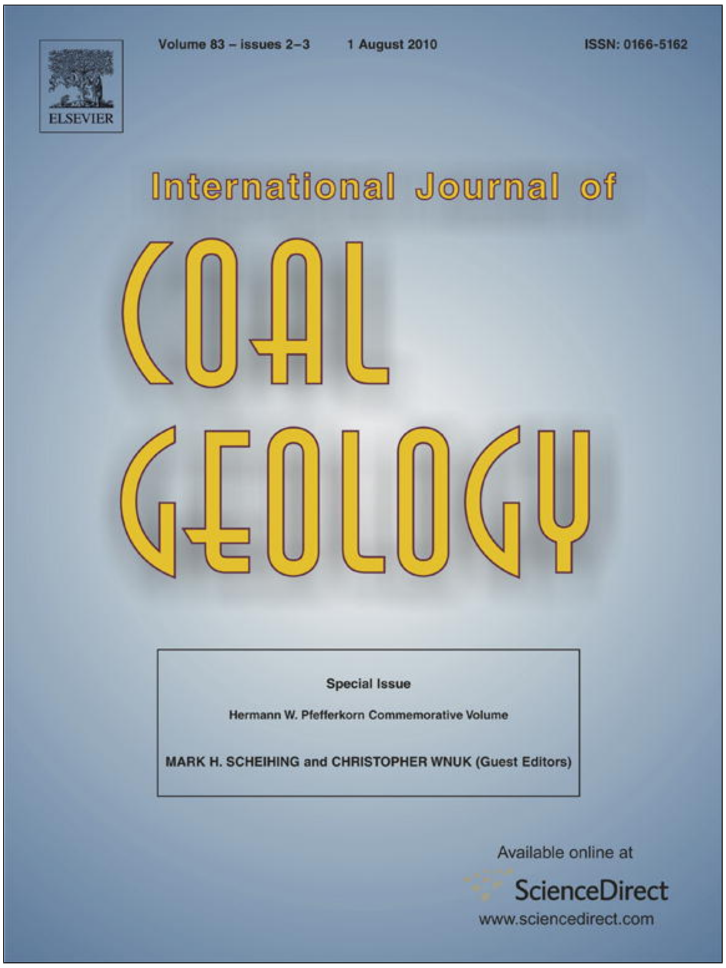
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Peat or no peat: Why do the Rajang and Mahakam Deltas differ?

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ABSTRACT

Coastal and deltaic Holocene peat accumulations around the equatorial island of Borneo, Southeast Asia, have served as models for economic coal-bearing sequences in the stratigraphic record. Although climatic conditions, vegetational communities, and sedimentary regimes are comparable, peat accumulations are not found on both the western and eastern sides of the island. The Rajang River delta and coastal plain, Sarawak, East Malaysia, are covered in areally extensive, thick peat deposits that have attained at least a thickness of >13 m in ombrogenous peat domes (Marudi, Baram River). Peat-swamp biomass began to accumulate over Pleistocene podzols when sea level stabilized ~7.5 ka and delta progradation was initiated. The Mahakam River delta and coastal plain, East Kalimantan, Indonesia, also began progradation at this time, but there is no evidence in any part of the coastal region for peat accumulation. Rather, poorly developed organic-rich gleysols occur throughout the delta plain. Both the Rajang River and Mahakam River deltas are tidally influenced, fine-grained systems, with a sediment provenance in the Central Massif. Sediment transported through the Rajang River delta differs in that as much as 60% of the clay minerals deposited in the system are mixed layer (I/S) and expandable (K/E) clays that act to restrict pore water flow in the tidal and overbank deposits that comprise the delta plain. These result in the development of an aquiclude above which paludal conditions develop, promoting accumulation of organic matter. In contrast, there is a low proportion of mixed layer and expandable clays transported in the Mahakam River system. This precludes the development of a stilted water table within the delta, allowing for organic matter recycling without peat accumulation. The presence of a high proportion of expandable clay minerals on the western side of Borneo is a reflection of the weathering and eroding source rocks on this side of the Central Borneo Massif.

1. Introduction

Models for the development of extensive peat accumulations (histosols) have been published based on studies of Holocene coastal–deltaic regimes, ranging from the Northern hemisphere subtropics (*e.g.*, Kosters et al., 1987; Cohen, 1984; Staub and Cohen, 1978, 1979) to the tropics of Central America (*e.g.*, Cohen et al., 1989; Cohen and Stack, 1996) and South America (Wagner and Pfefferkorn, 1997; Aslan et al., 2003), and Southeast Asia (*e.g.*, Supiandi, 1988; Staub and Esterle, 1994; Supardi et al., 1993). These studies have been used to better understand and constrain the genesis of economic coals and the sedimentology of coal-bearing sequences in the stratigraphic record (e.g., McCabe, 1984, 1987; Cecil et al., 1993; Edgar et al., 2003). It is recognized that an interdependence of factors controls the accumulation of organic matter as ombrogenous peat in various terrestrial depositional settings. These include the contribution of organic matter (OM) within a landscape where: (1) a high, reducing and oxygen-deficient water table persists (McCabe, 1984; Kosters et al., 1987) dependent upon prevailing hydrological conditions (Gore, 1983; Moore, 1987); (2) there is a differential rate between organic matter (OM) production and decay (Belyea and Clymo, 2001); (3) the underlying peat composition controls the standing vegetation (Page et al., 1999); and (4) a climate of everwet (perhumid) conditions prevails (Cecil and DuLong, 2003). Nevertheless, even when these conditions might be satisfied, there is a complex interplay between the rates of OM accumulation and siliciclastic deposition over various temporal and spatial scales that affect peat accumulation. Such processes will influence whether OM will be concentrated with a moderate silt or clay component forming a peat, or concentrated with a moderate silt or clay component, forming a peaty muck or muck (Wüst et al., 2003). But, there is one additional factor that ultimately controls whether or not paludal conditions develop within which OM can accumulate as a true peat. The composition and porosity of the subjacent sediments are an overriding constraint because there is no chance for OM to avoid complete decay and re-utilization without a mechanism to maintain a high regional or stilted water table (paludal conditions) in which anoxic and reducing conditions are maintained. When significant water-table fluctuations occur across the landscape, such as during extended periods of low or no rainfall, the introduction of oxygenated waters to the subsurface promotes bacterial activity and oxidation of buried matter negating any chance for peat formation.

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Thick, areally extensive Holocene peat bodies in Southeast Asia have been used as a model over the past century for the development of economic coals (see Potonie, 1909, 1920; Stevenson, 1913; White and Thiessen, 1913). The initiation of Recent OM accumulation began soon after sea level stabilized as delta and coastal plain progradation commenced, sometime between 8.5 and 6.5 ka (Stanley and Warne, 1994). Since then, separate geographic areas within the region have witnessed peat accumulation to thicknesses in excess of 7 m (*e.g.*, Sarawak — Staub and Esterle, 1994; Indonesia — Neuzil et al., 1993; Peninsular Malaysia — Wüst and Bustin, 2004), with some domed peat deposits attaining a thickness of >13 m (Anderson and Muller, 1975). But, although the everwet climate on Borneo supports a coastal dipterocarp forest (MacKinnon et al., 1996; Maury-Lechon and Curtet, 1998), the principal taxa that contribute organic matter to organic-rich soils and peat are not found in every coastal area. The contrast between peat-accumulating and non-peat-accumulating interfluves and coastlines is best exemplified between the near-equatorial Rajang River delta, Sarawak, Malaysia, and the Mahakam River delta, Kalimantan, Indonesia, on the opposite sides of the island of Borneo. The purpose of this paper is to provide an explanation for this enigma.

2. Rajang River Delta

2.1. Physiographic setting

The Rajang River delta, located in the East Malaysian state of Sarawak on the western side of Borneo (Fig. 1), is a tropical, peat-dominated coastal plain system that occurs in an embayment formed by the folded Mesozoic and Cenozoic strata of the Central Borneo Massif (Fig. 2; Staub and Esterle, 1993; Staub and Gastaldo, 2003).

The delta plain and river valley upstream cover an area of approximately 6900 km^2 and include an alluvial valley floodplain (approximately 400 km^2), an "abandoned" tidally flushed delta plain, and an actively accreting, rectilinear delta plain (combined area approximately 6500 km^2). The main trunk of the Rajang River follows a relatively straight path through the Central Borneo Massif, drains an approximately 50,000 km^2 area (Staub and Gastaldo, 2003), and begins to bifurcate in a rectilinear pattern at the approximate position of the town of Sibu (Fig. 3). The resultant main distributaries are, from the southwest to northeast, the Rajang, Belawai, Paloh, Lassa, and Igan.

The influences of tides and waves along the Sarawak coastline vary in response to the topography of the adjacent shelf in the South China Sea. Semi-diurnal tides within the Rajang River delta range from

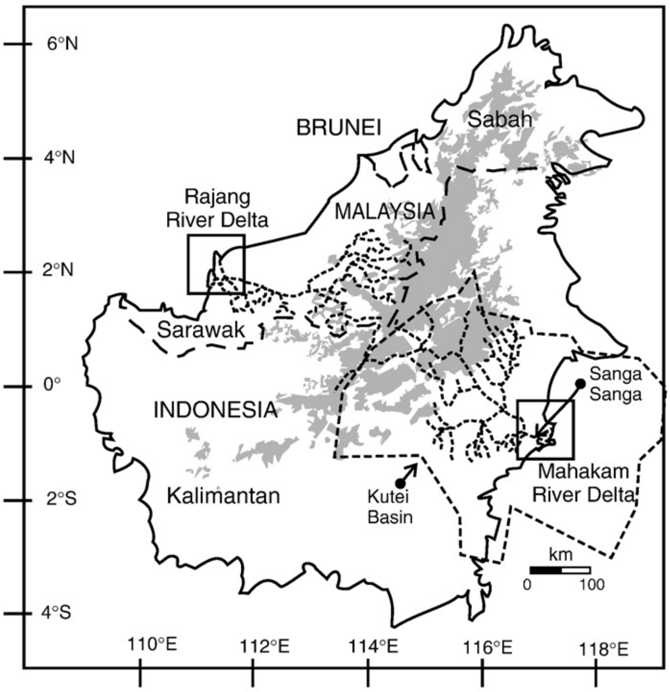

Fig. 1. Outline map of the island of Borneo on which the Rajang River Delta, Sarawak, East Malaysia, and the Mahakam River Delta, Kalimantan, Indonesia are illustrated. Rivers in each drainage basin are depicted in dashed lines; gray polygons represent the Central Massif where elevations are >500 m (from Hall and Nichols, 2002).

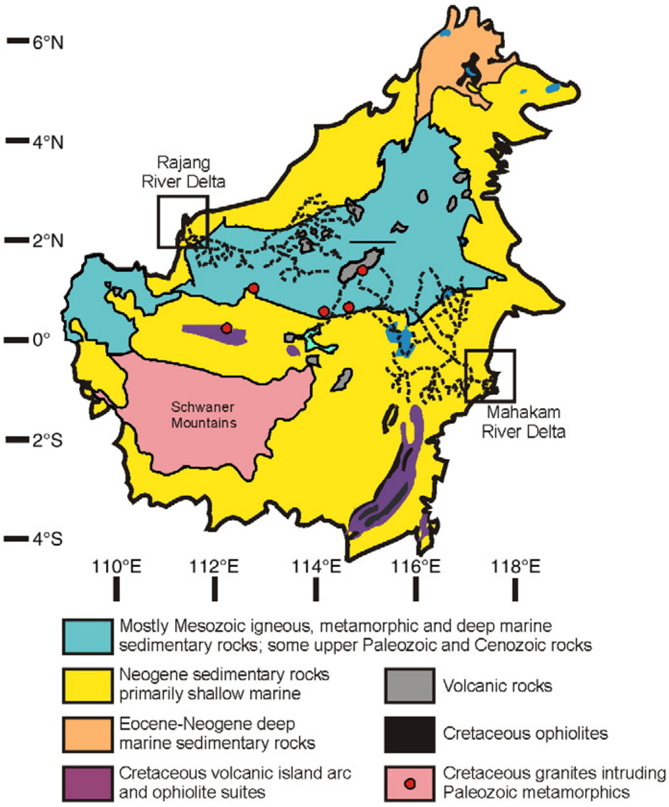

Fig. 2. Simplified geology of Borneo (after Hall and Nichols, 2002).

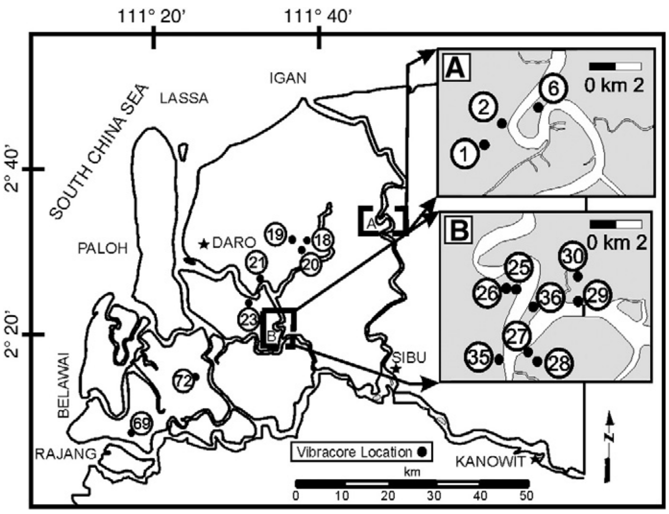

Fig. 3. Outline map of the Rajang River Delta, Sarawak, East Malaysia with locations of numbered vibracores extracted from peat swamps. See Staub et al. (2000) for distribution of peat deposits >1 m in thickness and position of main peat domes. A. Enlargement of area along the Igan distributary depicting coring sites. B. Enlargement of area where the Batang Lebaan bifurcates into the northward-directed Lassa distributary. (Modified from Staub and Gastaldo, 2003). Cores within 100 m of channel margin — 2, 21, 25, 27, 29, and 35; peat-swamp cores — 1, 6, 18, 19, 20, 23, 26, 28, 30, 36, 69, and 72.

meso- to macrotidal, and increase in amplitude from northeast (Igan River) to southwest (Rajang River; Staub et al., 2000). Maximum tidal displacement at Sarikei, a standard port, in 1993 was 5.5 m during spring high tides and a low of 0.0 m at the lowest astronomical tide (Royal Malaysian Navy, 1992), with the average tidal displacement ranging from 2 to >4 m. Both the northeast monsoon (December to March) and southwest monsoon (remainder of the year) control wind and waves, with maximum wave height of approximately 2 m.

Sediments transported through and deposited within the delta primarily are fine-grained (Staub and Esterle, 1993; Staub et al., 2000; Staub and Gastaldo, 2003). The sand fraction ranges from 49 to 55% in channel grab samples taken in the dry and wet seasons, respectively, with a 29% average sand fraction throughout the suite of vibracores (McBeth, 1995). Both channel margin and swamp cores average <10% sand. The sediment is dominantly silt. Vibracores recovered from channel-and-mouth bars average <70% silt fraction, with channel margin and swamp cores averaging >85% silt. The clay fraction can be as high as 5% in the interfluves.

The delta and coastal plains are covered by thick peat accumulations with an upper surface elevation ranging between 4 and 6 m higher than spring high-tide levels, and both areas contain domed peat deposits up to 15 m in thickness that accumulated within the past 7 to 7.5 ka (Staub and Esterle, 1994; Staub and Gastaldo, 2003). Peat-swamp forests are dominated by dipterocarps (Anderson and Müller, 1975; Fig. 4A) wherein several ecological catenas are recognized (Anderson, 1961, 1983), each of which probably is related to the thickness and chemical and textural composition of underlying peat as in other accumulations in Central Kalimantan (Page et al., 1999). Peat greater than 1 m thick covers ~50% of the delta plain surface, ~80% of the adjacent coastal plain, and ~75% of the alluvial valley. Riparian vegetation flanks the river channels (Fig. 4B) and tidal flats are colonized by marine to brackish water-fed mangroves (*Rhizophora, Avicennia, Sonneratia*), and *Nipa* is established in the distal reaches of the delta.

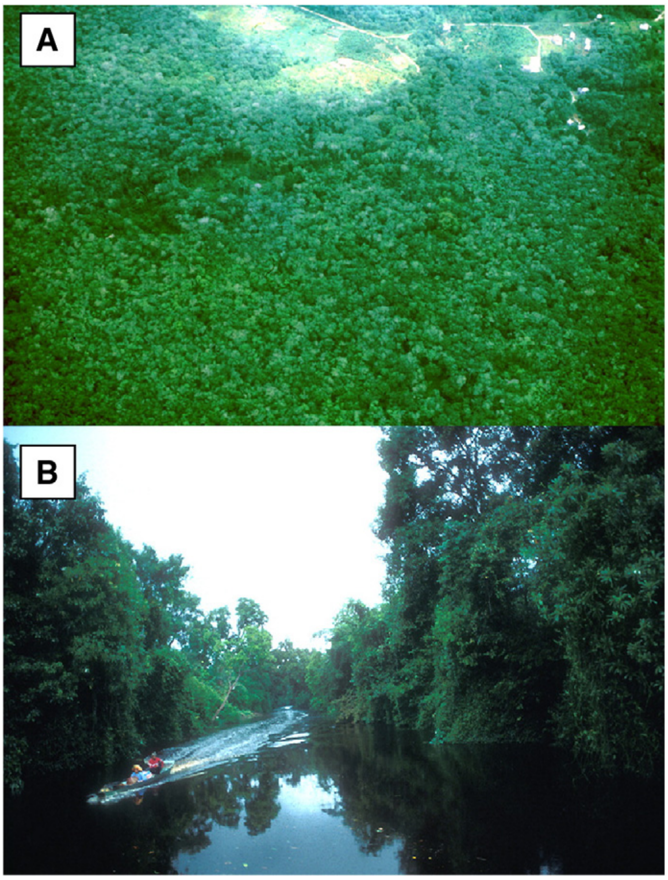

Fig. 4. Rajang River Delta, Sarawak, Malaysia. A. Oblique aerial photograph of peat-swamp vegetation across the delta plain. B. Riparian vegetation flanking a black-water channel in the Lassa distributary system in the vicinity of vibracore 18 (see Fig. 2).

2.2. Geology of provenance sediment

The provenance of deltaic sediments is the western side of the Central Borneo Massif (Fig. 1), an area dominated by Cretaceous to Eocene-age deposits that accumulated in accretionary complexes and forearc basins in response to the opening and spreading of the South China Sea (Hutchinson, 2005). Early to Middle Eocene sediments are sandstone and shale turbidites, most likely deposited upon ocean crust, that were uplifted and deformed by the "Sarawak orogeny" (Hutchinson, 1996). Hutchinson (2005) placed these rocks in the Sibu Zone, with some areas having undergone low grade metamorphism (Lam, 1988).

The Sibu Zone is 200 km in width and extends from the coastline to the interior (Hutchinson, 2005). The highly deformed, steeply dipping flysch sequences are assigned to the Belaga Formation of the Rajang Group. These are distal deep-water bathyal deposits comprised of monotonous intervals of laminated argillite, slate, rare phyllite, and occasional fine-grained greywacke. They are overlain by post-Eocene shallow marine and continental molasse sediments assigned to the Post-Rajang Group. Carbonates are conspicuous in the stratigraphy due to their erosional resistance relative to mudrock, and several limestone formations have been recognized. Geographic outliers are molasse nearshore-sandstone bodies that attain thicknesses of up to 9 m.

3. Mahakam River Delta

3.1. Physiographic setting

The Mahakam River delta, located at the eastern edge of the island, has its headwaters originate in the central highlands of Kalimantan and debouches into the Makassar Strait at the edge of the Kutei Basin (Fig. 1). The Mahakam River drainage system encompasses a 75,000 km^2 area and deposition of the modern delta began at the end of the Holocene transgression between 6 and 5 ka. Since then it has prograded up to 70 km across the shelf (Allen and Chambers, 1998). Presently, the delta is approximately 50 km in "length", as measured from the delta front to the initial bifurcation of the river at Sanga-Sanga, and stretches along the coast for nearly 100 km (Fig. 5). The resultant distributaries are, from the south to the north, Sungai Mahakam, Sungai Batangbanyumati, Sungai Bekapal Baru, Sungai Bekapai lama, Sungai Terusan Pamakaran, and Sungai Badak. The subaerial delta covers about 5000 km^2, consisting of approximately 2000 km^2 of wetlands subdivided into an upper and lower zone, and 1800 km^2 of delta front and prodelta sediments. The delta contains both active bifurcating distributaries and tidal channels, with a central zone dominated by tidal processes. Allen and Chambers (1998) report that the entire delta covers a ~10,000 km^2 area.

Marine processes that influence the delta differ on the eastern side of the island due to its position within the Makassar Strait, with semi-diurnal tides characterized as micro- to mesotidal, ranging from ~0.5 m during the neap cycle to 1.7 m for spring tides. The average tides are 1.2 m, with a maximum of 2.9 m reached during equinox high tide ([1]TOTAL internal report, 1986). Wave energy is generated by the dominant monsoonal pattern, but waves do not exceed 80 cm less than 5% of the time, with average wave height ~60 cm (Allen and Chambers, 1998). Hence, the Mahakam is considered a mixed tide-

[1] TOTAL, 1986. Meteorological and oceanographical campaign Balikpapan Final Report. Total Internal Report.

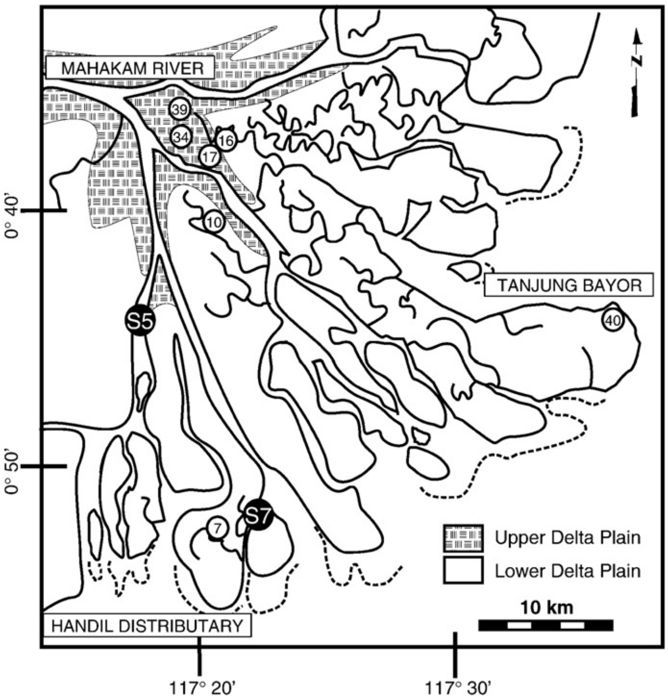

Fig. 5. Outline map of the Mahakam River Delta, Kalimantan, Indonesia, with plotted locations of vibracores extracted from upper delta plain swamp forests (modified from Gastaldo and Huc, 1992). Mangrove core — 40; *Nipa* swamp cores — 7, 10; Hardwood swamp cores — 16, 17, 34, 39. Cores described by Allen et al. (1979) are located at S5 (proximal delta) and S7 (distal delta).

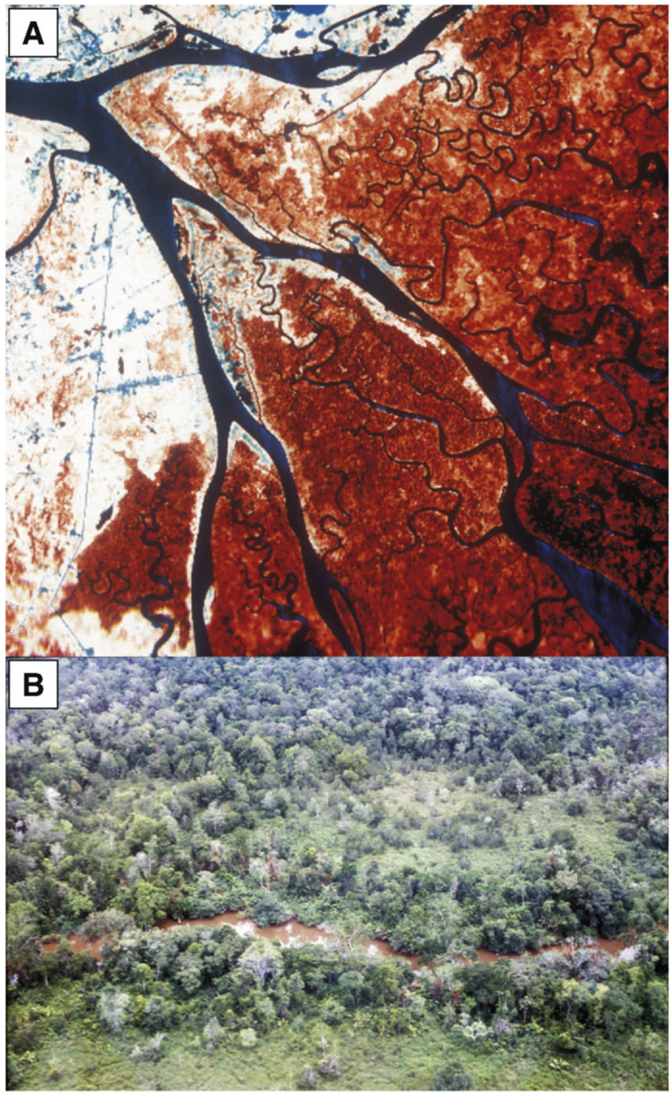

Fig. 6. Mahakam River Delta, Kalimantan, Indonesia. A. SPOT satellite image, processed at the Institut Français du Pétrole, in which the lower delta plain *Nipa* swamps (orange and reddish orange) are discriminated from upper delta plain hardwood vegetation restricted to proximal zones. B. Oblique low altitude aerial photograph of hardwood forests in the upper delta plain adjacent to a sediment-laden tidal channel. Non-woody areas were sites where rice growth and agriculture were attempted during relocation efforts in the 1960's.

and fluvial-controlled delta and has been considered a mixed energy, low mesotidal-dominated coastline (Allen et al., 1979).

Sediments in the delta range from medium and coarse sand in the upper delta plain to fine sand and silt at the distributary mouth bars, dominated by silt (personal observation, 1989; Allen and Chambers, 1998). Both Allen and Mercier (1994) and Roberts and Sydow (2003) report only sand and mud in the delta front and offshore facies, whereas massive clay is restricted to the prodelta (Allen and Chambers, 1998). Unlike the Rajang River delta, grain-size distribution data are not published for the modern Mahakam delta, but grain-size data do exist for the subsurface Misedor core (Pelet, 1987). In these deposits, Guyet and Legigan (1987) report medium sand (median 300 μm) occurs in the mouth bars, whereas fine silt and clay (median grain size 3 μm) dominate in mangrove and prodelta facies, respectively. The fine-grained fraction in sand-dominated distributary barforms ranges from 24 to 42%, and is up to 84% in intertidal to supratidal facies.

Vegetational components in the delta are the same as those found in the Rajang River system, although the distribution of taxa differs significantly (MacKinnon et al., 1996). There are neither peat forests nor autochthonous peat deposits. Peat occurs only in allochthonous deposits formed along the headlands (Tandjung) within an intervening inactive interdistributary (Gastaldo et al., 1993) that consists of a series of tidal channels distal to the fluvial regime. The upper delta plain is colonized by mixed tropical hardwood, whereas the lower delta plain is a monoculture dominated by *Nipa* palm swamp (Gastaldo and Huc, 1992; Fig. 6A). Brackish water-fed mangroves fringe the headlands and estuarine mouths of the lower delta.

3.2. Geology of provenance sediment

The provenance of deltaic sediments is the eastern side of the Central Borneo Massif, the rocks of which are primarily shallow marine and continental Neogene deposits (Hall and Nichols, 2002; Fig. 2). The modern delta is located on the eastern edge of the Kutei Basin, which was rift-initiated during the middle Eocene and filled subsequently by syn–rift clastic and carbonate sedimentation until the early Miocene (Payenberg et al., 2003). Allen and Chambers (1998) note that the fine sand and mud are derived from a mixed provenance that includes Cretaceous basement. But, to date, only one provenance study exists for the Kutei Basin (Tanean et al., 1996), with sediments reported to be from a recycled Miocene source that includes Pliocene volcanics. Hall and Nichols (2002) report that younger sediments are derived from pre-existing sedimentary sequences that had been inverted within the basin, and Moss and Wilson (1998) note that the large volume of transported sediment has resulted in progradation of the delta and prodelta throughout the Pliocene to Recent. Estimates, based on vitrinite reflectance values (van de Weerd and Armin, 1992), are that as much as 5 km of Lower and Middle Miocene strata have been recycled. The loss of this much stratigraphic section has been attributed to the everwet climate of these tropical areas (Hall and Nichols, 2002).

4. Materials and methods

Coring programs were conducted in both the Rajang (1992–1993) and Mahakam (1989) River deltas from which vibracores, ranging from less than 1 m to greater than 7 m in length, were recovered throughout each delta. Vibracores were extracted from a variety of barforms in fluvial- and tidal-dominated river channels (including black-water channels), mires, swamps, distributary mouth bars, and beaches. Fourteen vibracores were extracted from peat mires in the Rajang River Delta, recovering not only the histosol but also the subjacent clastic soils (Fig. 3). In the Mahakam, 4 vibracores were extracted from the hardwood forest in the upper delta plain, one each was extracted from the *Nipa* swamp, mangrove swamp, and detrital peat beach in the lower delta plain (Fig. 5). The reader is referred to Gastaldo and Huc (1992), Gastaldo et al., (1993, 1995), and Staub and Gastaldo, (2003) for analytical methods applied to samples.

5. Delta plain deposits

5.1. Rajang River Delta

Staub and Gastaldo (2003) note that thick peat deposits in the delta and coastal plain are underlain by near-surface Pleistocene erosional remnants, with the bases of peat domes below Mean Sea Level. These deposits are found primarily in the central and northern parts of the delta, with basal ^{14}C ages averaging 6.3 ka, with a limited range of peat initiation 7.4 to 5.8 ka. Little significant peat accumulation has occurred in the southwestern part adjacent to the Rajang River, which is a reflection of an absence of Pleistocene sediment in the area (except adjacent to the VIIa terrace; see Staub and Gastaldo, 2003). Vibracores recovered from the interfluves illustrate the relationships between peat accumulations and underlying sediment (Fig. 7).

Surficial peat accumulations in the central part of the delta plain vary based on the distance of the coring site from the active channels. In sites adjacent to the channels, overbank flooding accompanied by silt and clay deposition result in organics derived from riparian forest, admixed with the periodic influx of siliciclastics (Fig. 7A, D). These organic-rich bedded deposits characterize levees in this part of the delta. Roots may penetrate to several meters in depth (*e.g.*, Fig. 7D), but high decay rates prevent well-developed peat to form. A basal ^{14}C age date of 5485 ± 385 ybp in core 35 indicates that the course of the Lassa distributary has been stable for several millennia (Staub and Gastaldo, 2003). Core sites only a few 100 m distal to channel margins (*e.g.*, 23, 26) preserve a different aspect. These areas exhibit peat accumulation (Fig. 7B, C), with thicknesses exceeding 4 m, that overlie organic-rich silt and clay. Fine to coarse hemic peat, derived from the dipterocarp swamp forest, can be intermixed with peaty clay and muck. Scott (1985) placed such accumulations into the Anderson soil series of deep to very deep organic soils. At both of the sites illustrated, several decimeters of organic-rich clay overlie the peat body, the basal age of which ranges between 7.4 and 6.3 ka (Staub and Gastaldo, 2003).

In more northern areas adjacent to the abandoned channel of the Lassa distributary (Fig. 3, cores 18–20), peat overlies gray-to-white ball clay of Pleistocene age. Roots that have penetrated these clay soils range in age from 2.3 to 4.5 ka (Fig. 7E, F; Staub and Gastaldo, 2003), above which peat in excess of 1 m has accumulated. Peat in this area ranges from fine hemic with fibers to sapric, with a higher proportion of degraded plant debris mixed with siliciclastics (muck) found in the area more distal to the channel margin. Staub and Gastaldo (2003) characterize the ball clay soil as a podzol, following Scott (1985; Bijat soil family), that is of Pleistocene age and representing the VIIa highstand surface of 125 ka. Similar podzols are reported from western Kalimantan, interpreted to have formed during lowstands (Thorp et al., 1990).

5.1.1. Inorganic soil characteristics

Three basic inorganic soil types are recognized in the vibracore suite — marine-influenced gleyed soils, podzols, and freshwater alluvial soils (Staub and Gastaldo, 2003). Mangroves and *Nipa* palms colonize dark gray clay or silty clay composed of mixed layer illite/smectite, illite, and kaolinite with minor amounts of chlorite. Gray-white to white podzols are clays, which may be mottled by iron staining, and consist of kaolinite and illite with minor mixed layer clays. Mottled alluvial soils are yellow-to-brown clay and silty clay, composed of mixed layer illite/smectite and illite with kaolinite. Sediments underlying all peat can consist of as much as 50% clay minerals, and the system averages over 60% mixed layer and expandable clays. Even when the subjacent clay is light gray-to-white in color, mixed layer and expandable clays comprise an average of more than 50% (Table 1). This is true throughout the deltaic system, as the proportion of clay minerals in soils is similar to those transported in river channels (Table 1; McBeth, 1995).

5.2. Mahakam River Delta

Although organic-rich soils are common in the mangrove, *Nipa*, and hardwood swamps (TOC: 2.9–3.0%, unpublished LECO data), the interfluves of the Mahakam River delta show no evidence of autochthonous peat accumulation in any part of the system. Depending upon their position along the delta front, mudflats are composed of organic-rich sand-and-silt couplets or silt couplets deposited in response to spring-neap tidal processes (Gastaldo et al., 1995; Storm et al., 2005). Mangrove root structures occur within the upper few decimeters of sediment, but there is no peat accumulation other than thin intervals of detrital OM, similar to that reported by Gastaldo et al. (1993), at depth (Fig. 8A). A similar aspect is imparted to the subsurface sediments in the *Nipa* swamps (Fig. 8B) where buried aerial litter is subjected to sulfur-reducing conditions (personal observation, 1989). Many of these lower delta plain areas are subjected to inundation by either fresh or brackish waters during spring and King (exceptionally high spring) tides, depending upon geographic position in the delta plain.

Hardwood swamps in the upper delta plain are rooted in organic-rich silt in which dispersed aerial plant parts may appear bedded. Voss (1982) characterizes these as humic gleysols or dystric fluvisols. Rooting penetrates up to 1 m in depth (Fig. 8C) with oxidation halos developed around their exteriors. Subjacent to the soil may be either bioturbated delta front sand or sand-and-mud couplets of tidal origin in which *Nipa* debris often is preserved. Core 39, recovered from the most proximal part of the upper delta plain, shows a well-developed organic-rich soil with a dense O-horizon (Fig. 8D). This soil horizon consists of roots and aerial debris, beneath which vertical and inclined roots extend down for ~1 m depth. As in other cores, the sediment underlying these poorly developed soils was deposited in response to tidal processes as reflected in the sedimentary structures (*e.g.*, wavy and flaser bedding) interpreted to be tidal in origin (see: Gastaldo et al., 1995).

5.2.1. Inorganic soil characteristics

Unlike studies in the Rajang River delta, there are only cursory data on the composition of clay minerals identified from grab samples from the Mahakam River delta derived from grab samples (Allen et al., 1979) and core (Latouche and Maillete, 1987). Allen et al. (1979) reported a wide range of values for clay minerals (Table 2), with up to 40% montmorillonite (smectite) or mixed clay (illite–montmorillonite). Samples originated from cores in the proximal and distal delta plain (Fig. 5), with clay mineralogies derived from intervals of sand recovered from barforms, and the prodelta where only mixed illite/montmorillonite was identified (<20%). They do not report values for mixed layered kaolinite/expandable clay in the system. Similar values for clay minerals were obtained by Latouche and Maillete (1987) from the Misedor project for samples recovered at depths to >600 m. They

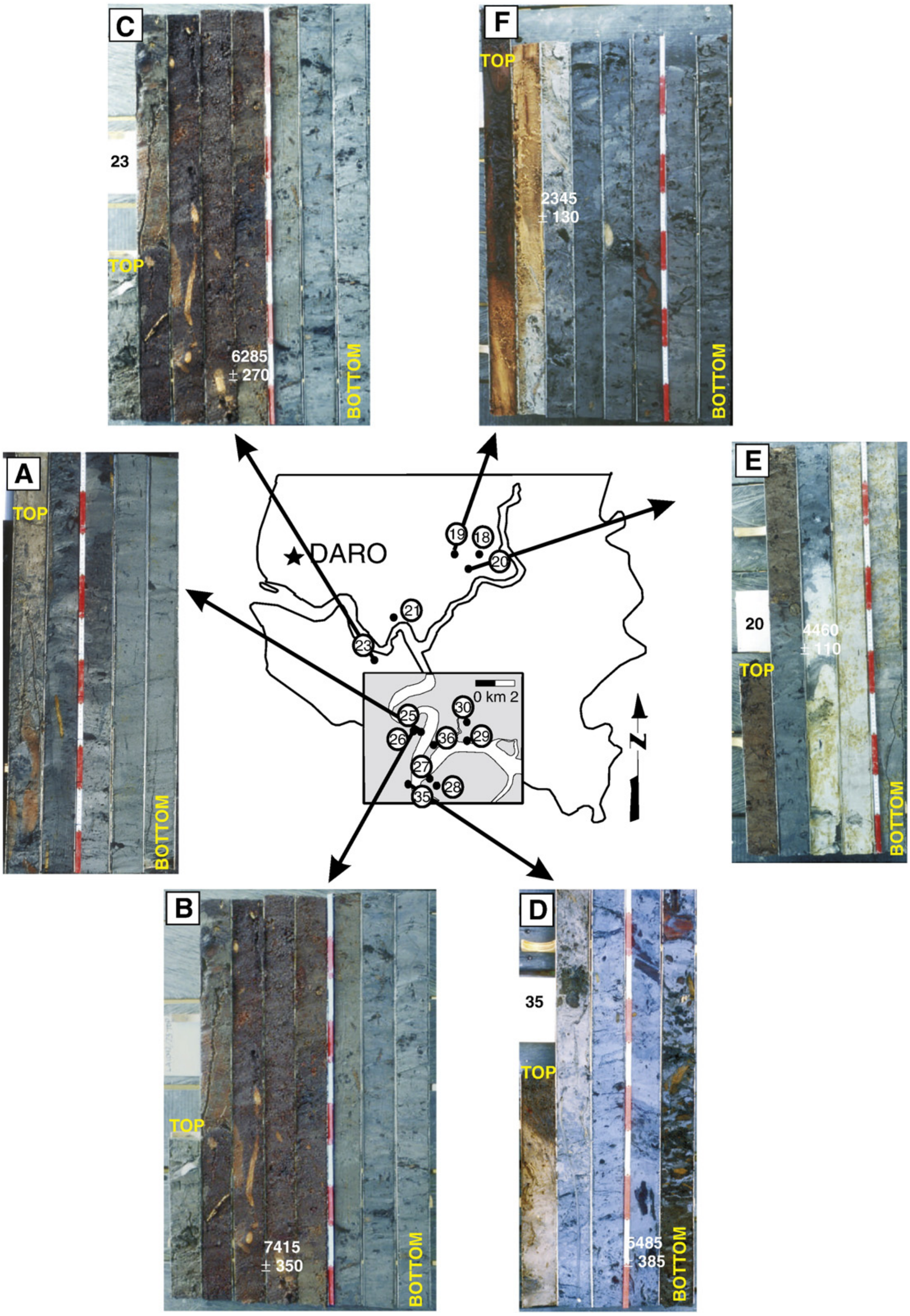

Fig. 7. Vibracores from the Rajang River delta plain. A. A 5-m vibracore from coring locality 25 (see Fig. 2) <100 m from the channel margin. Clastic sediments dominate the core and represent levee deposits in response to overbank flooding with subsequent colonization by plants. Tidal deposits occur in the lower 2.4 m of the core overlain by increasingly organic-rich rooted sediments. Overbank flood sediments occur between −2.4 to −2.20 m depth, as measured from the core top. Although well-rooted, organic concentration is diluted by siliciclastics in the soil at this locality, resulting in no peat accumulation at this site. B. Vibracore 26, a few 100 m west of core 25, in which ~4 m of hemic peat, peaty clay, and muck occur above a rooted clay. A basal ^{14}C age of 7415 ± 350 ybp is reported by Staub and Gastaldo (2003) for this peat body. Scale in dm (red/white) and cm. C. Vibracore 23 in which >4 m of peat has accumulated above a rooted clay. Peat composition ranges from muck to fibric and coarse hemic with large roots. A rooted clay occurs in the uppermost 65 cm of this core. A basal ^{14}C age of 6285 ± 270 ybp is reported by Staub and Gastaldo (2003) for this locality. D. Vibracore 35 in which a short section of sapric peat with woody root fragments occurs above a mottled olive gray clay in which roots, isolated leaves, and dispersed organic matter are preserved. A basal ^{14}C age of 5485 ± 385 ybp is reported by Staub and Gastaldo (2003) for this locality. E. Vibracore 20 in which 90 cm of muck and sapric peat overlies a root-penetrated clay and Pleistocene ball-clay remnant. Roots preserved in the white ball clay have been dated at 4460 ± 110 ybp (Staub and Gastaldo, 2003). F. Vibracore 19 in which >2 m of accumulated histosol (peat), along with a decayed stump and rooting system, are preserved above a kaolinite-rich ball clay. This interval (−1.8 to −2.55 m depth) represents the 120 ka lowstand (Staub and Gastaldo, 2003). Note organic-rich tidal deposits beneath the gray-white impervious zone. All scales in dm (red/white) and cm.

Table 1
Percentage of clay minerals in the <2 μm size fraction in the Rajang River Delta samples recovered from vibracores and water-column grab samples in the dry and wet seasons (see Staub et al., 2000). Data are presented for a subset of vibracore samples that originated from light gray and white clay that underlies peat. I/S = mixed layered illite/smectite; I = illite; K = kaolinite; K/E = mixed layered kaolinite/expandable clay; C = Chlorite.

	% I/S	%I	%K/E	%K	%C
Vibracores *N* = 95	32	26	32	3	7
Dry season *N* = 38	34	25	34	2	5
Wet season *N* = 18	35	26	31	2	6
Light gray-to-white clay *N* = 7	25	29	31	12	3

report smectites averaging 23% and kaolinite averaging 42% of the clay mineral suite within the upper 180 m of the drill core. Clauer et al. (1999) reported clay fractions below 1000 m depth to consist mainly of mixed–layer illite–smectite (I/S) with accessory kaolinite and/or dickite, discrete detrital illite, and chlorite. They attribute increasing amounts of illite and kaolinite at depth to burial diagenesis of the I/S component. The shallowest Misedor sample, though, is −37.6 m below the surface. Hence, it is parsimonious to maintain that the proportion of expandable clays in the present Mahakam surface soils, formed through tidal flat aggradation and overbank flooding, is similar to values reported by Allen et al. (1979) and not those reported from depth in the Misedor core. In contrast, then, the lower proportion of an expandable clay fraction in the Mahakam differs from the Rajang River delta.

Table 2
Clay mineralogy as reported from the literature for sediments in the Mahakam River Delta. S = smectite; I = illite; K/E = mixed layered kaolinite/expandable clay; K = kaolinite; C = Chlorite.

	%S	%I	%K/E	%K	%C
Pelet (1987)	23	25	NA	42	11
Allen et al. (1979)	15–40	30–50	NA	20	10–15

6. Discussion

Of the many factors that control peat accumulation, hydrology and the degree to which the site is waterlogged (paludification) are fundamental for the accumulation of organic matter (Clymo, 1983; Whitmore, 1985; Moore, 1987). Hydrology, in turn, is controlled by climate, precipitation/evaporation ratios, local topography, vegetation cover, and any regional groundwater flow paths that result in recharge or discharge. General models for peat deposits related to global mean temperature and vegetation can be assembled, with parameters in cool temperate ecosystems differing from equatorial regions (*e.g.*, Clymo, 1983, 1984; Martini and Glooschenko, 1985; Winston, 1994; Almquist-Jacobson and Foster, 1995; Craft et al., 2008). In the tropics where decay rates are high (k-constants; Gastaldo and Staub, 1999), annual biomass production is similar to those reported in other parts of the globe (Bray and Gorham, 1964). Thick tropical peat is the result of a high fiber content from the incorporation of aerial and subterranean woody debris (Staub and

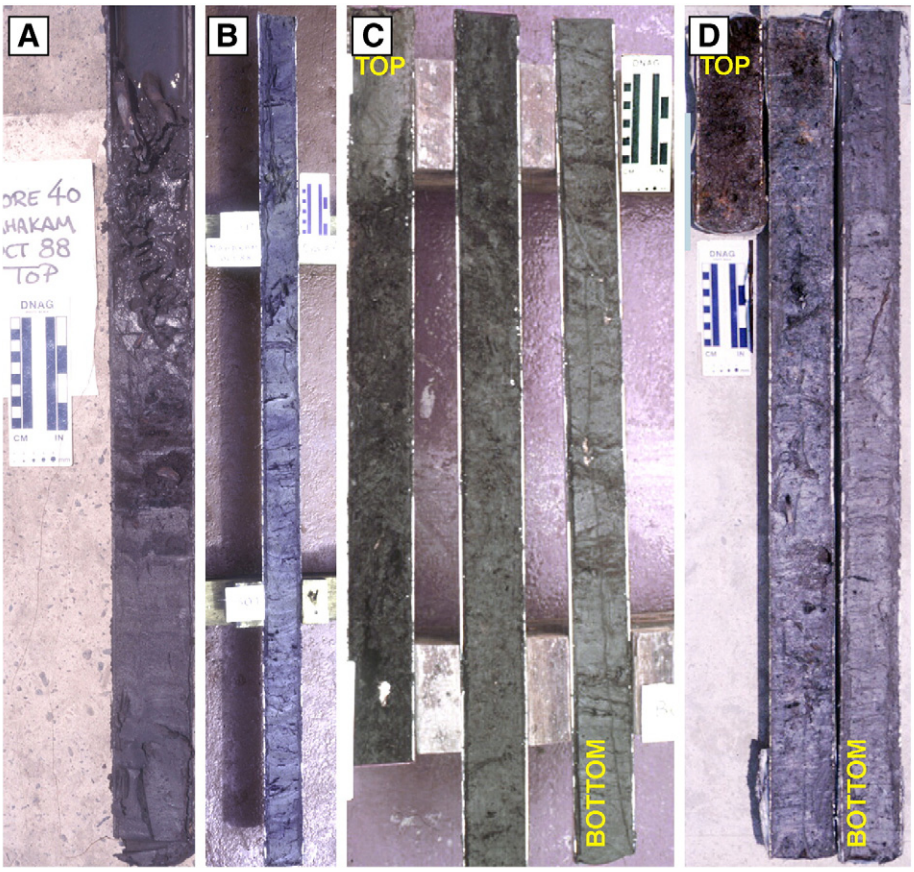

Fig. 8. Vibracores from the Mahakam River Delta plain; see Fig. 5 for core locations. A. A 0.6 m vibracore from core site 40 in the mangroves of the Tandjung Bayor headlands where organic-rich silt acts as the soil horizon for rooting. An accumulation of detrital organic matter occurs between −30 and −45 cm depth as measured from the core top. B. A 1.6 m vibracore recovered from a *Nipa* palm swamp (core site 7) with rootlets interspersed with petioles and laminae. Bedded dicot laminae (?mangrove) occur at −1.39 m depth along with allochthonous resin clasts. C. A 2.75 m vibracore recovered from core site 10 in a hardwood forest adjacent to an upper delta plain tidal channel. An organic-rich, rooted soil of this character may be the result of tidal channel abandonment, organic fill, and colonization (see Gastaldo and Huc, 1992). Tidal depositional features of silt- or sand-and-mud couplets (see Gastaldo et al., 1993) occur beneath the organic-rich interval. D. A 2.3 m vibracore from an upper delta plain forest (coring site 39) showing a short, organic-rich, rooted soil overlying tidal deposits. All scales in dm and cm.

Esterle, 1994; Rieley et al., 1996). Even so, when thick peat accumulations occur outside of valleys and basins, where a high water table can be maintained, precipitation exceeding evapotranspiration is required (Moore, 1987; Wüst and Bustin, 2004). But, even where the main controlling climate variable is rainfall, not all geographical areas that receive similar amounts of high precipitation per year accumulate peat.

Rainfall around the island of Borneo averages >2 m per year (Fig. 9A) with maximum rainfall varying aerially and temporally across the island due to the monsoons that affect the western side of the island more than the eastern coastal areas (compare Kuching and Balikpapan, Fig. 9). Recently, Dambul and Jones (2008) devised a climate classification for the island using statistical methods on normalized monthly and long-term averages to identify similar rainfall-pattern sites; three groups were identified, each of which was subdivided into 2 sub-categories. The closest meteorological station to the Rajang River delta is Sibu, placed into the Samarahan climatic group; the closest station to the Mahakam River delta is Samarinda, classified in the Selor climatic group (Fig. 9B). The wet season period for these climate groups begins in October/November and extends to March/April, with moderate to strong seasonality identified in the Samarahan group when compared to a weak to moderate seasonality in the Selor group. The number of absolute wet months (when total precipitation is above the long-term average for all meteorological stations used in the study) is more variable in Kalimantan, ranging from 0 to 6, whereas this part of Sarawak routinely experiences 5–7 months of absolute wet per year. In contrast, both climate groups experience 3 dry months, during the Southwest Monsoon. Hence, although there is variability in rainfall patterns over the past 42 years in a few data sets, both sides of the island can be considered perhumid (everwet) following the classification of Cecil (2003). It should be noted, though, that the additional annual rainfall on the western side of the island acts to maintain a higher regional water table during prolonged drought intervals when peat fires can develop (Page et al., 2002).

The Rajang and Mahakam deltas do not differ significantly in topography, although there is a difference in areal extent of land surface influenced by tidal inundation. The extent to which daily, Spring or King (maximum Spring) tides flood the lowest lying areas is reflected in the distribution of mangrove and *Nipa* palm communities. These are restricted to the delta front tidal flats and along distributary channel margins in the active part of the Rajang River delta, whereas extensive mangrove forest exists in the southwest inactive delta (Staub and Esterle, 1993; Staub and Gastaldo, 2003). Recently, the area immediately to the south of the Rajang River distributary mouth, covering 9374 ha, was designated as a national park in an attempt to conserve mangrove forest. But, overall, the majority of the subaerial delta plain is not influenced by tidal processes with high spring tides rising to near the levee tops. In contrast, the delta plain topography in the Mahakam River delta is subtle. Most of the subaerial interfluves in the Kalimantan delta are covered in tidal waters at some point during each tidal cycle as evidenced by the presence of fringing mangroves and an extensive *Nipa* palm monoculture (Fig. 6A; Gastaldo and Huc, 1992). Hence, there are not prominent natural levees adjacent to the distributary channels (Roberts and Sydow, 2003). But, where mixed hardwood tropical rainforest exists, the area in the proximal part of the delta is above tidal influence with moderate levee development (Fig. 6B).

The vegetational patterns across parts of Indonesia have changed since the last glacial maximum. At ~18 ka, there was an increase in

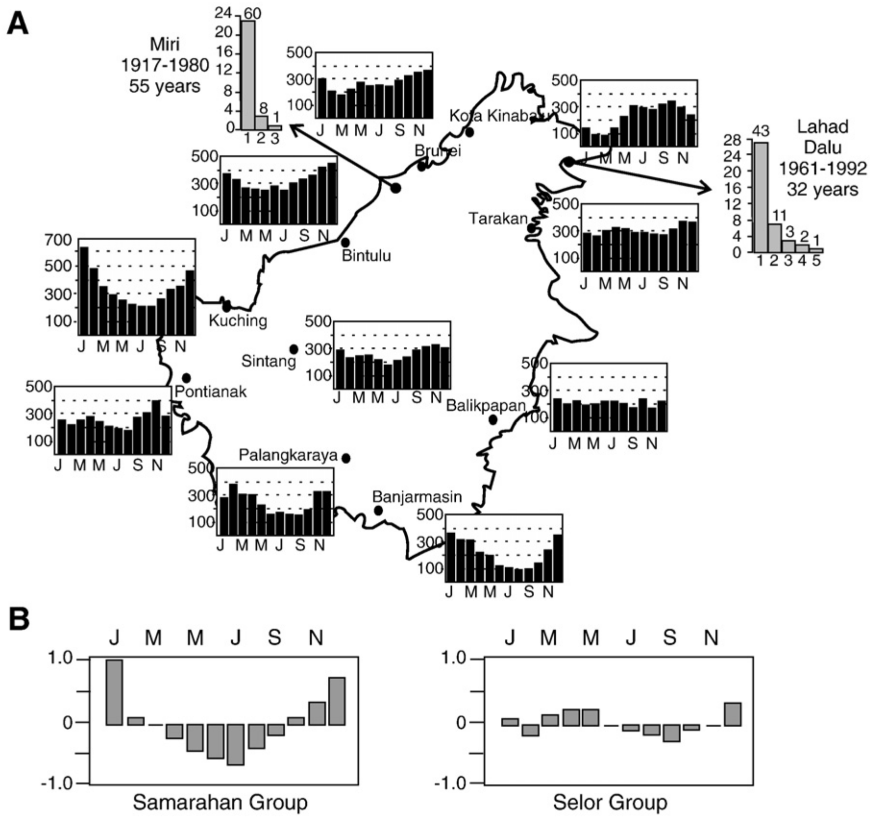

Fig. 9. Rainfall and drought magnitude–frequency distribution in Borneo. A. Annual rainfall patterns (black bar graphs) for coastal locations and one interior recording site, Sintang, Kalimantan, Indonesia (from National Environment Agency, Meteorological Services Division, Singapore Government). Drought magnitude–frequency distribution (gray bar graphs) for Lahad Dalu and Miri, northern Borneo. Frequency per 20 years plotted on *Y* axis, drought length in months plotted on *X* axis. The numbers above each bar are the total number of droughts in the record (after Walsh, 1996). B. Normalized annual precipitation cycles for Samarahan climate group, Sarawak, and Selor climate group, Kalimantan (after Dambul and Jones, 2008).

the extent of montane and savannah vegetation with an accompanying decline in rain forest in parts of peninsular Malaysia, Java, southern Kalimantan and Sulawesi, and eastward to the island of East Timor (Heaney, 1991). Subsequently, rain forests recolonized these areas when climate patterns changed. But, according to palynological records (Heaney, 1991), coastal areas in both Sarawak and eastern Kalimantan were unaffected and there essentially was no change in the geographic distribution of mixed (dipterocarp dominated; Phillips et al., 2002) rain forest. Maloney (1992) notes that vegetational changes in the Mahakam delta were very localized within freshwater-swamp forest or mangrove swamp, or represent a change from mangrove to freshwater-swamp taxa. Hence, communities along coastal areas of both Sarawak and eastern Kalimantan have remained stable.

Cecil and Dulong (2003) proposed that peat accumulation is solely a function of climate and occurs in areas dominated by high uniform rainfall throughout the year (Cecil et al., 1993) that experience low seasonality. These conditions are more persistent on the western side of the island (Rajang) than in the eastern side (Mahakam) where dry season rainfall may drop below 100 mm/month during El Nino events (Aldrian and Susanto, 2003). And, because the total annual rainfall in the Selor climate group (Dambul and Jones, 2008; Fig. 9B) is nearly half that of the Samarahan climate group, it could be argued that rainfall and the extent of the dry season might be the factor controlling peat accumulation. But, if this were the case, then one would not expect to find peat in areas of Sarawak where similar rainfall and drought patterns prevail (Fig. 9A). The historical dry-month pattern in Lahad Dalu, Sabah, is similar to that found in Miri, Sarawak. Annual rainfall patterns also are similar, and both areas are classified in the Sepanggar climate group of Dambul and Jones (2008). Peat is not reported from this part of Sabah, but extensive thick blanket peat is documented in and around Miri (Staub and Esterle, 1994) that extends northeast to the Klias Peninsula in Sabah (Phua et al., 2008). Hence, if rainfall dry-month patterns, alone, were the controls on peat accumulation, there should be none across northern Borneo.

The factor that controls paludification, and hence, the buildup of organic matter in the region, cannot be attributed solely to climate in this tropical setting but the hydrological properties of the sediments that act as soils for the mixed hardwood swamps. Although both systems can be characterized as fine-grained in nature, the clear distinction between sediment characteristics in the Rajang and Mahakam delta plains is the proportion of expandable clay minerals. Sediment samples from the Rajang River delta average more than 60% mixed layer and expandable clays, and the proportion of these minerals is high (55%) even where leached clay residuum underlies peat (Table 1). This is in direct contrast with the reported values for expandable clays in the Mahakam (Table 2). Peat in the Rajang River delta is not restricted just to sites where gray-to-white ball clay exists (Staub and Gastaldo, 2003; Fig. 7). Rather, it occurs above sediments that show little to no visual alteration of the substrate (Fig. 7). The high proportion of expandable clays in the fine-grained nature of the Rajang system essentially plug and/or severely retard the movement of water into the subsurface, forming an aquiclude above which stilted water can develop. This is evidenced when attempting to vibracore channel deposits.

There is a stark contrast in the ease of introduction and extraction of vibracores in channel barforms between these two deltas. Vibracores greater than 9 m in depth were extracted easily from silt-dominated, lateral channel bars in the Mahakam delta, with the weight of the empty core barrel and vibrator head sufficient to sink the barrel (Gastaldo et al., 1995). Ample pore waters allowed for liquefaction of the sediment to the interior and exterior of the vibracore, with coring times on the order of a few minutes even for the deepest cores. In contrast, vibracoring in the Rajang delta was hard fought. Cores attempted in channel barforms within the delta plain rarely exceeded 3 m depth. At depths greater than ~2 m, ropes had to be affixed to the vibrator head and manual down-force applied by two to four workers to force the core barrel deeper. When the vibracore was extracted and cut, the silt fraction in these cores was virtually dry to the touch. This is indicative and reflective of the clay mineralogical character on this side of the island. The difference, then, results in a virtually impermeable substrate over which paludification results.

Once paludal conditions are initiated, organic matter that settles on the soil can accumulate. Highly labile components (leaves, fruits, small branches) degrade whereas more resistant components (wood, seeds, etc.) aggrade. The combination of fine hemic and sapric elements, intermixed with more resilient plant parts, allows for retention of an acidified water table above the ground level, promoting topogenous and ombrogenous mire aggradation (Staub and Esterle, 1994). Such conditions are not found in the Mahakam River delta due to the relatively low proportion of expandable clays that promote a stilted water table.

The sediment provenance for both deltas is the Central Borneo Massif, the result of orogenesis during the latest Oligocene and Early Miocene (Hall, 1998; Hall and Nichols, 2002). It is estimated that as much as 5 km of rock has been eroded since the Early Neogene and deposited in the various basins surrounding the island. Rocks presently exposed and undergoing erosion on the Sarawak and Kalimantan sides of the Massif, the only source for deltaic systems around the island, originated in different depositional settings. All Tertiary exposures in the Sibu zone were deposited as turbidites in deep basins (Hutchinson, 2005), supplied from areas in southwest Kalimantan and Indochina (Hall and Nichols, 2002). In contrast, eastern Kalimantan was emergent until the early Paleogene when extension and subsidence in the Makassar Straits allowed for accumulation of Miocene nearshore and continental facies. Lower Miocene sandstones in the Kutei Basin are quartzitic with a significant volcanic lithic component (Tanean et al., 1996), whereas uppermost Lower to lowermost Upper Miocene sandstones are volcanogenic in character. The nature of the sandstones changes from the Middle to Upper Miocene, recording the recycling of the older units, a product of basin inversion (Hall and Nichols, 2002). The high proportion of expandable clay minerals in Rajang River delta sediments, when compared with those in the Mahakam River delta, may be a consequence of these sedimentation patterns and diagenesis associated with these abyssal plain versus shallow marine depositional regimes.

7. Summary and conclusions

Extensive, thick peats have accumulated in planar and ombrogenous mires in the coastal and delta plains around the island of Borneo throughout parts of Sabah, Sarawak, Brunei, and Kalimantan since the last rise in global sea level, circa 7 ka (*e.g.*, Supiandi, 1988, 1990; Staub and Esterle, 1994). These peat bodies have served as models for understanding the development of aerially extensive coals in the Phanerozoic stratigraphic record. It generally is agreed that fine-grained sediments before peat accumulation and climate, hydrology, vegetation during peat accumulation all are factors controlling plant-matter accumulation. It is envisioned that when all these factors are in phase in a terrestrial setting, a peat body will form. Yet, all these conditions exist in deltas on either side of this equator island, but peat is not ubiquitous.

A comparison of recent interdistributary sediment patterns in the Rajang River and Mahakam River deltas indicates that although both can be characterized by fine-grained siliciclastics that exhibit tidal depositional signatures (Gastaldo and Huc, 1992; Gastaldo et al., 1993; Staub et al., 2000; Staub and Gastaldo, 2003), only the Rajang River delta plain contains thick, extensive blanket peat. Here, high degradation and OM accumulation rates result in convex or domed peat bodies, the surfaces of which rise above the adjacent channels to thicknesses of 15 m (Staub and Esterle, 1994). In contrast, organic accumulation in the Mahakam River delta is restricted to thin O- and A-horizons in poorly developed soils. High degradation rates with no OM accumulation result in an absence of autochthonous peat in the delta. The principal difference between the fine-grained fractions transported and deposited in these two areas is the proportion of expandable (mixed) clays. The relatively high proportion of these clay minerals in the Rajang River delta (>60%), when compared with values reported for the Mahakam River delta (15–40%), results in the development of a regionally extensive aquiclude (either in Pleistocene remnants of the 125 ka highstand or Holocene deposits) that promotes landscape paludification and subsequent OM accumulation. These clay minerals originate from the Borneo Central Massif, where erosion of now exposed Tertiary deep-basin turbidites serve as their provenance. And, although siliciclastic sediments found in the Mahakam River delta also originate in the Central Massif, rocks now exposed there originally were deposited in continental and nearshore, shallow marine environments. Hence, the difference in clay mineralogy appears to be a function the original depositional setting from which sediment now is derived for these two deltaic systems.

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