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Seasonal sediment transport and deposition in the Rajang River delta, Sarawak, East Malaysia

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Abstract

The Holocene Rajang River delta plain, which covers an area of 6500 km^2, has developed in a tropical, ever-wet climatic setting. Peat deposits, up to 15 m thick, occur in this delta plain. The tributary system to the delta is about 50,000 km^2 in area. Elevations exceed 2000 m in the drainage basin and hill slopes are steep. Rainfall in the region exceeds 370 cm/year, with highest rainfall levels or the "wet" season being coincident with the December–March monsoon. The monthly drainage-basin discharge is calculated to average about 3600 m^3/s, and the discharge normally ranges from 1000 to 6000 m^3/s. Spring tides in coastal areas range from 2.9 to 5.8 m. Tide data indicate that the tides are semidiurnal with a noticeable diurnal inequality. Vibracores recovered from bar forms in tidally influenced distributary channels contain laminated silts and sand-silt couplets that show evidence of rhythmic heterolithic stratification. Grain-size data indicate that these preserved delta plain siliciclastic sediments are the result of estuarine depositional processes that occur during intervals of reduced rainfall or the "dry" season (April–November). The number of laminae preserved per neap–spring cycle is the highest ($\cong$18–20), and the average thickness is the greatest in the middle part of the delta plain. Distributary channels in this region normally contain low-salinity brackish water to freshwater. Vibracores recovered from delta front and prodelta sediments show evidence of heterolithic stratification, but rhythmicity is absent. Grain-size data indicate that preserved delta front and prodelta sediments are implaced by "wet" season processes (December–March) when fluvial flux and delta-plain erosion are at their maxima. Individual silt laminae and/or silt and sand interbeds are sometimes many centimeters thick, but average about 1 cm. These silt laminae and silt and sand interbeds or varves represent annual sedimentation events. These varves demonstrate that about 24 million MT of sediment produced by the drainage basin is deposited in the delta front and prodelta region annually.

Keywords: monsoons; deltaic environment; tides; tidal rhythmite; peat

1. Introduction

Studies of sedimentary processes and deposits in tide-dominated deltas are relatively rare (Coleman, 1969; Allen, 1987; Barua, 1990; Harris et al., 1993). Studies of tide-dominated deltas that contain extensive, low-ash peat deposits are even more rare (Coleman et al., 1970; Styan and Bustin, 1983; Staub and Esterle, 1993; Hart et al., 1998). Tidal currents and surface waves in many cases play important roles in sediment dispersal and deposition in tide-dominated systems (Harris et al., 1993), but seasonal variation in

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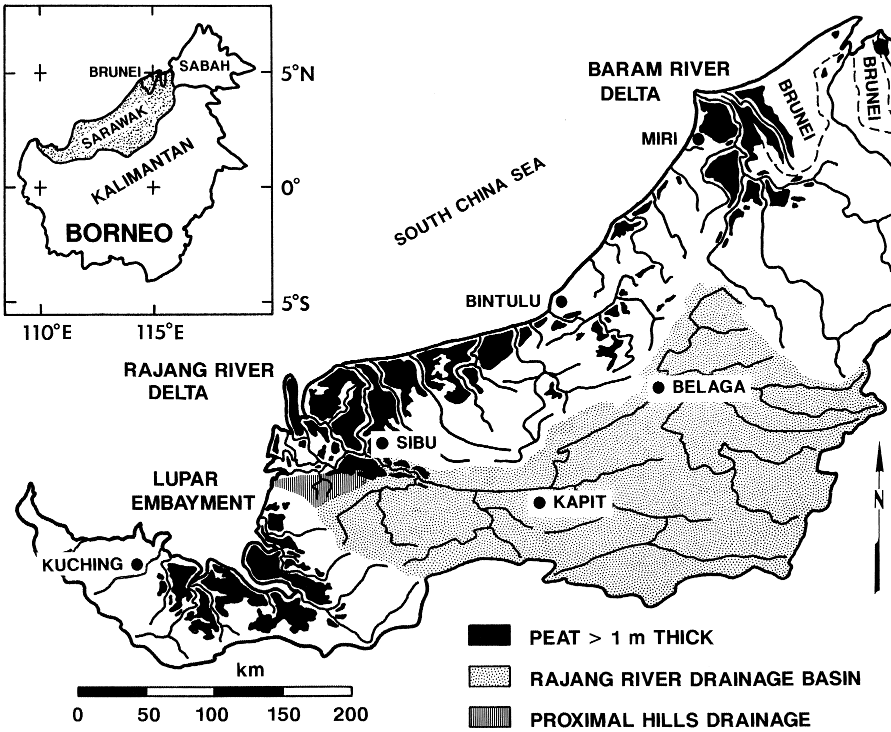

Fig. 1. Map of Sarawak, East Malaysia, showing the locations of the major peat forming regions and all peat deposits greater than 1 m thick. The location of the Rajang River delta, the drainage basin of the Rajang River, and the proximal hills drainage that is adjacent to the delta also are shown.

discharge may well be the most important factor. In situations where seasonal discharge varies by more than an order of magnitude, estuarine processes can dominate the delta plain for much of the year. Galloway (1975) gave strong emphasis to the estuarine component present in tide-dominated deltas, and this flexibility in definition is particularly important in areas where seasonal variation in discharge is extreme, such as monsoon influenced Southeast Asia.

This paper presents an assessment of seasonal discharge and sedimentation patterns in the Rajang River delta. This assessment is done in an effort to define the spatial distribution of deltaic and estuarine sediments, the nature of deltaic and estuarine sediments, and determine sedimentation rates.

2. Physiographic setting, climate, and previous work

The Rajang River (Fig. 1) drains part of the Central Borneo Massif, which is dominated by Cretaceous–Eocene age sediments. These rocks are accretionary complexes and forearc basin deposits that formed during the Tertiary opening and spreading of the South China Sea (Hamilton, 1979; Hutchison, 1989, 1996). They are composed of folded and faulted, fine-grained siliciclastics, with minor amounts of carbonates. Igneous intrusive and extrusive rocks also are present, and many sedimentary rocks have been metamorphosed (Lam, 1988).

The Rajang River drainage basin is about 50,000 km^2 in area. Elevations exceed 2000 m and hill slopes are steep, generally in excess of 25° in the interior highlands and 20° in lower elevation areas. Flood plains, when present, are of limited area. The soils present are poorly developed and represent the mineral composition of the parent materials (Scott, 1985; McBeth, 1995).

The Rajang River delta also receives discharge and sediment from the proximal hills region (Fig. 1) to the immediate south of the Rajang distributary, and from

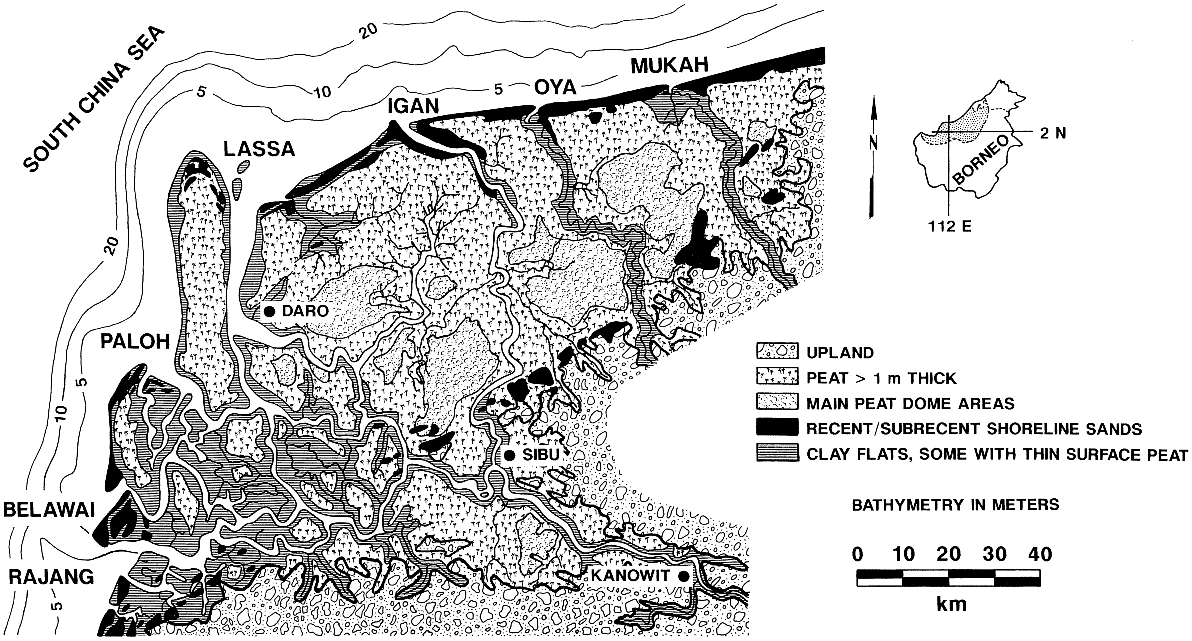

Fig. 2. Physiography of the Rajang River delta and part of the adjacent coastal plain (modified from Staub and Esterle, 1994). The physiographic break between the delta plain and the adjacent coastal plain occurs between the Igan distributary of the Rajang River and the Oya River. The alluvial valley is located upriver from the town of Sibu.

the Retus River drainage basin to the southeast of the Igan distributary (Fig. 2). These additional drainage areas are about 2000 and 1500 km^2 in size, respectively. In both areas elevations exceed 250 m, hill slopes average about 20°, and the rock types and soils present are similar to those found in the Rajang River drainage basin.

The Rajang River delta plain (Fig. 2) covers about 6500 km^2. Unpublished drilling records (Geotechnique East Malaysia Sdn. Bhd.) indicate that Holocene siliciclastic sediments are 25–35 m thick in the vicinity of Daro. The delta plain contains subtidal to supratidal siliciclastic sediments and raised or domed, low-ash, low-sulfur peat deposits. The surfaces of the peat deposits are as much as 4–6 m higher than spring high-tide levels in the adjacent distributary channels, with elevation differences increasing inland from the coast. Peat greater than 1 m thick covers 50% of the delta plain surface and dominates the area to the northeast of the town of Daro (Fig. 2). Maximum peat thickness is 15 m. The physiographic separation between the delta plain and the adjacent coastal plain occurs between the Igan distributary of the Rajang River and the Oya River of the coastal plain.

The alluvial valley is located between the towns of Sibu and Kanowit (Fig. 2). It covers 400 km^2 and peat deposits greater than 1 m thick cover 75% of its surface. Maximum reported peat thickness is in excess of 20 m (Staub and Esterle, 1993). Elevation differences between the surfaces of the raised peat deposits and the water level in the Rajang River are 9 m at spring high-tide. Explanations of peat-swamp formation and descriptions of the vegetation types are not discussed here, but can be found in Anderson (1961, 1964, 1983), Anderson and Muller (1975), and Esterle and Ferm (1994).

Tides along the Sarawak coast (Fig. 1), responding to the widening and shallowing of the shelf, increase from less than 1 m in the northeast (Baram River delta) to more than 9 m in the southwest (Lupar embayment). Tides are semidiurnal within the delta plain of the Rajang River, range from meso- to macrotidal (Table 1), and increase in range from northeast to southwest (Igan to Rajang distributary). Tidal influence extends about 120 km inland (approximate

Table 1
Tidal ranges and seasonal changes in estuary type

Distributary channel	Tidal range[a] (m)	Estuary type[b]	
		Dry season[b]	Wet season
Igan	2.9	Salt wedge	Partially mixed
Lassa	4.2	Partially mixed	Partially mixed[c]
Paloh	4.6	Partially mixed	Partially mixed[c]
Belawai	5.2	Fully mixed	Partially mixed
Rajang	5.8	Fully mixed	Fully mixed

[a] Maximum spring tide.
[b] Classification scheme after Postma (1980).
[c] Increased vertical stratification.

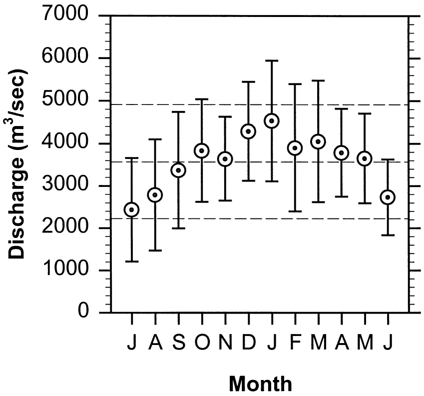

Fig. 3. Hydrograph showing seasonal variation in discharge from the Rajang River drainage basin. Values are month long averages based on 30 years of rainfall data. Error bars are one standard deviation.

position of the town of Kanowit, Fig. 2). Winds and waves from the northeast monsoon dominate from December to March and from the southwest monsoon during the middle months of the year. Maximum wave heights are on the order of 2 m. The cuspate to recti-linear morphology of the delta plain is the result of prevailing wind patterns.

Rainfall averages in excess of 370 cm/year, with the rainy or wet season coincident with the northeast monsoon. Temperature averages about 25° C, and humidity ranges from 55% in the day to almost 100% at night (Scott, 1985). Climate is classified as tropical ever-wet (Morley and Flenley, 1987). Typical single-month discharge rates (calculated from 30 years of rainfall data) for the Rajang River drainage basin range from about 1000 to 6000 m^3/s, and the average monthly discharge rate is about 3600 m^3/s (Fig. 3). Peak discharge rates during the northeast monsoon (December to March) can exceed ≅25,000 m^3/s (Jeeps and Gates, 1963). Channels in the alluvial valley and the more landward part of the delta-plain commonly exceed 25 m in depth, but shallow toward the coast. With the exception of the Rajang distributary, distributary channel mouths are less than 5 m in depth at spring low-tide.

During the Quaternary, base-level lowering/epirogenic uplift of the Central Borneo Massif is estimated at 0.15–0.22 m/ka (Farrant et al., 1995) and, as a result, siliciclastic sediment production from the upland drainage basin is substantial. Staub and Esterle (1994) estimated that before anthropogenic development, the Rajang River drainage basin provided ≅30 million MT of sediment annually to the delta. Inspection of aerial photographs covering the last 50 years reveals that the delta plain has been expanding at a rate of 1.0 to 1.5 km^2/year (Scott, 1985). Long term accretion rates on the order of 8 m/year and aggradation rates of 1.5 mm/year have existed in the delta plain for the last 7500–8500 years. The oldest dated Holocene fresh-water peat deposits in the delta-plain are in excess of 7000 years old (Staub and Esterle, 1993, 1994).

3. Methods

Bottom and suspended sediment samples were collected during both dry and wet seasons from the alluvial valley drainage, delta-plain distributaries, and the delta front. All bottom and suspended sediment samples in tidally influenced areas were collected during slack water. Most vibracores from the alluvial valley drainage and delta-plain distributaries were obtained during high-tide slack water, and most delta-front vibracores were obtained during low-tide slack water.

Grab samples of channel-bottom sediments (Fig. 4) were obtained using either an Ekman dredge or a Wildco gravity-type core sampler. Additional samples were obtained from beach, delta front, midchannel bar, and point bar environments using grab, box core, and trenching methods. Vibracores (Fig. 4) were obtained on land using standard methods and

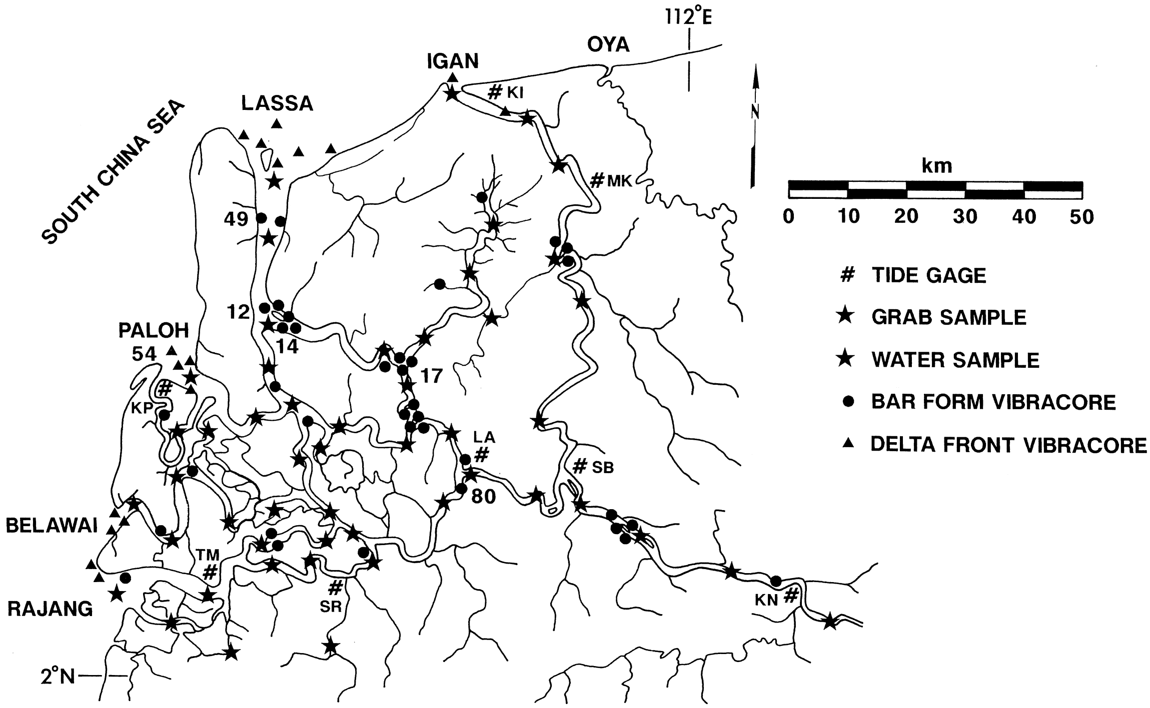

Fig. 4. Map showing the locations of vibracores and grab samples from delta front/prodelta and channel environments in the Rajang River delta and alluvial valley that were utilized in this study. The numbers of vibracores specifically discussed in the text are shown. The locations of tidal gauge stations also are shown (KI = Kuala Igan; MK = Maura Kut; SB = Sibu; KN = Kanowit; LA = Liba An; KP = Kuala Paloh; TM = Tanjung Manis; and SR = Sarikei).

from channel environments using a 23 m long express boat specially modified for coring operations. Vibracores ranged from 4 to 9 m in length. All sediment samples and vibracores were photographed and described in the field (grain size/shape, color/composition, and sedimentary structures). Subsamples from all grab samples and from each sediment type present in each vibracore were retained.

Suspended sediment samples were collected during 1992 and 1993 with a LaMotte water sampler at depth (usually at 2 m from bottom) and at the surface. Samples were collected at 84 locations in the delta plain and delta front during the dry season and 54 locations during the wet season. The locations of 49 wet and dry season sample sets were the same. Salinity and pH of each sample was determined in the field. Each sample was filtered in the field through a <2 μm ashless filter paper. Individual filter paper sheets were rinsed (refiltered) with distilled water to remove solution load materials, dried for 24 h, and then low-temperature ashed. The individual weights for the two samples (surface and depth) from each locality were then averaged to estimate the suspended sediment load.

Rainfall data for the dry season and wet season sampling intervals from Kapit and Belaga (Fig. 1) were used to calculate discharge from the drainage basin. Data from Sibu was used to determine proximal hills region and Retus River discharge. Surface runoff was estimated at 60% of measured rainfall based on research results from Sarawak (Whitmore, 1984). Suspended sediment values, per unit volume, from the dry (July/August) season were normalized to the wet (February) season discharge rate to track seasonal changes in suspended load transport in the delta.

Bulk density of sediment samples ($n = 104$) from vibracores was determined. Sediment sample volume was determined by field measurement. Sediment samples were then dried at 105°C for 24 h and weighed. Sediment weight was then divided by sediment volume.

Grain-size analysis for all siliciclastic-dominated sediment samples was conducted. Organic matter was destroyed with hydrogen peroxide. The >63 μm part of each sample was analyzed according to Folk (1980), whereas the <63 μm fraction of each sample was treated with dispersant and sized by a Spectrex laser particle counter. Grain-size frequency distributions were calculated in whole ϕ increments. Mean ϕ and standard deviation were calculated following McBride (1971).

The grain-size data subsets were compared statistically using the Mann–Whitney rank sum test. Sample subsets were limited to those obtained from the alluvial valley and delta plain distributary channels, the delta front, and prodelta, which are the areas most influenced by seasonal changes in discharge. Grab sample grain-size results used from the wet and dry season data sets were from 49 matched geographic locations and a total of 160 grain-size analyses from 54 core locations. The vibracore data were divided into two subsets. The first subset ($n = 110$) was composed of samples from point and midchannel bars. The second subset ($n = 50$) was composed of samples from the delta front and prodelta.

Tide data (Royal Malaysian Navy, 1992, 1993) were examined to determine tidal range and the degree of diurnal inequality that is present in the tidal flux in different parts of delta plain and alluvial valley. Data from eight gauging stations was utilized (Fig. 4).

Many sediment intervals in vibracores from the delta-plain and alluvial valley contained rhythmically laminated silts and sand-silt couplets. Individual silt laminations and sand-silt couplets were measured to determine thickness. Measurements of this type were obtained from 27 of 37 channel cores ($n = 3963$). Thickness measurements were plotted graphically and divided into cycles based on thickest laminae/couplet occurrence.

Most sediment intervals in vibracores from the subtidal delta front and prodelta contained burrowed, laminated silts and/or laminated silts and sands. Individual silt or silt-and-sand laminations from the lower intertidal and upper subtidal zones were measured to determine thickness. The percentage sand present in each lamina was determined. Measurements of this type ($n = 1413$) were obtained from all 17 delta front cores. Thickness measurements for each core were plotted on the basis of average laminae thickness and percentage of sand present.

4. Results

4.1. Seasonal discharge and sediment transport

Seasonal changes in drainage basin discharge during the wet season caused changes in estuarine circulation patterns (Table 1) in the mouths of the active distributaries. The active distributaries (Igan, Lassa, Paloh, and Belawai) are defined as those channels that transport sediment from the Rajang River drainage basin to the South China Sea. The Rajang distributary is considered to be inactive. At present, it receives most of its discharge and sediment from the proximal hills region to the south of the delta plain. In contrast, the Igan distributary receives discharge and sediment from the Retus River, but its majority of discharge and sediment is derived from the Rajang River.

Estimated discharge from the Rajang River drainage basin during the dry season sampling interval averaged 3000 m^3/s, and during the wet season sampling interval discharge averaged 5200 m^3/s. Additional discharge received from the proximal hills region averaged about 275 and 530 m^3/s for the dry and wet seasons, and the Retus River drainage basin averaged 200 and 400 m^3/s, respectively.

The approximate doubling of drainage basin and delta plain discharge during the northeast monsoon impacted the delta plain. The most pronounced changes occurred in the alluvial valley and the Lassa, Paloh, and Belawai distributaries. The data presented in Fig. 5 are for the alluvial valley and these distributaries only. Total salinity decreased (Fig. 5A) while, at the same time, the degree of vertical stratification increased. For most regions in the delta plain, the position where brackish water was encountered at the surface moved 20–30 km seaward when compared to the dry season. Also, water in the distributary channels went from acidic during the dry season to slightly basic (Fig. 5B) during the wet season.

The geographic positions of the turbidity maxima

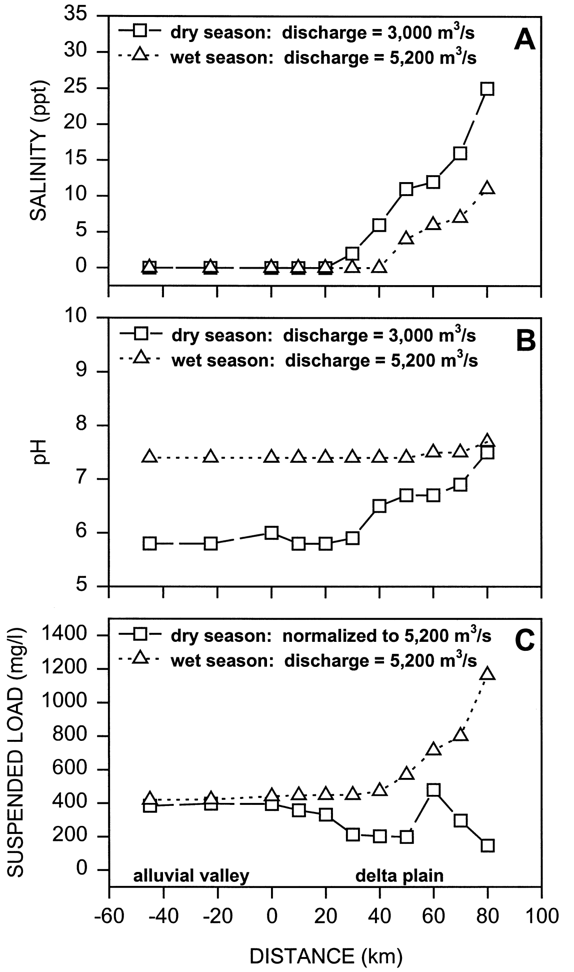

Fig. 5. Seasonal variation in delta plain and alluvial valley salinity (A), pH (B), and suspended sediment load (C). Positive distances along the *x*-axis are in the delta plain and negative distances are in the alluvial valley. The zero value on the *x*-axis is coincident with the physiographic separation between the delta plain and alluvial valley.

(Fig. 5C), which are characterized by unusually high (>1000 mg/l) suspended sediment concentrations in the bottom half of the channel, were affected by the increased fluvial flux. The approximate position of turbidity maxima moved from an onshore dry-season location to the distributary mouths or beyond during the wet season.

The amount of suspended sediment delivered from the Rajang drainage basin to the delta plain only varied slightly on a seasonal basis (≅2.0 MT/s dry season versus 2.2 MT/s wet season). Although drainage basin discharge nearly doubled during the wet season sampling interval, the amount of sediment supplied to the delta plain from the drainage basin only increased by 10%.

What did change substantially (Fig. 5C) was the amount of sediment delivered from the delta plain to the South China Sea. During the dry season, the amount of suspended sediment transported by the Lassa, Paloh, and Belawai distributary channels generally decreased in a seaward direction, and as expected elevated suspended sediment levels were encountered at the positions of the turbidity maxima. The situation changed during the wet season, with continually increasing amounts of suspended sediment encountered in a seaward direction.

Sediment grain-size data (Table 2 and Fig. 6) from grab samples indicate that there are two different sediment populations. Wet season sediments are coarser grained than the dry season sediments. Comparison indicates that, with regard to mean ϕ, the two sample sets are probably not derived from the same parent population ($p = 0.15$). Comparison of the second statistical moment (sorting) showed no significance.

Grain-size data (Table 2 and Fig. 6) from vibracores were compared to the seasonal grab sample data. Point/midchannel bar mean ϕ data are similar to the dry season grab sample data ($p = 0.85$). Delta front/prodelta data are similar to wet season data ($p = 0.89$). Comparisons indicate that sorting in the delta front/prodelta sediments is different from sediments in bar forms ($p = 0.08$) and from the dry season grab samples ($p = 0.04$).

4.2. Tides and intertidal sediments

Tidal gauge data indicate that tides are semidiurnal with a noticeable diurnal inequality (Fig. 7). Apogean–perigean effects are manifested in the tidal curves by a higher spring series followed by a lower spring series. The lower ebb tide of the daily duplex is much lower. In the Igan distributary, tides are very close to diurnal during neap phases of neap-spring cycles. Tides at Sibu, although greatly reduced in range, are most similar to Kuala Paloh. Even at Kanowit the river maintains a long-term average of tidal heights related to neap-spring cycles and short term cycles (semi-diurnal) are superimposed.

Table 2
General Statistics: number of samples in each sample group and the mean and median for both mean ϕ and sorting are listed

Sample group[a] (n)	Mean ϕ	Median ϕ	Mean sort	Median sort
Dry (049)	4.71	5.25	1.29	1.33
Bar (110)	4.86	5.20	1.29	1.32
Df (050)	4.19	4.00	1.26	1.18
Wet (049)	4.07	4.33	1.30	1.30

Mann–Whitney Rank Sum Test: probability results of the parings for sample groups are listed for both ϕ and sorting values

Parings	ϕ	Sort
Dry-bar	0.85	0.42
Dry-df	0.22	0.04
Dry-wet	0.15	0.32
Bar-wet	0.02	0.64
Df-bar	0.01	0.08
Df-wet	0.89	0.36

[a] Sample groups listed are dry (dry season grab samples), bar (point bars and midchannel bars), df (delta front and prodelta), and wet (wet season grab samples).

Many of the vibracores recovered from tidally influenced areas contain yellow–brown (oxidized) to dark olive-green (reduced) laminated silts and sand–silt couplets that show evidence of rhythmic heterolithic stratification (Fig. 8A). Couplets are often wavy- to lenticular-bedded. In cores that penetrated intertidal sediments, neap-spring cycles are sometimes prominent and the alternation of thick-thin lamina within cycles indicates diurnal inequality (Fig. 9). Apogean–perigean influence on sedimentation is indicated by the alternating thicknesses of spring tide maximums and the record of this influence is most prominent in the middle part of the delta plain. This is also the area where the number of laminae preserved per neap-spring cycle (≅18–20) is highest and where laminae average the greatest thickness. Similar sediments have been described previously from other tidally influenced systems (e.g., Dalrymple and Makino, 1989; Dalrymple et al., 1991).

Table 3 shows salinity, pH, and suspended sediment load values obtained at approximately the same locations as the cores shown in Fig. 9 and plotted on the map illustrated in Fig. 4. Cores 49 and 14 were recovered from brackish water areas, whereas core 17 was obtained from a region that only showed a trace of salinity during the dry season, and core 80 was obtained from a wholly freshwater area. Even though there is substantial salinity variation (mesohaline to tidal freshwater) between core locations, rhythmic heterolithic stratification is present in each core. Core 14 was recovered from a shoal in the Lassa Distributary that coincides with the approximate location of the dry season turbidity maximum.

Three other sediment types were observed in vibracores from bar forms in delta plain and alluvial valley channels. These are yellow-brown to dark olive-green laminated silts, brown to gray cross-bedded sands, and brown to gray flaser-bedded sands. All contain occasional layers of organic detritus, and many are burrowed. Most show some evidence of rhythmic stratification, but it is not as pronounced as the sediments described above. Laminated silts are most common in the upper few meters of bar forms, whereas flaser-bedded and cross-bedded sands usually are found at greater depth.

4.3. Distributary mouth and beach sediments

The delta coastline is about 160 km long and is composed of five distributary channel mouths separated by sand beaches (Fig. 2). Distributary mouth

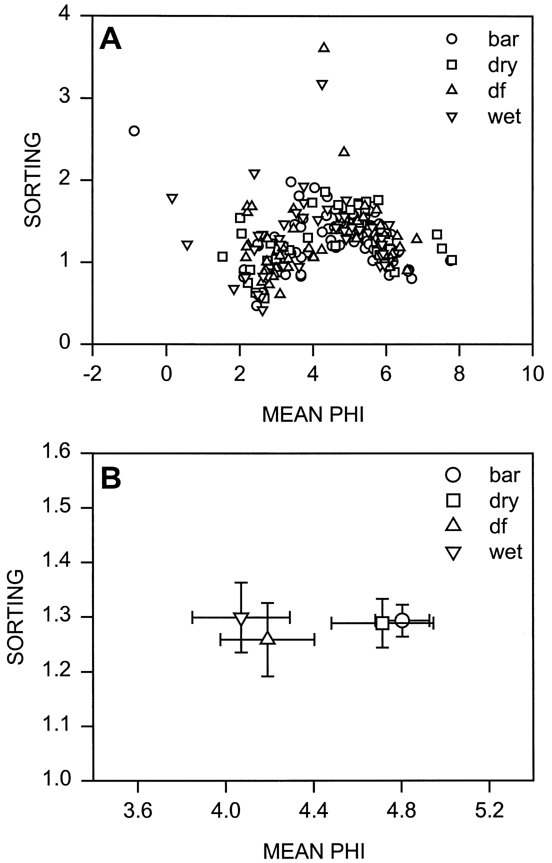

Fig. 6. Scatter plot (A) of mean ϕ values versus sorting values for the samples utilized. Mean values of ϕ and sorting (B) show the separation and grouping of sample sets. Error bars (B) are one standard error. Sample groups listed are dry (dry season grab samples), bar (point bars and midchannel bars), df (delta front and prodelta), and wet (wet season grab samples). Wet and dry comparisons are from grab samples and bar and delta front comparisons are from vibracore samples.

width ranges from 2 to 12 km, and the intervening beaches are up to 35 km in length. Beach ridges are readily apparent in aerial photographs up to 10 km inland from the coast in the southwestern part of the delta plain. In other areas, however, ridges are rapidly obscured by vegetation or buried beneath a layer of peat. Intertidal to supratidal beach sands are cross-bedded, brown to gray, and burrowed. Ridge and swale topographic relief on the delta plain is about 2 m, and beach sands are up to 5 m thick.

Distributary mouth sediments are composed primarily of massive to cross-bedded brown to gray shallow-subtidal to intertidal sands. Layers of organic detritus are occasionally present in these sands. Distributary mouth sands are usually no more than 4–5 m thick. Sand body geometry changes from one distributary mouth to the next in response to increasing tidal range. Following the classification scheme of Pigott (1995) sand body geometry at the mesotidal Igan distributary mouth is lobate; at the macrotidal Lassa distributary mouth sand body geometry is elongate tidal-ridged; and at the macrotidal Paloh, Belawai, and Rajang distributary mouths is tidal-ridged. In distributary mouths where sand body geometry is tidal-ridged, the intervening low areas between sand ridges are usually composed of silt and clay.

4.4. Delta front and prodelta sediments

At depths of 3 m or more below spring low tide, delta front and prodelta sediments are encountered and consist of gray to olive-black, burrowed, laminated silts and/or laminated silts and sands. Layers of organic detritus and carbonate nodules are occasionally present in these sediments. The carbonate nodules are composed primarily of calcite with minor amounts of siderite (Alan Bailey, personal communication 1998).

Subtidal delta front and prodelta sediments show evidence of heterolithic stratification (Fig. 8B), but evidence of rhythmicity is absent. Individual silt laminae and/or silt-and-sand interbeds are sometimes many centimeters thick. Examination of thickness variation of interbeds between cores within individual delta front areas (Fig. 10) shows similarity between cores in each area, but variation between areas. Harris et al. (1993) reported similar annual non-rhythmic, sand-and-silt delta front and prodelta interbeds in the Fly River delta.

4.5. Sediment budget

The delta front and prodelta of the Rajang River covers about 1650 km^2 and occurs between the depths of $\cong 3$ and 25 m below spring low tide. The upper limit was determined in this study and the lower limit is based on the work of Jackson (1962) and Pimm (1964). The mean thickness value for the annual silt laminae and silt-and-sand interbeds observed in vibracores is 1.02 ± 0.2 cm (90% confidence interval). The average bulk density of sediment in these cores from

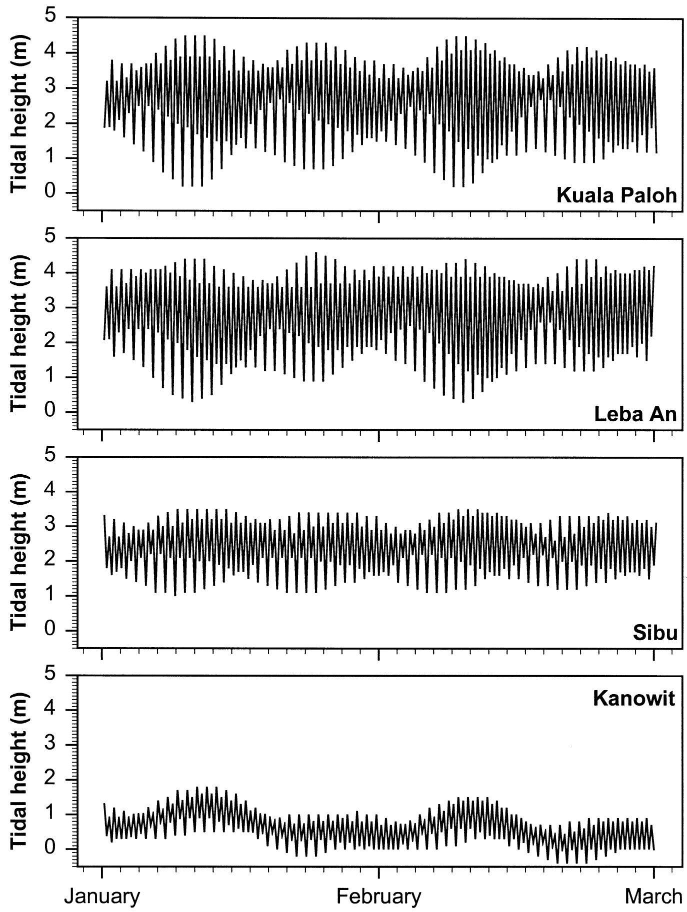

Fig. 7. Tide data from January to March 1993 for stations at Kuala Paloh, Leba An, Sibu, and Kanowit. See Fig. 4 for station locations.

the delta front and prodelta is 1.42 ± 0.17 g/cc (90% confidence interval) or $\cong 1.4\ \mathrm{MT/m^3}$. Assuming a uniform sediment distribution and density throughout the delta front and prodelta these values equate to $\cong 24 \pm 7.5 \times 10^6$ MT per year. A "rough" estimate of the amount of sediment deposited per year in delta front and prodelta areas is on the order of 24 million MT.

5. Discussion

5.1. Seasonal sediment transport and delta front sedimentation

Drainage basin discharge is reduced during an average dry season, channels in the alluvial valley and delta plain are not in bank-full conditions, and tidal processes dominate sediment transport. Much of the sediment delivered from the drainage basin goes into storage (Fig. 5C) on the delta plain. An unknown amount of sediment can, however, reach the South China Sea via the Igan and Lassa distributaries (Staub and Esterle, 1993) during the dry season.

In an average year, drainage basin discharge approximately doubles during the wet season. This additional discharge causes the water level in the alluvial valley channel to rise by 2 m or more (Royal Malaysian Navy navigation chart, 1979). Delta plain channels are in bank-full to over-bank conditions. The prevailing winds change direction from west and

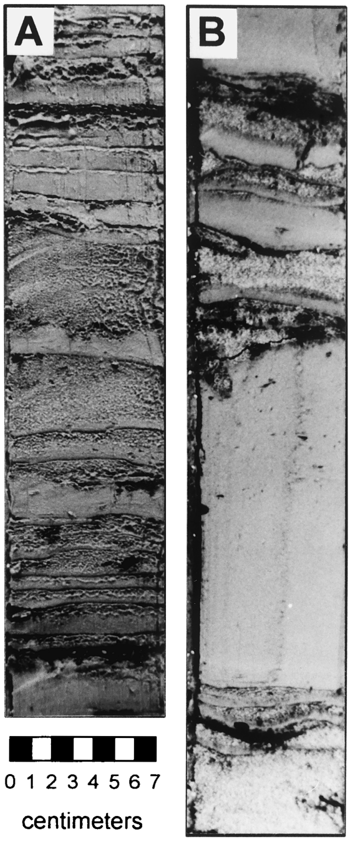

Fig. 8. An example of rhythmic heterolithic stratification (A) from a midchannel bar (vibracore 12) and an example of non-rhythmic heterolithic stratification from the delta front (vibracore 54). The location of vibracores 12 and 54 are shown on Fig. 4.

southwest to north and northeast, and average velocity nearly doubles (Scott, 1985).

Most drainage basin discharge flows west during the rainy season with accompanying changes in sediment transport, salinity, and estuarine circulation in the western part of the delta plain (Table 1; Fig. 5). The seaward parts of the Lassa and Paloh distributaries maintain partially mixed estuarine circulation patterns, but they are more vertically stratified than in the dry season. The Belawai distributary changes from a fully mixed estuary to a partially mixed estuary with good vertical stratification. These changes are the result of increased fluvial flux. The position of the turbidity maxima in each distributary channel moves to the distributary mouth or beyond, some 10 to 30 km seaward of their dry season locations. This seaward movement in the position of the turbidity maxima enables sediment to be transported directly to the delta front and prodelta during the wet season. Suspended load data combined with discharge data indicate that the amount of sediment transported to the coast during the wet season is in excess of the amount supplied by the drainage basin.

Changes in the distribution patterns of foraminifera within the Lassa distributary mirror the observed seasonal circulation changes. Murphy (1996) noted that the distributary channel samples do not contain a dominant foraminifera genus during the dry season, but the genus *Miliammina* dominates during the wet season. He suggested that the genus *Miliammina* was best adapted to the decreased salinity and increased pH of the distributary waters that occurs during the wet season.

The data demonstrate that siliciclastic suspended sediment is supplied to the delta plain from the drainage basin on a continuing basis. The amount of suspended sediment supplied from the alluvial valley (Fig. 5C) only increased by 10% in the wet season. This supply is a function of the nature of the source terrain. It is composed predominantly of fine-grained siliciclastic sediments, structural activity has been intense, and the rate of base-level lowering/epirogenic uplift is high (Farrant et al., 1995). Even though the drainage basin is densely vegetated in response to the ever-wet climate, the relief combined with the three factors just mentioned is sufficient to cause rapid weathering of siliciclastic sediments (Scott, 1985). This overall situation produces a constant supply of sediment.

Mean ϕ values (Table 2 and Fig. 6) generated from seasonal grab samples indicate they are from different populations. Comparison of dry season grab and core samples from point and midchannel bars indicates that the sediments preserved in the delta plain and alluvial valley channels are part of the same population as the dry season samples.

The comparison of mean ϕ and sorting data from wet season grab samples, and delta front and prodelta core samples demonstrates a high degree of similarity, indicating that sediment is transported to and deposited in the delta front and prodelta regions during the

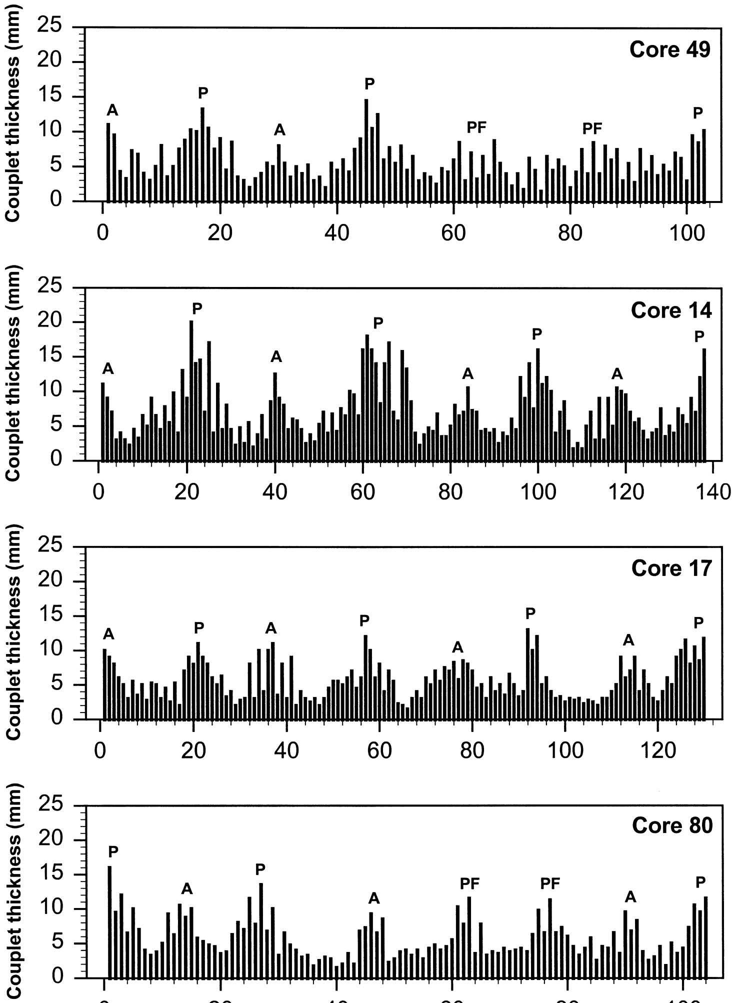

Fig. 9. Graphical representations of tidal laminae/couplet thickness variation present in vibracores 49, 14, 17, and 80. See Fig. 4 for core locations. In the graphs A equals spring tide at/near apogee, P equals spring tide at/near perigee, and PF equals phase flip (full or new moon occur on minor axis of lunar orbit).

wet season. These comparisons of sample sets indicate that not only do differences exist between dry and wet season sediment suites, but that differences also exist between the geographic regions where they are deposited and preserved.

Staub and Esterle (1994) estimated that prior to anthropogenic development the Rajang River drainage basin provided about 30 million MT of sediment annually to the delta. This estimate was corroborated by the work of Farrant et al. (1995). Volumetric analysis of varved delta front and prodelta sediments in this study indicates that about 80% (roughly 24 million MT) of this amount is supplied to the delta front and prodelta in an average year. The fate of the remaining sediment tonnage provided from the drainage basin is unknown, but it is probably either sequestered within the delta plain or supplied to the distal delta and shelf.

Direct sediment transport to the delta front and prodelta occurs primarily during the wet season and results in the deposition of annual sediment layers or varves. During the wet season a mud-drape covers

Table 3
Water sample values for cores shown in Fig. 9

Discharge 3000 m^3/s	Salinity (ppt)	pH	Suspended load (mg/l)
Dry season			
Core 49	15	7.0	610
Core 14	10	7.0	1240
Core 17	1	6.2	330
Core 80	0	6.4	340
Wet season			
Discharge 5200 m^3/s			
Core 49	10	7.8	720
Core 14	6	7.6	620
Core 17	0	7.3	360
Core 80	0	7.5	330

delta front deposits. Then wave reworking during the dry season results in the formation of a sandy, bioturbated, lag deposit. This results in silt and sand interbeds with a typical laminae thickness of about one cm. Harris et al. (1993) reported a similar situation for delta front of the Fly River. Thickness data (Fig. 10) indicate that the Paloh and Lassa distributaries deliver the most sediment to the coast, and percent sand data indicate that wave reworking is most intense on the west facing delta front.

5.2. Intertidal sedimentation, foraminifera assemblages, and progradation

Intertidal sediments in cores from the delta-plain bar forms show evidence of rhythmic heterolithic stratification (Fig. 8A) as a result of neap-spring variation in tidal current speed. These sediments are tidal rhythmites (e.g. Kvale and Archer, 1990). Neap-spring cycles can be prominent (Fig. 9) and alternation of thick-thin lamina preserved within some cycles indicates the presence of diurnal inequality.

Apogean–perigean influence on sedimentation (Fig. 9) is most prominent in the middle part of the delta plain. In both seaward and landward directions the signature amplitude is reduced. This reduction in amplitude is probably related to variations in wave and/or fluvial energy.

In cores 49 and 80 (Fig. 9) intervals are recorded where the semimonthly inequality of spring tides disappears. This disappearance in inequality may

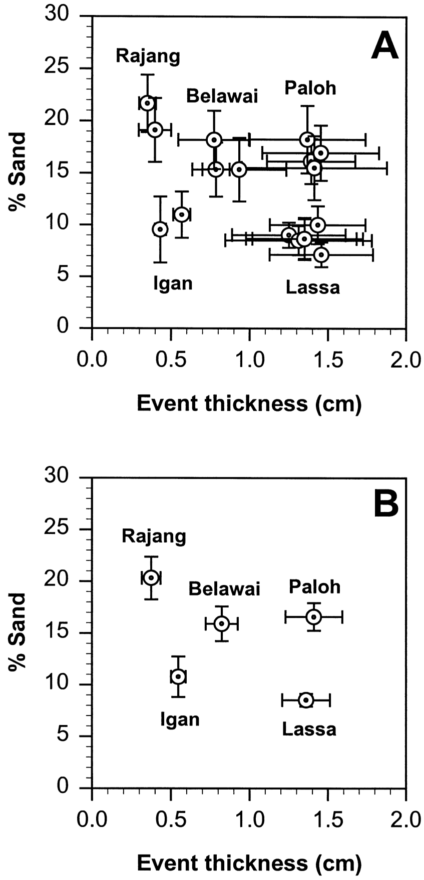

Fig. 10. Average annual event thickness values (A) for individual delta front/prodelta vibracores and average values (B) for each delta front/prodelta region. Error bars in each case are standard error. See Fig. 4 for the locations of cores and regions.

record phase flips. The semimonthly inequality of spring tides disappears (termed phase flip) when syzygy occurs along the minor axis of the lunar orbit. The recognition of this phenomenon in tidal rhythmites is discussed at length in Kvale et al. (1999).

In the middle part of the delta plain the number of preserved laminae per neap-spring cycle is highest (≅18–20) and the average thickness of laminae is also greatest. It is of interest that salinity data (Fig. 5A; Table 3) and channel margin vegetation (Scott, 1985) indicate that the channels in this region normally are filled with low-salinity brackish water to freshwater.

Suspended sediment data (Table 3) and core data

(Fig. 9) indicate that during the dry season thickest laminae development is coincident with the turbidity maximum position. Estuarine circulation models (Nichols and Biggs, 1985; Hart, 1995) suggest that this might be where these phenomena (highest number of laminae and greatest thickness) are most likely to occur. During the dry season upstream of this region, fluvial processes start to dominate transport and downstream sediments are generally transported upstream toward the turbidity maximum.

The turbidity maxima in the Rajang distributary channels that occur during periods of reduced or low discharge are of tidal origin. They are coincident with channel regions where extensive mud shoals and tidal flats have developed. Similar situations in partially mixed estuaries have been noted elsewhere (Buller et al., 1975; Wells, 1995).

In the seaward part of the delta plain, intertidal sediments from cores contain foraminiferal (Arenaceous; *Asterorotalia-Pseudorotalia*) assemblages that are the same as those found in saline influenced, dry season delta plain grab samples. Conversely, the sediments present in cores from the delta front and prodelta contain a diverse foraminiferal (Miliolid-*Ammonia*) assemblage (Murphy, 1996). This assemblage is the same as that found in the delta front and prodelta sediments of the Mahakam River delta (Carbonel and Moyes, 1987). Murphy (1996), using the succession of foraminifera described above and ^{14}C dates concluded that a regressive event in the delta plain has been ongoing for a minimum of 2200 years.

Previous studies have indicated that long term (≅8000 years) accretion and aggradation rates are on the order of 8 m/year and 1.5 mm/year, respectively, for the delta plain, and that Holocene freshwater peats in the delta plain are greater than 7000 years old (Staub and Esterle, 1993, 1994). These independent lines of evidence (sedimentation rates versus foraminifera succession) indicate that the Rajang has been a regressive system for much of the Holocene. It is also suggested here that the initial formation of the Rajang River delta coincided with the early Holocene deceleration in sea-level rise (ca. 8500–6500 years BP), as did many deltas worldwide (Stanley and Warne, 1994).

5.3. Sediment preservation bias and depositional succession

The data demonstrate that siliciclastic sediment deposition and preservation in the delta plain channels is biased significantly toward the dry season. Dry season sediments have a strong tidal signature that results from the dominance of estuarine processes. These rhythmically bedded, intertidal dry season sediments overlie distributary mouth sands which, in turn, overlie subtidal, wet season delta front and prodelta sediments. Unpublished drilling data and work by Jackson (1962) and Pimm (1964) indicate that this siliciclastic sediment package is on the order of 25–35 m thick in present coastal areas.

Galloway (1975) emphasized the dominance of marine processes in high-tide deltas. In the delta plain of the Rajang River when discharge is low ($>1000\ m^3/s$), all distributaries are dominated by tidal processes and sediment transport to the coast virtually ceases (Geological Survey of Malaysia, Sarawak, unpublished data). During low discharge intervals, the delta plain distributary channels function as meso- to macrotidal estuaries. In the dry season of 1936, brackish water was reported as far inland as the town of Sibu (Haji Rosli Bin Sahari, personal communication 1992), which is about 80 km from the present coast.

Conversely, sediment is delivered to the delta front and prodelta during high-discharge intervals and results in the deposition of annual sedimentation layers or varves. Annual sedimentation rates observed are similar to rates reported from other tide-dominated deltas (Harris et al., 1993; Hart et al., 1998). Data also demonstrate that during high discharge events (the wet season) sediment transport is primarily to the west and northwest.

6. Conclusions

Seasonal variation in discharge is the primary control on siliciclastic sediment distribution patterns in the Rajang River delta. The amount of sediment moved to the delta plain from the drainage basin is essentially constant. Most of the sediment supplied from the drainage basin goes into storage on the delta plain during intervals of low to moderate discharge (dry season), whereas during intervals of high discharge (wet season) much of this same sediment is moved to offshore areas.

Dry season estuarine processes control deposition of delta plain siliciclastic sediments. Most delta plain channel sediments show evidence of rhythmic heterolithic stratification and are burrowed and contain foraminifera in salt water influenced areas. Tidal rhythmites are developed best in the middle part of the delta plain, where distributary channels normally contain low-salinity, brackish water to freshwater. Tidal rhythmites preserved in the sediments most closely mirror tidal gauge data in this area.

Most delta front and prodelta sediments are implaced by wet season events. Preserved annual sediment layers, or varves, are on the order of one cm thick. These varves demonstrate that up to 24 million MT of sediment produced by the drainage basin is deposited in the delta front and prodelta region annually.

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References

Allen, G.P., 1987, Deltaic sediments in the modern and Miocene Mahakam delta. TOTAL Exploration Laboratory, Pessac, France, 53pp.

Anderson, J.A.R., 1961. The ecology and forests types of the peat swamp forests of Sarawak and Brunei in relation to their silviculture. PhD thesis, University of Edinburgh, Scotland, 117pp. (unpublished).

Anderson, J.A.R., 1964. Structure and development of the peat swamps of Sarawak and Brunei. J. Trop. Geogr. 18, 7–16.

Anderson, J.A.R., 1983. The tropical swamps of western Malesia. In: Gore, A.P.J. (Ed.). Mires: Swamp, Bog, Fen, and Moor, Ecosystems of the World, Regional Studies, 4B. Elsevier, Amsterdam, pp. 181–200.

Anderson, J.A.R., Muller, J., 1975. Palynological study of a Holocene peat deposit and a Miocene coal deposit from NW Borneo. Rev. Palaeobot. Palynol. 19, 291–351.

Barua, D.K., 1990. Suspended sediment movement in the estuary of the Ganges–Brahmaputra–Meghna River system. Mar. Geol. 91, 243–253.

Buller, A.T., Green, C.P., McManus, J., 1975. Dynamics and sedimentation: the Tay in comparison with other estuaries. In: Hails, J., Carr, A. (Eds.). Nearshore Sediment Dynamics and Sedimentation, Wiley, London, pp. 201–249.

Carbonel, P., Moyes, J., 1987. Late Quaternary paleoenvironments of the Mahakam delta (Kalimantan, Indonesia). Palaeogeogr., Palaeoclimatol., Palaeoecol. 61, 265–284.

Coleman, J.M., 1969. Brahmaputra River: channel processes and sedimentation. Sediment. Geol. 3, 129–239.

Coleman, J.M., Gagliano, S.M., Smith, W.G., 1970. Sedimentation in a Malaysian high tide delta. In: J.P. Morgan (Ed.), Deltaic Sedimentation, Modern and Ancient, SEPM Spec. Publ. 15, 185–197.

Dalrymple, R.W., Makino, Y., 1989. Description and genesis of tidal bedding in the Cobequid Bay-Salmon River estuary, Bay of Fundy, Canada. In: Taira, A., Masuda, F. (Eds.). Sedimentary Facies in the Active Plate Margin, Terra Scientific, Tokyo, pp. 151–177.

Dalrymple, R.W., Makino, Y., Zaitlin, B.A., 1991. Temporal and spatial patterns of rhythmite deposition on the mud flats in the macrotidal Cobequid Bay-Salmon River estuary, Bay of Fundy, Canada. In: D.G. Smith, G.E. Reinson, B.A. Zaitlin, and R.A. Rahmani (Eds.), Clastic Tidal Sedimentology, Can. Soc. Pet. Geol. Mem. 16, 137–160.

Esterle, J.S., Ferm, J.C., 1994. Spatial variability in modern tropical peat deposits from Sarawak, Malaysia and Sumatra, Indonesia: analogues for coal. Int. J. Coal Geol. 26, 1–41.

Farrant, A.R., Smart, P.L., Whitaker, F.F., Tarling, D.H., 1995. Long-term Quaternary uplift rates inferred from limestone caves in Sarawak, Malaysia. Geology 23, 357–360.

Folk, R.L., 1980. Petrology of Sedimentary Rocks, Hemphill, Austin, TX, 184pp.

Galloway, W.E., 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In: M.L. Broussard (Ed.), Deltas, Models for Exploration. Houston Geol. Soc., 87–98.

Hamilton, W., 1979. Tectonics of the Indonesian Region. US Geol. Surv. Prof. Pap. 1078, 345pp.

Harris, P.T., Baker, E.K., Cole, A.R., Short, S.A., 1993. A preliminary study of sedimentation in the tidally dominated Fly River delta. Gulf of Papua, Cont. Shelf Res. 13, 441–472.

Hart, B.S., 1995. Delta front estuaries. In: Perillo, G.M.E. (Ed.). Geomorphology and Sedimentology of Estuaries, Develop. Sediment., 53. Elsevier, Amsterdam, pp. 207–226.

Hart, B.S., Hamilton, T.S., Barrie, J.V., 1998. Sedimentation rates and patters on a deep-water delta (Frazier Delta, Canada): integration if high-resolution seismic stratigraphy, core lithofacies, and ^{137}Cs fallout stratigraphy. J. Sediment. Res. 68, 556–568.

Hutchison, C.S., 1989. Geological evolution of south-east Asia, Oxford Monographs on Geololgy and Geophysics, 13, Oxford University Press, Oxford, 368pp.

Hutchison, C.S., 1996. The 'Rajang accretionary prism' and 'Lupar Line' problem of Borneo. In: R. Hall, D. Blundell (Eds.), Tectonic Evolution of Southeast Asia. Geol. Soc. Spec. Publ. 106, 247–261.

Jackson, A., 1962. Sea-bed sampling off northwest Borneo. Brit. Borneo Geol. Surv., Ann. Rep., 51–55.

Jeeps, M.D., Gates, R.I., 1963. Physical aspects of the January–February, 1963, floods in Sarawak. Sarawak Hydrol. Yearbook Water-Year, 1962–1963, pp. 40–95.

Kvale, E.P., Archer, A.W., 1990. Tidal deposits associated with low-sulfur coals, Brazil Fm. (Lower Pennsylvanian), Indiana. J. Sediment. Petrol. 60, 563–574.

Kvale, E.P., Johnson, H.W., Sonett, C.P., Archer, A.W., Zawistoski, A., 1999. Calculating lunar retreat rates using tidal rhythmites. J. Sediment. Res. 69, 1154–1168.

Lam, K.S., 1988. Sibu Area, Central Sarawak Malaysia, Explanation Sheet 2/111/12. Geol. Surv. Rpt., Geol. Surv. Malaysia, Sarawak, 151pp.

McBeth, J.L., 1995. Composition of coarse-grained siliciclastic sediment from a tropical peat-accumulating delta: Rajang River delta, Sarawak, East Malaysia. MS thesis, Southern Illinois University, Carbondale, 104pp. (unpublished).

McBride, E.F., 1971. Mathematical treatment of size distribution data. In: Carver, R.E. (Ed.). Procedures in Sedimentary Petrology, Wiley, New York, pp. 109–127.

Morley, R.J., Flenley, J.R., 1987. Late Cainozoic vegetation and environmental changes in the Malay Archipelago. In: Whitmore, T.C. (Ed.). Biogeographical Evolution of the Malay Archipelago, Oxford Monographs on Biogeography, 4. Oxford University Press, Oxford, pp. 50–59.

Murphy, S., 1996. Distribution and ecology of Holocene foraminifera within the Lassa distributary of the Rajang River delta, Sarawak, East Malaysia. MS thesis, Southern Illinois Univ., Carbondale, 121pp. (unpublished).

Nichols, M.M., Biggs, R.B., 1985. Estuaries. In: Davis Jr, R.L. (Ed.). Coastal Sedimentary Environments, Springer, New York, pp. 77–186.

Pigott, J.D., 1995. A seismic classification scheme for clastic shelf wedges (deltas). In: Oti, N.M., Postma, G. (Eds.). Geology of Deltas, A.A. Balkema, Rotterdam, pp. 17–29.

Pimm, A.C., 1964. Seabed sediments of the South China Sea. Geol. Surv., Borneo Reg., Malaysia, Ann. Rpt., pp. 122–146.

Postma, H., 1980. Sediment transport and sedimentation. In: Olausson, E., Cato, I. (Eds.). Chemistry and Biochemistry of Estuaries, Wiley, Chichester, pp. 153–186.

Royal Malaysian Navy, 1979. Navigation chart SAR 51C. Dir. Mar., Kuching, Malaysia.

Royal Malaysian Navy, 1992. Tide tables, volume 2. Hydrogr. Dir., Kuala Lumpur, Malaysia, 146 pp.

Royal Malaysian Navy, 1993. Tide tables, volume 2. Hydrogr. Dir., Kuala Lumpur, Malaysia, 146 pp.

Scott, I.M., 1985. Soils of the Central Sarawak Lowlands, East Malaysia. Soil Mem. 2, Depart. Agriculture, Soils Div., Kuching, Sarawak, East Malaysia, 302pp.

Stanley, J.S., Warne, A.G., 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. Science 265, 228–231.

Staub, J.R., Esterle, J.S., 1993. Provenance and sediment dispersal in the Rajang River delta/coastal plain system, Sarawak, East Malaysia. In: C.R. Fielding (Ed.), Current Research in Fluvial Sedimentology, Sediment. Geol. 85, 191–201.

Staub, J.R., Esterle, J.S., 1994. Peat-accumulating depositional systems of Sarawak, East Malaysia. Sediment. Geol. 89, 91–106.

Styan, W.B., Bustin, R.M., 1983. Sedimentology of Fraser River delta peat deposits: a modern analogue for some deltaic coals. Int. J. Coal Geol. 3, 101–143.

Wells, J.T., 1995. Tide-dominated estuaries and tidal rivers. In: Perillo, G.M.E. (Ed.). Geomorphology and Sedimentology of Estuaries, Develop. Sediment., 53. Elsevier, Amsterdam, pp. 179–205.

Whimore, T.C., 1984. Tropical Rain Forests of the Far East. 2nd Edn, Oxford University Press, Oxford, 352pp.