmes reflect periods of expansion of either *kerangas* vegetation or *kerapah* swamp, but in instances where coals are present and which have been sidewall cored, the coals typically yield common *Casuarina* type and *Dacrydium* pollen, suggesting *kerapah* swamp. In several instances from the Early Miocene of West Natuna, meandering channel deposits were sidewalled, anticipating channel sands, but the channels proved to be coal-filled, and the coals were dominated by *Casuarina* type pollen, again suggesting *kerapah* swamps infilling valleys, presumably at times of sea level rise when incised channels may have been abandoned.

Demchuck and Moore (1993) studied a thick Middle Miocene coal, the Sarongga lignite from Southeast Kalimantan (Fig. 11). This coal is over 20 m thick and Demchuck and Moore (1993) suggested that it formed from vegetation which was virtually identical to modern peat-forming vegetation in Indonesia. They interpreted three palynological assemblages, but emphasised that due to the coarseness of the sampling interval, it was doubtful that these zones reflected a floral succession in the sense of modern peats, but that they reflected large-scale successional changes which were a product of long-term ecological shifts and changing depositional conditions within the original mire. The most distinctive feature of the Sarongga diagram is the regular occurrence of *Casuarina* and *Dacrydium* pollen, clearly suggesting an affinity to *kerapah* peat swamp forests rather than basinal peats, and also suggesting that the Sarongga peat formed as a drape, or as a result of drainage impedance during a prolonged period (or periods) of heavy rainfall. The profile also yields some mangrove pollen, which consistently increases in representation, thus suggesting that the peat also formed during a long period of rising sea levels or a succession of phases of rising sea levels followed by marine transgressions. Similar thickness coals in the Latrobe valley in Australia have been shown to reflect successive depositional phases on a sequence scale (Holdgate *et al.*, 1995). For the Sarongga coal, however, insufficient data is available on rates of sediment accumulation to determine whether there were similar controls with respect to thick coals in Kalimantan.

The conclusion to be reached from the Sarongga coal is that that the formation of very thick, Tertiary peats probably coincided with periods of prolonged high rainfall, and rising, or intermittently rising sea levels, and not to short-lived periods of stable, but high sea levels, as is the case with Quaternary and Carboniferous peats, and this may indicate the reason why there are parallels between many Carboniferous and Quaternary peats, but seemingly less so with Cenozoic coals.

Very thick, Middle and Late Miocene coals to the northwest of Samarinda in Kalimantan were studied for geochemistry by Widodo *et al.* (2009). They recorded several biomarkers which reflect the nature of the peat forming vegetation, and these included bicadinene, which is thought to be a geochemical derivative of resins from members of the family Dipterocarpaceae (van Aarssen *et al.*, 1990, 1994). They also used the ratio of diterpenoids *vs* diterpenoids+triterpenoids as an indicator of the proportion of angiosperms *vs* gymnosperms within the peat forming vegetation, following Bechtel *et al.* (2002), and demonstrated that during the Middle Miocene and earliest Late Miocene, gymnosperms were likely to have been major contributors to the peat swamp vegetation, but that they contributed little to later Late Miocene peatswamp vegetation. They interpreted this trend as indicating cooler climates during the Middle and early Late Miocene, in contradiction to global climate trends (Zachos *et al.*, 2001). More realistically, the dominance of gymnosperm indicators in the Middle and early Late Miocene suggests that peats formed at this time were *kerapah* peats, with *Dacrydium* and possibly *Agathis* being important components, but that later Late Miocene peats formed in more basinal peat swamp settings (see below).

Basinal peats

Palynological analyses show that during the later part of the Early Miocene there was an increase in the representation of taxa typical of modern peat swamps, such as *Melanorrhoea* (Anacardiaceae), *Durio* (Bombacaceae), *Blumeodendron* and *Neoscortechinia* (Euphorbiaceae), *Calophyllum, Garcinia cuspidata type* (Guttiferae), and *Gonystylus,* first brought to attention by Muller (1972). This is thought to reflect the expansion of basinal peats from this time onward. Anderson and Muller (1975) went on to analyse in detail a 1 m thick coal from Berakas in Brunei to determine whether parallels could be seen between the succession in a Miocene coal and that reported from Holocene peats (Fig. 12). They suggested an age of about 7 million years (Ma) for the Berakas coal, on the basis of the rarity of *Florschuetzia trilobata*, which is probably an underestimate. It is likely that the rarity of *Florschuetzia* spp. in this section is due to the freshwater

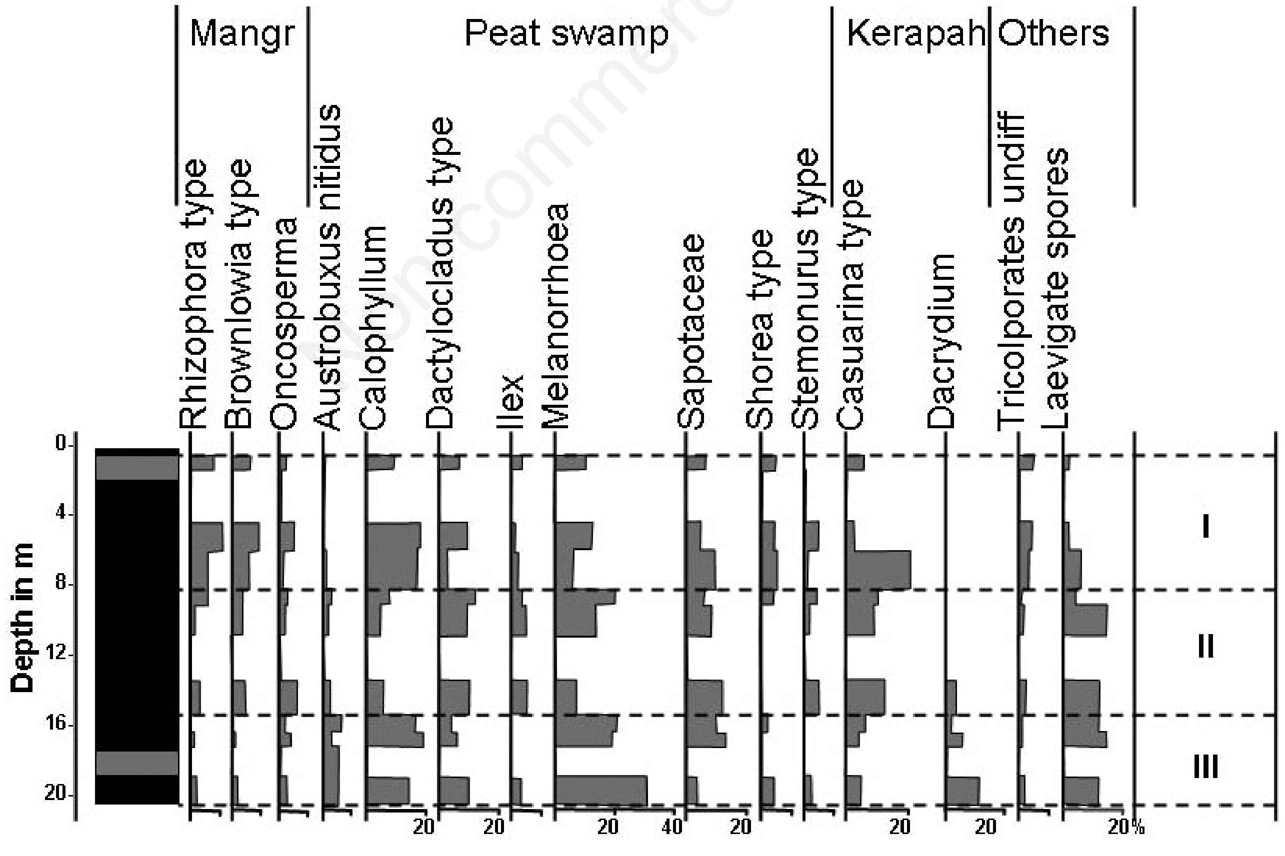

Fig. 11. Palynological analysis of Sarongga coal, Early/Middle Miocene, East Kalimantan [summarised from Demchuck and Moore (1993)]. Lithologies: grey=shale; black=coal.

facies; the presence of common *Stenochlaena areolaris* (Blechnaceae), and absence of *S. milnei* type suggests that the age is more likely to be a little older than 10 Ma (Morley, 1991, 2000), probably latest Middle Miocene.

Anderson and Muller (1975) emphasised that the similarity between the palynomorph spectra from the Berakas coal and the Holocene peat from Marudi suggested a close relationship between the Middle Miocene peat swamp flora and the flora of present day basinal peat swamps. There is, however, a major difference which was not previously brought to attention; the diversity of the peat swamp element in the Berakas section was markedly less than in the Marudi profile (Berakas, 28 pollen types in a count of about 15,000; Marudi, 40 pollen types in a count of about 3000), and bearing in mind that indeterminate pollen types were excluded from consideration, the similarity between the two successions was probably overestimated.

The Berakas coal (Fig. 12) clearly illustrates three separate intervals of peat buildup (A-C), the first being terminated by a phase of apparent disturbance, and subsequent phases being terminated by marine transgression, with the third transgression overriding the peat, and depositing beach sands. Within each of these phases of peat buildup, Anderson and Muller (1975) suggested that the peat-forming vegetation never passed beyond ph. 1, in particular by the common occurrence more or less throughout of *Durio* pollen. The absence of more advanced phasic communities was also explained by the low representation of *Shorea albida* [which may have been present in the Middle Miocene, as leaf fragments recorded from Middle Miocene of East Kalimantan, near Samarinda (nannofossil zone NN5) closely resembled *S. albida* (Morley and Morley, 2010)]. The upper part of peat buildup B contains abundant *Cephalomappa* pollen, and locally reduced pollen of *Durio*. C*ephalomappa beccariana* is more typical of deep peat within ph. 1, and also in ph. 2-4. There is a strong possibility that a more advanced stage within the peat swamp catena is represented between 43 and 49 cm.

The different sampling strategies employed for the study of the Berakas by Anderson and Muller (1975), the Sarongga and Nanggulan coals, and the Marudi peat are compared in Fig. 13 by assuming a 1:7 compaction ratio for Cenozoic coals. The comparison provides a guide as to the sampling densities needed in order to differentiate veg-

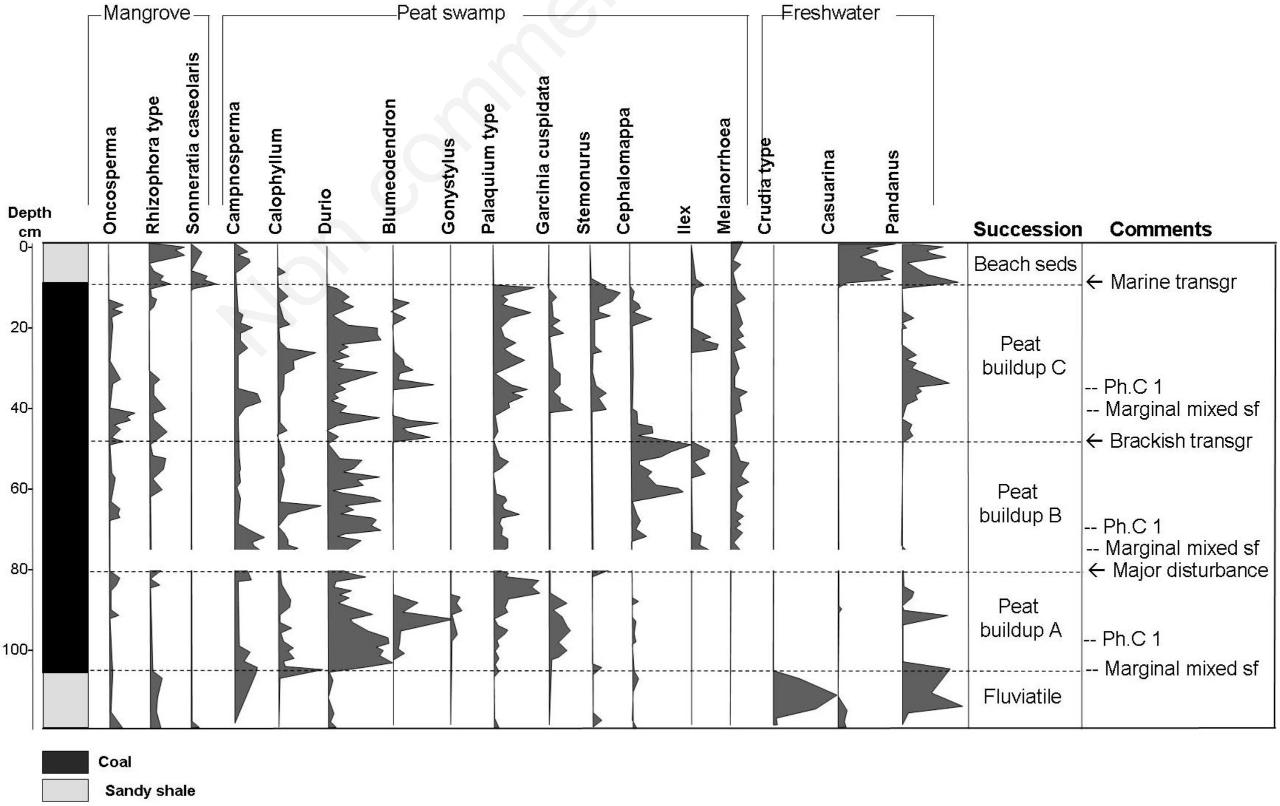

Fig. 12. Summary of palynological analysis of Middle/Late Miocene Berakas coal, Brunei (Anderson and Muller, 1975). Lithologies are to the left of diagram.

etational successions in sufficient detail to permit the differentiation of ombrogeny. The very closely spaced 1 cm samples from the Berakas coal (each equivalent to 7 cm of peat accumulation; Anderson and Muller suggested something less than 1:10) were sufficient to pick out individual tree generations; the 50 cm sample spacing in the Marudi peat facilitated the differentiation of phasic communities, whereas the 50 cm-2 m *crushed interval samples* from Sarongga (equivalent to 3.5-14 m of peat) were sufficient to pick out only the broadest, regional succession.

Rheotrophic peats

Calamus type pollen is common in many coals within the Early Miocene, but is much less well represented in Middle Miocene and younger coals. In 1972, an Early Miocene shaley coal from the Kerinci area of Sumatra was collected by the author and sent to the late Jan Muller for analysis. This coal also proved to be dominated by *Calamus* type pollen. (Muller, personal communication), but unfortunately the detailed results of this study were never published. However, based on comparisons with present day swamps, it is likely that the peat which formed the coal accumulated in a rheotrophic swamp setting. Rattan pollen-dominated successions rich in coals were widespread, especially during the Early Miocene, and hence rheotrophic peat-forming swamps could have been widespread at this time. Rattan-dominated swamp successions often occur in sedimentary successions which suggest slight seasonality of climate.

Fern-dominated peats

Fern spores are often prominent elements in the initial stages of both basinal and *kerapah*/watershed peat development. Sometimes the basal part of a coal is dominated by spores of the climbing fern *Stenochlaena palustris*, and it is of note that when peat swamp forests are felled, the initial growth is often of *S. palustris*, prior to the establishment of tree cover. Sometimes other fern spores may

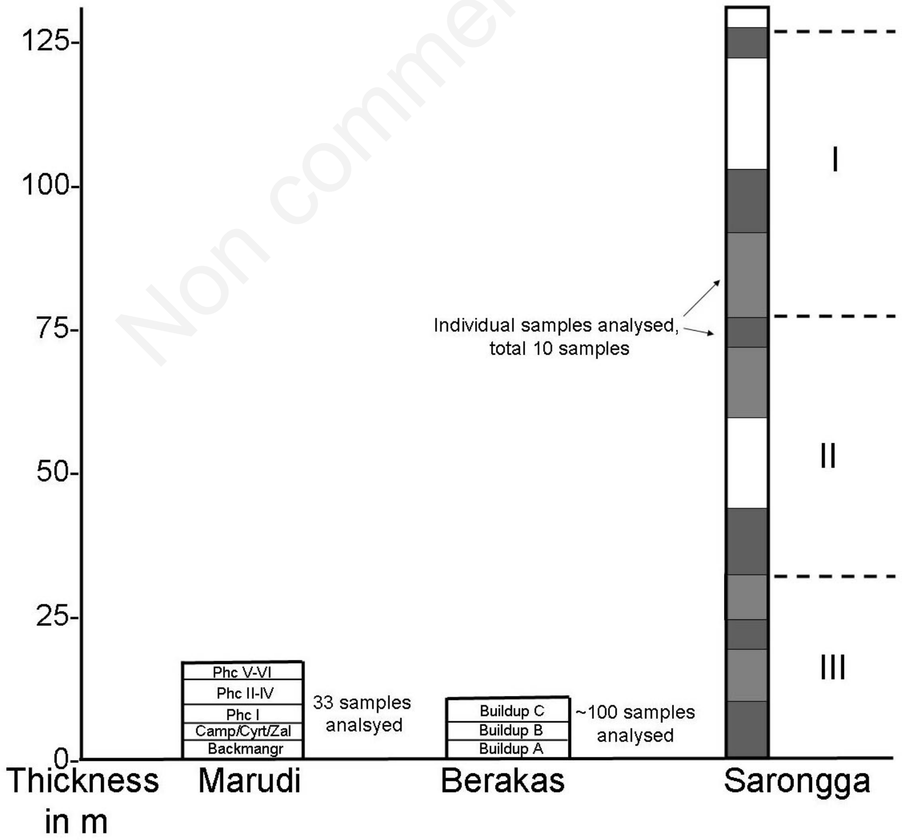

Fig. 13. Estimated decompaction thicknesses for Southeast Asian coals.

be prominent, either of the *Nephrolepis* type, or undifferentiated laevigate fern spores. The basal horizon of the Sebangau peat was characterised by abundant fern smooth spores (Morley, 1981a).

Barringtonia *peats*

These have been reported from the Early Miocene of the Malay basin, and the Middle Miocene Warukin formation in SE Kalimantan and probably reflect peats which formed under an everwet climate in localities which exhibited extreme seasonal flooding. No present day analogues are known.

Mangrove peats

Thick, Middle Miocene coals and carbonaceous shales from the Belait formation of Brunei sometimes contain extremely high frequencies of *Rhizophora* type pollen (Gupta, unpublished report). A profile through a typical section (Fig. 14) shows that the carbonaceous shales accumulated in a very widespread mangrove swamp, whereas the peats which formed the coals accumulated in a slightly saline backmangrove, or possibly intertidal, but freshwater setting, based on the common occurrence of *Sonneratia* and *Pandanus* pollen.

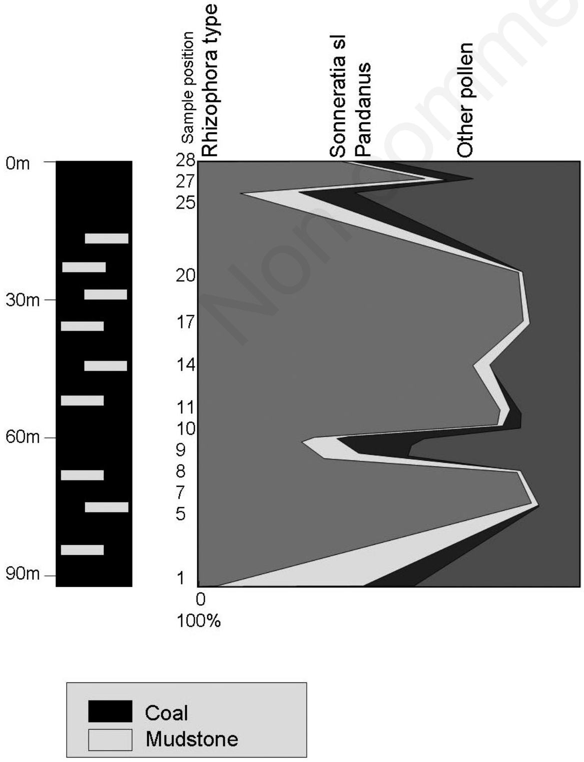

Fig. 14. Summary of palynological analyses of a coal and carbonaceous shale from Subok, Belait formation, Brunei (Gupta, unpublished report).

Thick (5 m) and very widespread coals occurred in the Late Miocene of the Malay basin, marking the end of seismic group E. These were analysed palynologically (Shamsudin *et al*., 2011) and were also shown to be overwhelmingly dominated by *Rhizophora* type, Sonneratioid and *Pandanus* pollen, as with the Belait coal analysed by Gupta (unpublished report). The palynological succession showed successive alternations of mangrove pollen and *Pandanus*, suggesting that the coal is most likely formed from a stacked succession of peats, formed during perhaps five successive sea level oscillations.

Nypa peats have been reported in the Miocene of the Warukin formation (Witts *et al.,* 2011). They reflect periods of peat accumulation in areas of oligotrophic coastal water (devoid of nutrients) within a slightly brackish setting. No present day analogues are known. *Brownlowia* peats have been reported from the same area, and possibly reflect peat swamp accumulation in a freshwater but intertidal setting. Again, no present day analogues are known.

Coals rich in mangrove pollen have also been reported from limestone-dominated successions (Cole, 1987), for instance, from the Middle to Late Miocene Kais formation in Irian Jaya (Hendardjo and Netherwood, 1986), and similar age limestones from the Banggai-Sula area. Cole (1987) termed these *archipelagic* mangrove peats. Peats forming on limestones are unknown today in Southeast Asia, but occur on Pacific islands, as noted above, and also are well documented in Florida by Spackman *et al.* (1966), where they also appear to have formed in a mangrove environment, and clearly provide a close analogue to *archipelagic* coals.

DISCUSSION

At the present time, lowland Southeast Asian peats are forming mainly as ombrotrophic, oligotrophic basinal peats and *kerapah* peats, the latter characterised by the presence of *Gymnostoma* and *Dacrydium* as prominent elements of the tree flora. Rheotrophic peats tend to be geographically isolated, and also of restricted occurrence, although there are some extensive rheotrophic peat swamps. Palms, especially rattans, are prominent elements of present day rheotrophic peats. Brackish peats are rare, but were more widespread during the Holocene than today.

During the Cenozoic, the representation of these peat types differed substantially from that of the present day as follows (summarised in Tab. 1): i) during the early Cenozoic, transitional, brackish to freshwater rheotrophic peats were widespread, especially in the Middle to Late Eocene; ii) rheotrophic peats probably developed within the initial stage of infilling of Oligocene grabens, provided that the climate was favourable for peat formation. Otherwise, peat development was very limited until the Late Oligocene thermal maximum, during which time *kerapah* peats formed extensively along the southern coast of Sundaland, and brackish peats with common *Florschuetzia trilobata* pollen formed along the eastern coast; iii) *Kerapah* peats were very prominent during the Early and Late Miocene around the basins of the northern Sunda shelf, but seem to have been poorly represented in that area during the Middle Miocene thermal maximum. Many of the very thick coals observed in the Middle Miocene of Kalimantan are probably of this type; iv) basinal peats are probably widely preserved as coals from the Early Mocene onward, but became prominent from the Middle Miocene. Although few have been studied in detail, there is weak evidence for a vegetational *catena* from the Berakas coal studied by Anderson and Muller (1975), but otherwise no examples of a clear succession comparable to the succession seen in the domed peats of today have yet been reported. However, no thick peats have yet been studied so as to reveal the presence of doming; v) mangrove peats also formed extensively in the Middle and early Late Miocene in the Sunda shelf region. They also developed locally in Eastern Indonesia over carbonates, perhaps in settings analogous to those observed today on carbonates in Florida.

The floristic character of peat-forming vegetation has clearly changed during the course of the Tertiary. Paleocene and Eocene peats were mainly vegetated with palms, and many elements of the Eocene rheotrophic peat swamp floras became extinct during the Oligocene. Eocene peats also bore a rich vegetation of fresh and brackish water palms, which included *Nypa*, rattans, and extinct palms within the tribe Iguanurinae. Several other peat-swamp trees were also present at this time, such as *Ctenolophon*, and possibly *Durio*. Rattans formed conspicuous elements of peat-forming vegetation until the Early Miocene.

Peat-forming vegetation of more modern aspect first became established within the Late Oligocene, initially with *Dacrydium* and *Gymnostoma* (indicated by *Casuarina* type pollen) growing on widespread *kerapah* type swamps. The typical elements of modern basinal peats such as *Blumeodendron, Calophyllum, Combretocarpus, Dactylocladus, Garcinia cuspidata, Neoscortechinia* and *Melanorrhoea* became prominent principally in the Early and Middle Miocene. Greater diversity seen in present day *kerapah* peats compared to basinal may relate to the much greater geological age of *kerapah* peats.

Tab. 1. Generalised representation of peat forming environments over time.

	Basinal peats	*Kerapah* peats	Rheotrophic peats	Mangrove peats
Present/Late Pleistocene	Widespread after sea level stabilised	Limited today, widespread as sea levels rose	Extensive swamps locally, but mostly small, with *Pandanus*, rattans	Rare in Sunda, sometimes on oceanic islands
Late Miocene	Probably widespread but little-studied	Widespread in Kalimantan	*Pandanus* peats associated with mangrove peats	Thick peats in Malay basin, insular peats in Papua, Sulawesi
Middle Miocene	Widespread across region	Widespread from Sunda shelf to South Kalimantan	Rattan peats reduced, some *Barringtonia* peats	Extensive in Brunei, *Nypa* peats in SE Borneo
Early Miocene	Become common in later Early Miocene	Widespread around inland seas of N Sunda shelf	Rattan peats widespread, some *Barringtonia* peats	
Late Oligocene		Extensive along southern coast of Sundaland	Rattan peats along southern Sunda coast	*Florschuetzia* peats along eastern coast of Sundaland
Early Oligocene			Peat formation rare. Occ. palm and fern swamps in C Sumatra	
Late Eocene			Rattan swamps in Burma. Palm and *Meyeripollis* swamps in Java, Kalimantan	*Nypa* swamps in Java, Kalimantan
Middle Eocene			Palm-dominated swamps in Java	*Nypa*/*Florschuetzia* swamps in Java
Paleocene			Palm dominated swamps in Java sea area	

SE, South East; C, Central.

CONCLUSIONS

At the present time, peat swamps are undergoing widespread destruction from timber extraction and land conversion across the region. This review emphasises the antiquity and longevity of peat swamp communities from a deep-time perspective, and especially highlights the importance of *kerapah* peats as one of the most ancient vegetation types in the region, which, in fact, is given minimal specific consideration from a conservation point of view. The review also emphasises the importance of differentiating rheotrophic from oligotrophic swamps, also rarely taken into consideration by conservationists, and brings to the fore the importance of conserving areas such as the Berbak swamps in Sumatra, and Tasek Bera in the Malay peninsula.

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