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TAPHONOMIC CONTROLS ON THE DISTRIBUTION OF PALYNOMORPHS IN TIDALLY INFLUENCED COASTAL DELTAIC SETTINGS

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ABSTRACT

Palynomorph concentrations for water-column and sediment-water interface samples are presented for two coastal deltaic systems influenced by the range of tidal regimes to assess whether any taphonomic bias exists in pollen assemblages. The localities are the microtidally influenced Mobile-Tensaw River Delta, Alabama, United States, and the meso- to macrotidally influenced Rajang River Delta, Sarawak, East Malaysia. Mobile-Tensaw Delta data represent collections over a 13-month period; Rajang River Delta data represent sampling during the 1992 dry season. Results are reported for: (1) pollen concentration in suspended sediment loads and bottom sediments of distributary channels, and (2) selected spore-and-pollen frequencies in channels influenced by meso- and macrotidal processes. An increase in pollen concentration/liter occurs in all delta distributaries at water-column depth, and a positive relationship exists between pollen concentration and suspension load. Concentrations at the sediment-water interface are highest in tidally influenced areas where Heterogenous Aggregate Organic Matter (OM) clasts (floccules) dominate palynofacies assemblages, and statistically significant for Mobile-Tensaw lower delta plain sites. Hence, microtidal influence at the interface between fresh and brackish waters affects palynomorph concentration in bottom sediment and may be a function of flocculation induced by salinity flux. In contrast, concentrations are highest in bottom sediments of Rajang River distributaries where little active sediment transport occurs and tidal range is highest, and is due to several factors including a high proportion of Heterogenous Aggregate OM clasts. Additionally, the magnitude of tidal displacement impacts palynomorph distribution in the Rajang Delta, with mangrove pollen found in alluvial plain samples, a distance of ∼120 km from distributary mouth bars. Understanding the sedimentological conditions under which coastal deltaic pollen assemblages are preserved is critical before these can be used for paleoecological reconstruction.

INTRODUCTION

Interpretations of vegetational patterns in the sedimentological record based on dispersed palynomorphs—pollen and spores—form a fundamental basis for paleoecological reconstructions, as well as the identification for ecosystem perturbation and landscape recovery when viewed over stratigraphic intervals. Terrestrial palynomorph records often originate from lacustrine, fluvial, alluvial plain (overbank), and coastal deltaic deposits, but our understanding of palynomorph transport, deposition, and preservation potential in these modern environments is rudimentary. Our best understanding of pollen-and-spore taphonomy comes from studies of modern lakes in various settings (e.g., Chen, 1987; Goodwin, 1988; Jackson, 1994; Pennington and Tutin, 1996) used to document Quaternary climate change as reflected by changes in representative vegetation.

Phytoclast transport and deposition in fluvial and coastal regimes, on the other hand, have received little attention (Gastaldo, 1994), although it is demonstrated that these sediments receive a significant percentage of their pollen sum in response to seasonally influenced fluvial processes (e.g., Bonny, 1978; Brown et al., 2007). Pollen spectra in coastal environments are documented for a few fluvially dominated (e.g., Starling and Crowder, 1980; Chmura and Liu, 1990; Smirnov et al., 1996), estuarine and bay (incised valley fill) sediments (e.g., Groot, 1966; Brush and Brush, 1972, 1994; Farr, 1989; Traverse, 1994), and coastal tidal flat (e.g., Chmura and Eisma, 1995) regimes. Patterns recorded in deltaic sediments deposited under the myriad of fluvial, tidal, and wave processes, however, are understudied (e.g., Muller, 1959; Chmura et al., 1999; Hofmann, 2002; Hardy and Wrenn, 2009). More attention often is paid to offshore sediments where terrestrial palynomorphs are used to demonstrate the former presence of river influence on continental shelves (e.g., Cross et al., 1966; Farley, 1994; Moss et al., 2005).

This contribution examines water-column and sediment-water interface (grab) samples from two coastal deltaic systems developed under varying tidal influence, to assess what, if any, taphonomic bias may be present as indicated in their palynomorph content. Results are reported for: (1) the distribution of pollen concentrations in suspended sediment loads and bottom sediments of distributary channels throughout each delta, and (2) selected pollen-and-spore frequencies in channels influenced by meso- and macrotidal processes to demonstrate identified patterns that would influence interpretation if encountered in deep time records.

MOBILE-TENSAW MICROTIDAL BAYHEAD DELTA

The Mobile-Tensaw River delta, located north and east of Mobile, Alabama, is the largest inland delta complex, with water throughput originating from the fourth-largest drainage system in the conterminous United States (Ryan and Goodell, 1972; Fig. 1). The watershed drains approximately 115,513 km^2 (44,000 mi^2) of land in the southeastern United States (Ishphording et al., 1996), with a mean annual discharge of 1,670 m^3/sec (Ryan and Goodell, 1972). The deltaic deposits have prograded through an incised valley, the initial inundation of which began no earlier than 9.6 ka based on ^{14}C dates of articulated bivalves and wood directly above the exposure surface in Mobile Bay (Greene et al., 2007). Sediments in the incised valley were deposited subsequent to postglacial sea-level rise (Kindinger et al., 1994) and in an abrupt reorganization of the coast about 8.2 ka (Rodriguez et al., 2010). The bayhead delta, extending from just south of Battleship Parkway in Mobile, where distributary mouth bars now form, to the confluence of the Alabama and Tombigbee Rivers, approximately 56 km to the north, currently encompasses 756 km^2 (292 mi^2) of rivers, oxbow lakes, bayous, swamps, and marshes, and occurs at the head of Mobile Bay, a large microtidal estuary. Six distributary channel complexes comprise the delta including the Mobile, Tensaw, Middle, Apalachee, Spanish, and Blakely Rivers, all of which debouch directly into Mobile Bay.

The delta–bay complex is under the influence of a humid, subtropical climate, with an average annual temperature of 20 °C (68 °F). Winds average 13 km/hr (8 mi/hr) and generally are stronger and originate from the North in the winter, with calmer southerly winds prevailing in the summer. Rainfall occurs throughout the year, but is concentrated in

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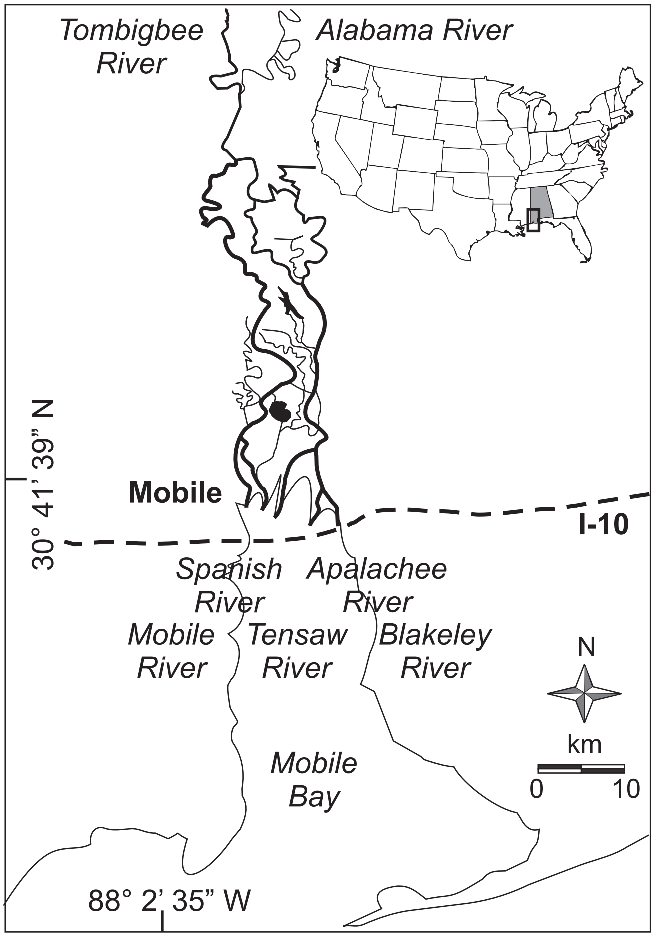

FIGURE 1—General location map of the United States in which Alabama (gray shade) and the Mobile-Tensaw River Delta, the terminus of which is just south of the Interstate 10 (I-10) causeway, are outlined. Five distributary channels—Mobile, Spanish, Tensaw, Apalachee, and Blakeley Rivers—discharge sediment and organics into Mobile Bay.

the summer due to thunderstorm activity (Hummell and Parker, 1995). Hurricanes affect the Gulf Coast periodically, which result in transport of large volumes of sediment from the delta into the bay.

The Mobile River drainage system is the fourth largest in the United States, with discharge rates in the delta reflecting seasonality. The highest discharge values are recorded in the spring (March–May) and lowest values in the fall (September–November) months (Ryan and Goodell, 1972). Floods occur mainly in the spring months, resulting in average daily discharge values up to 3,115 m^3/sec (110,000 ft^3/sec); autumnal discharge rates can be as low as 283 m^3/sec (10,000 ft^3/sec; Ishphording et al., 1996). Discharge rates into Mobile Bay for spring and fall intervals are 3,400 m^3/sec (120,064 ft^3/sec) to 280 m^3/sec (9,888 ft^2/sec), respectively.

Sediment load entering the delta and bay also is influenced by seasonal trends, with an annual suspended sediment load estimated to be 3.7 billion kg/yr (4.08 million tons/yr; Ishphording et al., 1996). Bedload estimates are 553 million kg/yr (0.61 million tons/yr) with the eastern Pleistocene escarpment contributing about 82 million kg/yr (0.09 million tons/yr), resulting in an overall sediment load of ~4.42 billion kg/yr (4.78 million tons/yr; Ishphording et al., 1996). Approximately 25% of the sediment load that enters the delta is retained, with the remainder being discharged into Mobile Bay.

Most areas along the Gulf Coast experience diurnal tides and are microtidally influenced. Mobile Bay and the Mobile-Tensaw River Delta experience mixed tides that include both daily and semi-daily oscillations (O'Neil and Mettee, 1982). Maximum displacement under nonstorm conditions is 1.16 m (3.8 ft), as recorded by the U.S. Army Corp of Engineers at the Mobile State Docks gauging station (Lat. 30.7083, Long. −88.0433). Over the course of a year, tides show a sinusoidal pattern with highest tidal amplitudes recorded in the spring and autumn months, corresponding to the vernal and autumnal equinoxes, and low tidal amplitudes near the summer and winter solstices. The greatest displacement occurs near the autumnal equinox; the lowest displacement near the summer solstice. Salt-water incursion occurs into the delta, in response to tidal bore, with midchannel depth salinities ranging up to 3 ppt (Slone, 1999), although salinities up to 5 ppt are reported during summer base flow (Chadwick and Feminella, 2001).

MESO- TO MACROTIDAL RAJANG RIVER DELTA

The Rajang River Delta in the East Malaysian state of Sarawak, Borneo (Fig. 2), 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 (Staub and Esterle, 1993; Gastaldo, 2010). The Rajang River drainage basin covers ~50,000 km^2 in area, with the delta plain and upstream river valley of an approximately 4,900 km^2 area that includes an alluvial valley floodplain, a sediment-starved, tidally flushed delta plain, and an actively accreting rectilinear delta plain (Staub et al., 2000). Progradation in the alluvial (incised) valley began with a thick succession of gravel in response to sea-level rise and flooding, followed by a complex depositional history in the northeast and southwestern parts of the delta (Staub and Gastaldo, 2003). Peat accumulation began in the northeast between 7.3 and 5.8 ka in response to a slowing in sea-level rise and continues to amass; the southeastern delta plain is dominated by beach ridges and gley soils mantled by mangrove and *Nypa* vegetation.

The alluvial valley, located between the towns of Sibu and Kanowit, is characterized by the main trunk of the Rajang River where it has cut a relatively straight path through the Central Borneo Massif. Bifurcation of the channel into a rectilinear north-south pattern, controlled by subsurface faults, occurs approximately at Sibu with the development five distributary channels. These are, from the north to southwest, the Igan Lassa, Paloh, Belawai, and Rajang rivers.

The climate on the western side of Borneo is classified as tropical everwet (Morley and Flenley, 1987; nonseasonal, no shortage of rainfall) with a mean annual temperature of 27 °C (81 °F) and humidity ranging from 55% in the day to almost 100% at night (Scott, 1985). Variable winds are in response to both the northeast monsoon (December to March) and southwest monsoons (remainder of the year), with rainfall averaging in excess of 370 cm/year (Gastaldo, 2010). Dambul and Jones (2008) place the delta in their Samarahan climatic group where the wet season period begins in October–November and extends to March–April, with moderate to strong seasonality. This part of Sarawak routinely experiences 5–7 months of absolute wet per year, and is considered perhumid following the classification of Cecil (2003).

Discharge rates vary in response to the monsoons, with typical single-month rates for the drainage basin ranging from ~1,000 to 6,000 m^3/s, whereas the average monthly discharge rate is about 3,600 m^3/s (Staub et al., 2000). Peak discharge rates during the northeast monsoon are reported to exceed 25,000 m^3/s (Jeeps and Gates, 1963), but Staub et al. (2000) note a marked difference between wet and dry seasons. Estimated discharge during the wet season when these researchers sampled averaged 5,200 m^3/s, whereas discharge averaged 3000 m^3/s during dry season sampling. Additional discharge is received from the proximal hills region in the southeastern delta (~275 and 530 m^3/s for the dry and wet seasons, respectively) and the Retus River drainage basin (200 and 400 m^3/s, respectively). Typical discharge for the five coastal-plain rivers ranges from about 250 to 1,000 m^3/s seasonally, but can be substantially higher and lower during extreme weather events.

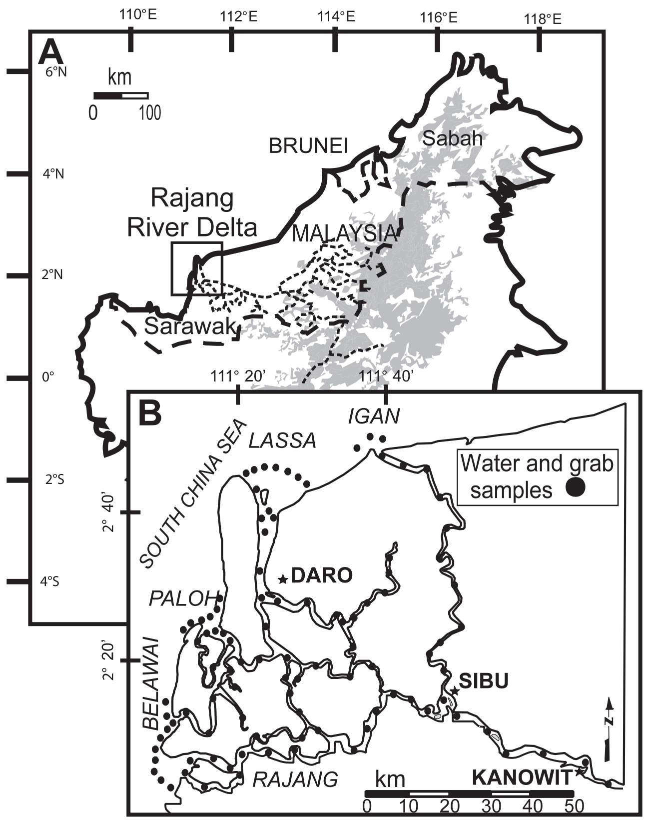

FIGURE 2—The island of Borneo on which the Rajang River Delta is located. A) The Rajang River Delta (outlined) in Sarawak, East Malaysia, receives its discharge from the Borneo Central Massif (gray), and empties in the South China Sea. B) Map showing the location of the distributary channels—Rajang, Belawai, Paloh, Lassa, and Igan rivers—in addition to water-column and grab sites utilized in this study (see Supplementary Data Fig. 1 for water-column/sediment-water interface grab-sample numbers).

Discharge during the northeast monsoon impacts the hydrogeochemistry of the delta plain channels, with the most pronounced changes in the Lassa, Paloh, and Belawai distributaries (Staub et al., 2000). Salinity values begin to increase from 0 ppt approximately 25 km down river from the boundary between the alluvial valley and delta plain, with maximum values of 25 ppt found in distributary mouths during the dry season. These values drop by half during the wet season while, coincidentally, the degree of vertical stratification increases. For most delta plain regions, the position where surficial brackish water is encountered moves 20–30 km seaward when compared to the dry season (Staub et al., 2000). Concomitantly, distributary channel water became slightly basic during the wet season.

The historical sediment load for the Rajang Delta is not known. Staub and Esterle (1993) estimate that the Rajang River drainage basin provided ~30 million metric tons (MT) of sediment annually to the delta before anthropogenic development, similar to the estimate of Farrant et al. (1995). Staub et al. (2000) report only a slight variance in suspension load delivered to the delta from the drainage basin, with ~2.0 MT/s during the dry season and 2.2 MT/s during the wet season. Included in the suspension load is a ~1-m-thick interval of fluid or fluff mud (McAnally, 2000), floccules resulting from surface ionic charged particle aggradation, that occurs above the sediment-water interface, and is transported up and down the channel in response to tidal cycles. Using aerial photographs, Scott (1985) calculated that progradation of the delta plain occurred at a rate of 1.0 to 1.5 km^2/year, with long-term accretion rates reported to be ~8 m/year in the delta plain for the last 7.5–8.5 kyr (Staub and Esterle, 1993). Approximately 24 million MT of sediment are supplied to the delta front and prodelta in an average year (Staub et al., 2000).

The delta plain and alluvial valley are affected by semidiurnal to diurnal tides, ranging from ~2 to 6 m in displacement (Staub and Esterle, 1993) with a noticeable diurnal inequality (Staub et al., 2000). Both mesotidal and macrotidal regimes influence parts of the delta, and increase in range from northeast to southwest from 2.9 m at Kuala Igan to 5.8 m at Kuala Rajang (Fig. 2). In the Igan distributary, tides are very close to diurnal during neap phases of neap-spring cycles, whereas tides more inland at Sibu, although greatly reduced in range, are most similar to Kuala Paloh. Even at Kanowit, nearly 120 km from the coast, the river maintains a long-term average of tidal heights related to neap-spring cycles with sedimentological evidence of superimposed short-term (semi-diurnal) cycles.

METHODOLOGIES

Samples of surface and at-depth (within 2–5 m of the bottom) waters, collected using a LaMotte JT-1 sampler, were complemented by grab samples obtained using a Wildco sediment sampler. Twelve sites in the Mobile-Tensaw River were repeatedly sampled over a ~13 month duration (19 April 1997–04 April 1998; Fig. 3), and 126 sites were sampled in the Rajang River Delta during the dry season in July–August 1992 (see: Staub and Esterle, 1993; Gastaldo and Staub, 1997; Supplementary Data Fig. 1). These include channels in the alluvial and delta plains. Collection sites in the Alabama coastal plain include one in each of the Alabama (site 8), Tombigbee (site 9), and Mobile (site 10) rivers. Collection sites in the delta include: four in the middle to upper delta plain (sites 6, 7, 11, 12); and five in the lower delta located in the Mobile (site 1), Tensaw (site 2), Spanish (site 3), Appalachee (site 5), and Blakeley (site 4) rivers. Although the position for each sampling Mobile-Tensaw delta site could not be exactly replicated, Smirnov et al. (1996) demonstrated that the concentration of palynological debris does not vary within a channel, making comparisons across time credible. Due to equipment failure and/or high discharge conditions in February and April 1998, there are no data for several sampling sites in the Mobile-Tensaw system. Seven water-column and bottom-sediment–sampling sites are in the alluvial plain to the southeast of the Rajang River Delta (see Staub et al., 2000), whereas the remainder of the samples originate from within the delta (Staub and Gastaldo, 2003). Whenever possible, suspended load sediment samples were taken during slack water in the tidal cycle when the tidal bore brought discharge to a stillstand which, depending upon the tidal phase, may last longer than one hour in duration before flow reverses.

Water-column samples were filtered either in the laboratory (Mobile-Tensaw) or field (Rajang) through a 10 μm screen, and the residuum rinsed into plastic bottles. Water-column samples also were tested for salinity and pH (Slone, 1999; Staub et al., 2000). A 1-gram subsample was recovered from bottom sediments, standardizing the amount to be processed.

The water-column and sediment-water interface samples were processed using standard palynological procedures as recommended by Doher (1980). One *Lycopodium* spike tablet (Lund University, batch 710961) with a known quantity of spores (13911 ± 2.2%) was added to each sample and used to calculate palynomorph concentration in each sample per liter or gram (following Traverse, 1988). All palynomorphs were subjected to acetylation, residua were stored in ethanol, and at least 5 glycerin jelly slides were made for each collection. Palynological preparations from the Mobile-Tensaw River Delta are housed at Colby College; preparations from the Rajang River Delta are in the possession of Dr. Kate Bartram (Seafood Industry Council) in New Zealand.

A minimum of three slides or 300 pollen-and-spore grains was point counted and identified to genus, where possible, for each sample. In addition, exotic *Lycopodium* grains also were counted when encountered during routine pollen counts and used to calculate pollen concentration following established methodologies (Traverse, 1988).

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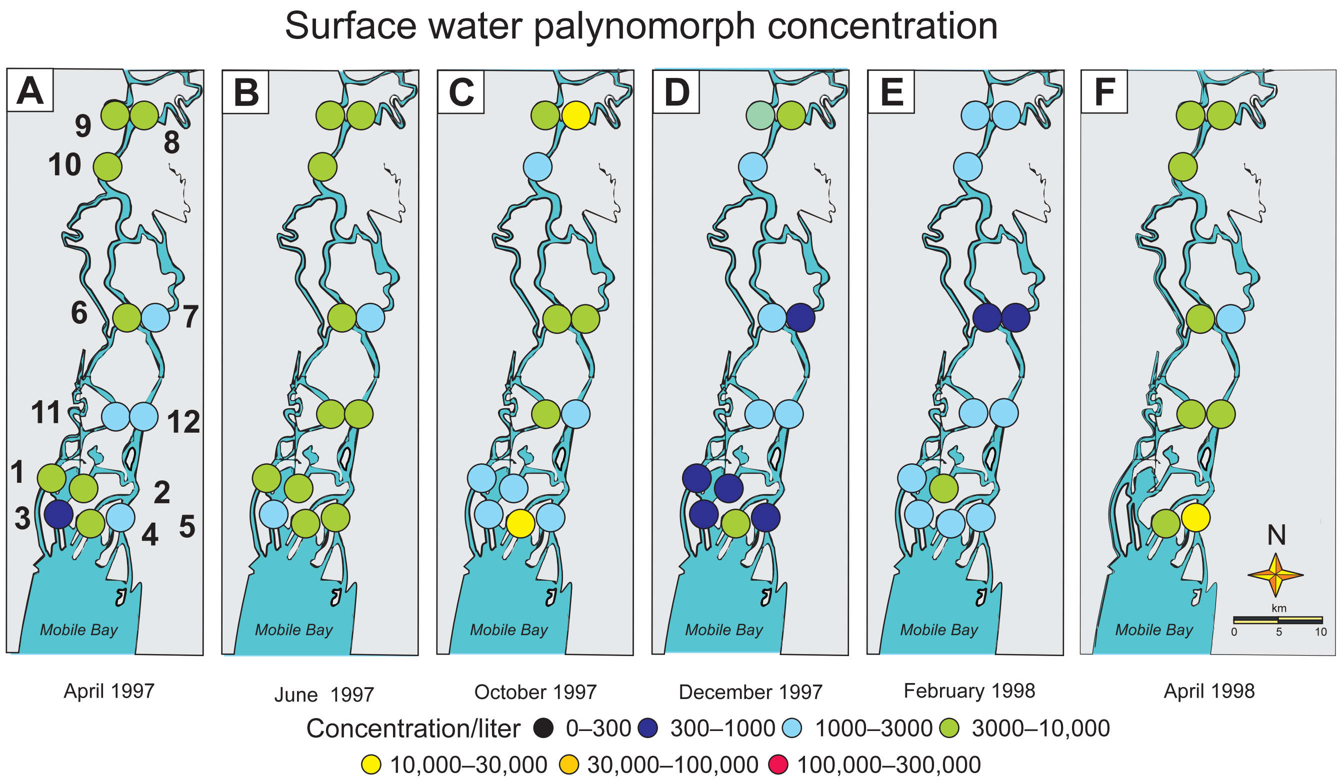

FIGURE 3—Pollen concentrations per liter in surface waters for six sampling dates at twelve stations across the delta. There are three upper delta plain sites, four middle delta sites, and five lower delta plain sites. Collection site numbers are provided in the April 1997 plot and are the same throughout the study. Pollen concentration/l in A) April 1997, B) June 1997, C) October 1997, D) December 1997, E) February 1998, and F) April 1998. Data are missing where river velocities or weather phenomenon precluded sample recovery.

No differentiation was made between fungal spore types, which were tallied in a single category. Water-column data are reported in palynomorphs/liter, whereas sediment-water interface data are reported in palynomorphs/gram.

Grain-size analyses were conducted on sediment-water interface samples using standard, dry sieving techniques for the $<4\ \Phi$ fraction. The $>4\ \Phi$ fraction for all Mobile-Tensaw River samples were assessed using pipette analysis; a Spectrex laser particle size analyzer was used to assess the fine fraction from the Rajang River Delta. Mean and standard deviation calculations follow Folk and Ward (1957). Total organic carbon (TOC) was performed using a Leco CHN-600 instrument, with a 10% HCl pretreatment to remove any carbonate fraction.

Meteorological and hydrological data for collection dates were acquired from various governmental agencies, where available. Rainfall data for the two weeks prior to sample collection for the Mobile-Tensaw River system originated from NOAA; tidal data were obtained from the Army Corp of Engineers gauging stations at Barry Steam Plant (N 31° 00′ 28.31″, W 88° 00′ 40.66″) and the Alabama State Docks (N 30° 43′ 08.89″, W 88° 03′ 10.96″). Rainfall data for the dry season and wet season sampling in the Rajang River Delta are for Kapit and Belaga, and originate from the Malaysian Meteorological Department, whereas tidal data from eight gauging stations come from the Royal Malaysian Navy (1992, 1993).

RESULTS

Mobile-Tensaw River

Total palynomorph concentration per liter of river water or gram of bottom sediment varied both temporally and spatially over the 13 month study, and concentration varied with collection depth in the water column (see Supplementary Data Tables 1–3). For analytical purposes, three physiographic provinces—the upper delta (sites 8–10; Fig. 3), the middle delta (sites 6–7, 11–12), and lower delta (sites 1–5)—are compared below. A relationship is found throughout the delta between total palynomorph concentration and mean Φ at the sediment-water interface, and is best defined by the natural log (ln) trend.

Surficial Pollen Concentrations.—Temporally, pollen concentration ranged from a low of 556/liter in December 1997 to a high of 25,140/liter in October 1997 (see Supplementary Data Table 1). Overall, the highest pollen concentrations are recorded in October (0 = 7,074/l), whereas the lowest concentrations occur during the winter months of December (0 = 1,794/l) and February (0 = 1,879/l). Surficial pollen concentrations during the other sampled months range between 3,371/l and 5,568/l, indicating that there is no wide variation in overall temporal pattern (Fig. 3). But, when the average pollen concentrations for each collection time are analyzed using Kruskal-Wallis ANOVA, at least one population's mean is significantly different (adjusted $H = 23.23$, $p = 0.0003$). This is the October data set.

There is a consistent pattern to the pollen distribution in the river systems of the delta (Fig. 3), with equivalent average values in the regions of the upper, middle, and lower delta. Lower concentrations only are found in the lower delta sites in December which are not statistically significant. Only in two collection sites, at different times of year, were concentrations statistically higher than either the regional or overall average; these are site 5 in the Tensaw River during October 1997 and site 4 in the Blakeley River during April 1998. When the pollen concentrations from the three regions are compared using the Kruskal-Wallis ANOVA statistic, there is no significant difference between the upper, middle, and lower delta (adjusted $H = 1.34$, $p = 0.51$).

Pollen Concentrations At Depth.—The depth from which water-column samples were collected ranged from 1.5 to 5 m above the

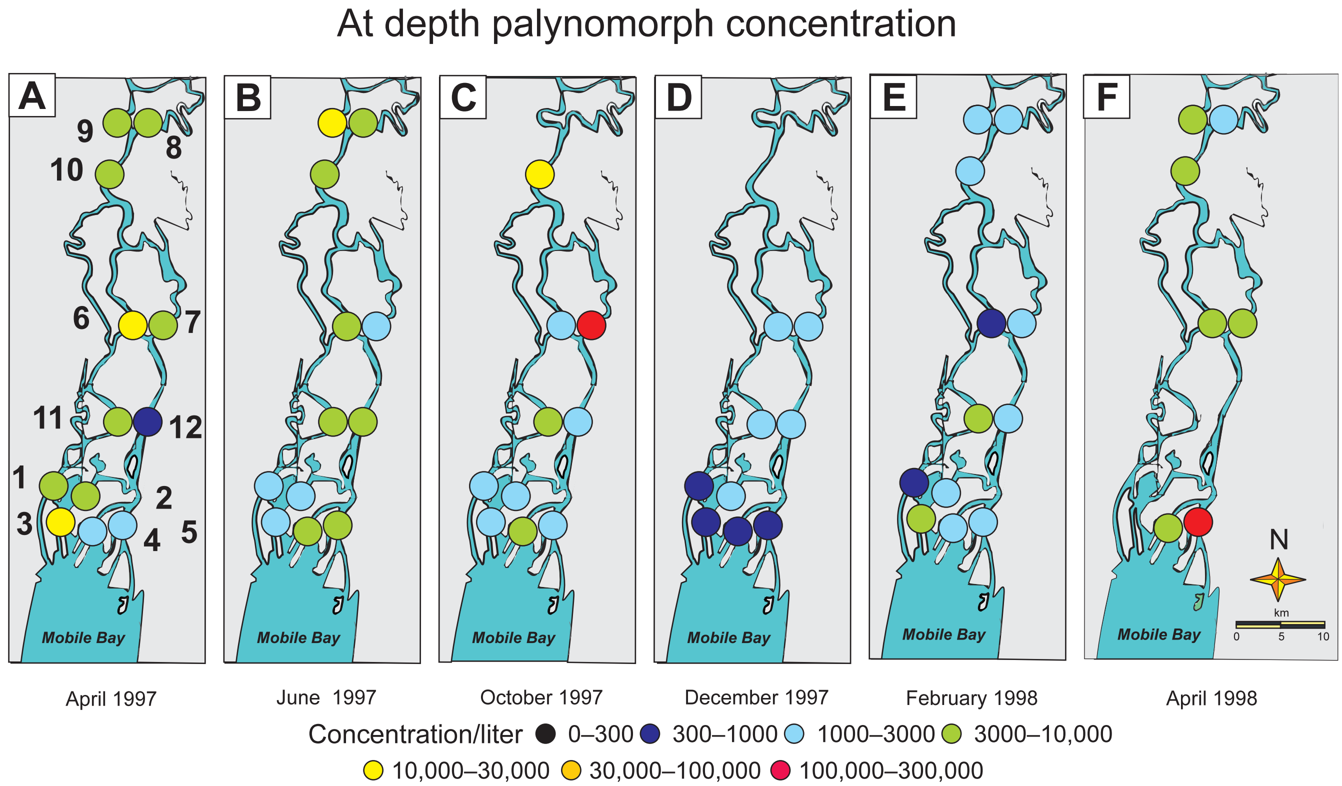

FIGURE 4—Pollen concentrations per liter of water-column samples recovered at depth for six sampling dates at twelve stations across the delta. Collection site numbers are provided in the April 1997 plot and are the same throughout the study. Pollen concentration/l in A) April 1997, B) June 1997, C) October 1997, D) December 1997, E) February 1998, and F) April 1998. Data are missing where river velocities or weather phenomenon precluded sample recovery.

sediment-water interface, depending upon location and river-flow stage (see Supplementary Data Table 2). The range of concentrations is similar to those obtained for surface waters, with a minimum of 404/l in December 1997, to a high of 115,379/l in April 1998, with overall highest concentrations also recorded for this sampling time (21,492/l). Similar to surface-water concentrations, the lowest values occur in December 1997 (1,445/l) and February 1998 (2,281/l; Fig. 4). One anomalously high value in the October 1997 data set (site 7; 119,297/l) raises the average value for this sampling date above the remaining months in the study. The October values for the other collection sites are more similar to those found in other parts of the delta during the remainder of the year, where they range between 1,403/l to 22,805/l. Again, when the collection dates are compared using the Kruskal-Wallis ANOVA, two populations' means are significantly different (adjusted $H = 20.33$, $p = 0.001$). These are the October 1997 and April 1998 data sets.

A relatively consistent pattern of pollen concentration emerges within the river channels of the alluvial plain and Mobile-Tensaw River Delta over the sampling interval, with lower values recorded mainly in the lower delta. The distribution of sites where high pollen concentrations occur varies through time, with only the June alluvial plain sample from the Tombigbee River and the April 1998 Blakeley River site appreciably and significantly different (Fig. 4). When the pollen concentrations from the three regions are compared using the Kruskal-Wallis ANOVA statistic, there is a statistically significant difference between the upper, middle, and lower delta (adjusted $H = 7.67$, $p = 0.02$), but it is noted that data are missing for some sites due to high river velocities that precluded sample recovery.

Sediment-Water Interface Samples.—Bottom sediment varies from collection site to collection site, and each site also varies over the course of the sampling period (see Supplementary Data Table 3). The coarsest sample is a coarse sand (0.17 Φ, site 4), whereas the finest is clay (8.17 Φ, sample 3); both of these sites are in the lower delta. There are more sand than silt or clay samples from the sediment-water interface, and most sites are skewed positively (to finer clasts). Grain-size sorting ranges from moderately well to very poorly sorted depending upon the position in the delta and time of year, and organic content is variable.

The Total Organic Content (TOC) of bottom sediments also varies from site to site across the study area. A maximum value of 5.16% was found in the lower delta (site 3, April 1997), whereas the minimum value of 0.035% occurs in the middle delta (site 6, April 1997). Highest TOC values are found in the southwestern part of the delta in the marshlands, and in the Mobile River; this also is reflected in the Total Organic Nitrogen (TON) values. Most TOC:TON ratios of samples analyzed are <10, indicating an algal origin of the organic matter, with a mixed signature (>10, <20; Meyers, 1994) found only in site 3 (lower delta); sites 7, 11 and 12 (middle delta); and site 9 (upper delta).

Pollen Concentrations.—Overall, pollen concentrations at the sediment-water interface are higher than values found in the water column, ranging from a single site low of 36/g in December 1997 to 70,467/g in April 1998. The lowest average pollen concentration is found during December 1997 (5,074/g), whereas the highest is in April 1998 (14,545/g). At two collection times, there was a higher average concentration in the Mobile River than in the Tensaw River and associated channels (Fig. 5). These were April 1997 (adjusted $H = 4.01$, $p = 0.045$) and December 1997 (adjusted $H = 7.469$, $p = >0.001$). There is no significant difference in bottom concentration when the collection dates are assessed with the Kruskal-Wallis ANOVA (adjusted $H = 2.573$, $p = 0.765$).

There is a statistically significant difference in pollen concentrations when the three different regions of the system are compared over the course of the yearly sampling (adjusted $H = 13.75$, $p = 0.001$). Absolute pollen concentrations are higher in the lower delta sites than in the other parts of the regime, with the highest values originating from the distributaries of the Mobile River (Fig. 4).

Pollen Concentration and Grain-Size Relationship.—A plot of palynomorph concentration against mean grain size depicts a trend of

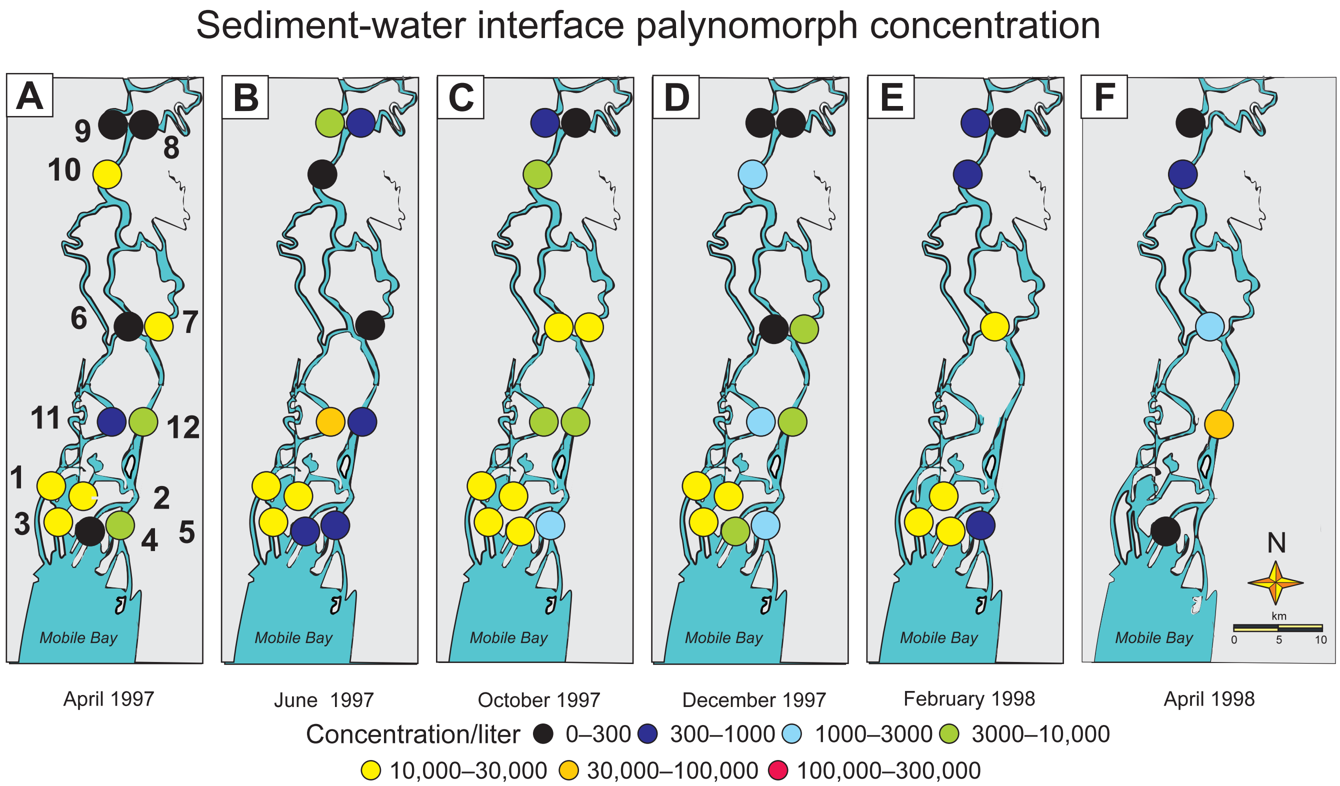

FIGURE 5—Pollen concentrations per gram of bottom-sediment grab samples for six sampling dates at twelve stations across the delta. Collection site numbers are provided in the April 1997 plot and are the same throughout the study. Pollen concentration/g in A) April 1997, B) June 1997, C) October 1997, D) December 1997, E) February 1998, and F) April 1998. Data are missing where river velocities or weather phenomenon precluded sample recovery.

increasing concentration with decreasing clast size (Fig. 6) until the hydrodynamic equivalency of pollen is reached (~6.25 Φ; medium-fine silt). As grain size continues to fine, a consistent palynomorph concentration is maintained into the clay-sized clast range. The relationship is best defined by a natural log regression-line trend with an r = 0.52. When evaluating these relationships in geographic context, more coarse samples with low palynomorph concentration occur in the upper and middle delta plain, whereas more fine samples with high palynomorph concentration are from the lower delta plain (Fig. 6).

Rajang River Delta

Although palynological data originate from sampling only in July–August 1992, as compared with the Mobile-Tensaw River data set, they represent conditions during the dry season when sediment deposition occurs (Staub et al., 2000). For analytical purposes, all water-column data in the cases where multiple samples were taken are combined due to the low number of samples processed. Palynomorph concentrations at the sediment-water interface are compared between mesotidal and macrotidal sites, as well as brackish and fresh-water areas (Fig. 7).

Water-Column Pollen Concentrations.—Pollen concentration in suspended sediment samples is low, with most values <3,000 grains/liter (ranging from 0 to 41,422/l; Fig. 8). Surficial water values are lower than samples taken at depth (range from 0 to 8,102 grains/l), with values more commonly lowest near the river mouths (Fig. 8A). Surficial water-column samples average 561 grains/l (see Supplementary Data Table 4). In contrast, pollen concentrations increase with water depth that are an order of magnitude higher (range 0–22,028 grains/l), with depths sampled within 1–2 m of the channel bottom (see Supplementary Data Table 5). Water-column samples from depth average 3,356 grains/l. When surface-water concentrations are compared with those taken at depth, there is a statistically significant difference between them (Mann-Whitney U Test; z = 13.965, p = 0.0002). The highest concentrations are found in the Lassa distributary system (Fig. 8B), and a strong positive correlation exists between suspension load and pollen concentration (r = 0.58, Fig. 9).

In general, there is a decrease in pollen concentration at depth westward in the delta plain towards the Rajang, Belawai, and Paloh distributary mouths, and an increase in concentration north through the Lassa. Concentration also is seen to decrease along the Igan distributary (Fig. 8B). Low pollen concentration at depth is associated with areas of highest salinity in the delta plain.

Sediment-Water Interface Samples.—The distribution of bottom sediment is variable throughout the delta, with river mouths or former strand plains dominated by sand (Fig. 7B; Staub and Gastaldo, 2003). A higher proportion of clay is found to the southwest in the Rajang River, whereas sediments are more mixed in the Igan River. Sediment samples processed for pollen range from medium sand (N = 1; 1.93 Φ, site 38 to the west of Sibu) to clay (N = 1; 7.8 Φ, site 66 in the Lassa River estuary), with the majority being silt (N = 21; average 5.64 Φ).

The Total Organic Content (TOC) of bottom sediments, as determined from vibracore samples, varies in relation to grain size. TOC values for silty sand (Φ = 3.25) range from 0.36% to 7.68%, those for silt (Φ > 4) range from 0.19% to 6.10%, and clay (Φ > 8) was found to range from 0.04% to 18.78%.

Pollen Concentrations.—Gastaldo and Staub (1997) report that palynomorphs average 0.7% of the total palynofacies (OM) fraction in grab samples from the sediment-water interface, but concentrations are high when compared with those in the water column (see Supplementary Data Table 6). These range from a low of 88/g (site 60 in the Paloh River) to 178,500/g (site 87 in the Belawai River), and show no relationship to water-column concentrations. There is a significant difference between the pollen concentration at depth and that found at the sediment-water interface (Mann Whitney z = 16.231, p = <0.0001). But, there is no significant difference in bottom concentrations when collection sites deposited within fresh-water or

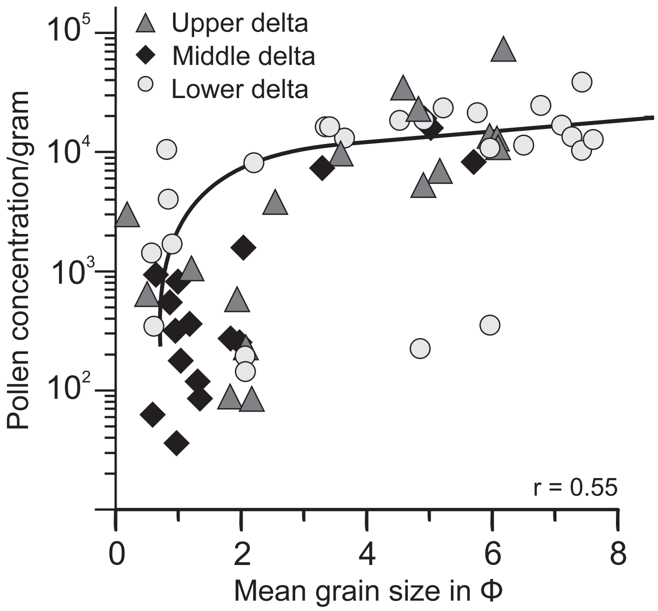

FIGURE 6—Palynomorph concentration per gram plotted against mean grain size in Φ for grab samples over the course of the 13 month study. The variance in sample-grain size throughout the delta is shown with respect to sites in the upper, middle, and lower delta. The correlation coefficient of the regression line is 0.55, indicating a positive relationship between grain size and pollen concentration. Concentrations do not increase significantly once the palynomorph hydrodynamic equivalence is reached at ~6.25 Φ.

brackish-water influences are compared ($z = 0.501$, $p = 0.479$), or when sites under mesotidal and macrotidal influences are assessed ($z = 0.02$, $p = 0.887$). When samples from individual rivers are compared, the highest concentration values characterize tidal environments with little active sediment transport (e.g., Rajang and Belawai Rivers; Kruskal-Wallis ANOVA, adjusted $H = 10.211$, $p = 0.037$). Hence, pollen concentrations at the sediment-water interface are not equivalent throughout the delta, with highest values from channels in the southwestern area where little active sediment transport occurs (Fig. 8C).

Pollen Concentration and Grain-Size Relationship.—A plot of palynomorph concentration against mean grain size depicts a trend of increasing concentration with decreasing clast size (Fig. 9B) until the hydrodynamic equivalency of pollen is reached (~6.25 Φ; medium-fine silt). The overall relationship is best defined by a natural log regression line with an $r = 0.13$; hence, no strong relationship exists between median grain size at the sediment-water interface and pollen concentration. The same relationship holds when pollen concentration is plotted against sorting coefficient, although with a higher correlation coefficient ($r^2 = 0.47$).

Distribution of Spores and Pollen.—The pollen spectra in the alluvial valley sample near Sibu (Fig. 2B) and the delta plain are dominated by riparian plants, those living along the river margins, and mangrove taxa, the geographic extent of which are limited by the landward incursion of salt water (Fig. 7). Few representatives of the peat-forming vegetation (Anderson, 1964, 1983; Staub and Esterle, 1994) are encountered in channel sediment and, where found, generally comprise <1% of the pollen count (see Supplementary Data Table 6). Two spore-and-pollen distributional patterns are presented to demonstrate the magnitude of tidal influence in the system.

Monolete and trilete spores, originating from epiphyllous riparian and groundcover ferns, are common and may comprise >50% of a sample (e.g., Fig. 10). The highest frequencies of monoletes are found in the southwestern delta plain within the macrotidal-dominated reaches of the Rajang River, with high counts in the Igan and upper reaches of the Rajang Rivers, near Sibu (Fig. 10A). These delta plain sites are in the areas of greatest tidal influence, and presently are associated with anthropogenically disturbed landscapes. When the absolute counts of monolete spores from fresh-water and brackish-water collection sites are compared, no statistical difference is found ($z = 2.949$, $p = 0.086$). The significant difference is in their relative frequency of occurrence in different parts of the delta plain (Fig. 10A). In contrast, trilete frequencies are lower than those of monolete taxa,

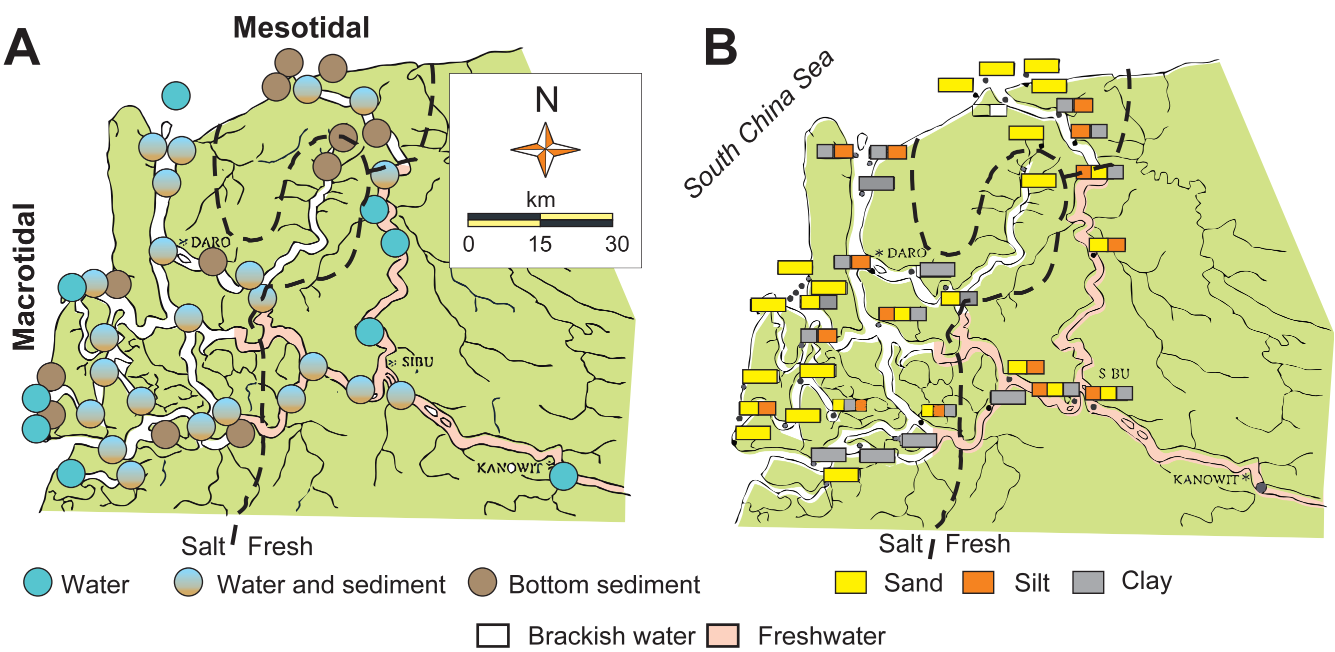

FIGURE 7—Location maps of the Rajang River Delta, Sarawak, East Malaysia. A) Sites where water-column (surface and depth), bottom grab samples, or both were collected that form the basis of the study. B) Distribution map of bottom sediment, grain-size fractions as determined from grab samples, and the demarcation (dashed line) between fresh-water and salt-water (estuarine) areas in the delta, which also marks the landward limit of mangrove taxa along channel margins (adapted from Staub and Esterle, 1993; Staub et al., 2000; and Staub and Gastaldo, 2003).

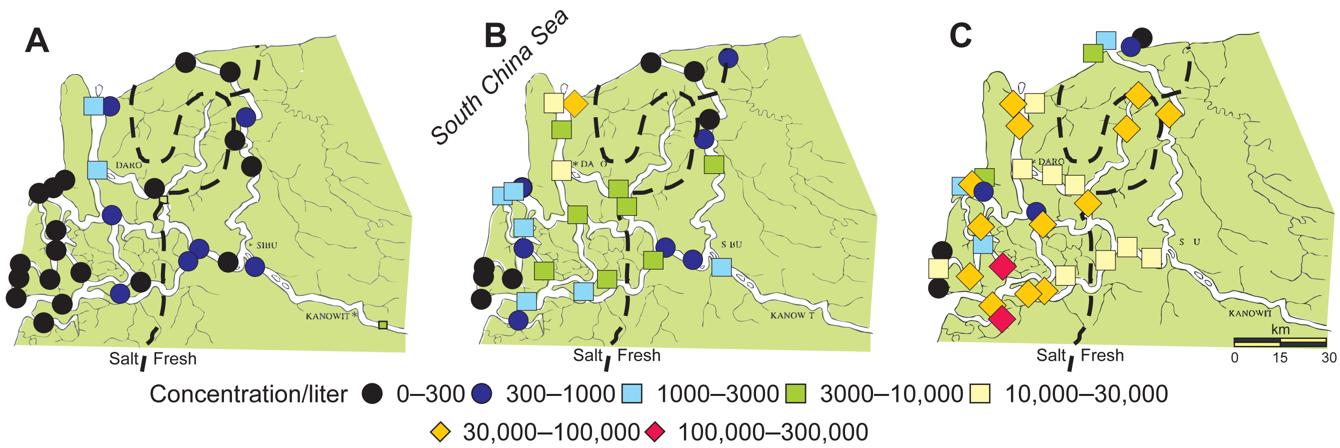

FIGURE 8—Distribution of palynomorph concentrations across the Rajang River Delta during the dry season sampling in July–August 1992. The demarcation between fresh-water and salt-water (estuarine) areas in the delta marks the landward limit of mangrove taxa along channel margins. A) Concentration of pollen/liter in surface water samples. B) Concentration of pollen/liter in water samples recovered at depth. C) Concentration of pollen/gram in grab samples from the sediment-water interface. Low palynomorph recovery is indicated by circles; moderate pollen recovery is indicated by squares; high pollen recovery is indicated by diamonds.

and exhibit a consistent pattern throughout the delta (Fig. 10B). There are higher proportions of triletes in the inactive southwestern regions near anthropogenic disturbance than in other parts of the system.

Mangrove pollen originate from the distal parts of the delta plain but are found throughout the delta and into the alluvial valley sampling site (Fig. 10C). Hence, mangrove taxa are encountered as far inland as Sibu (~75 km straight-line distance from the mouth of the Igan and Rajang Rivers; ~120 km river distance) in frequencies of 5% of the pollen spectra. There is a clear and abrupt increase in mangrove pollen frequency at the salt-water limit in the macrotidally flushed delta; a pattern that is not evident in the Igan River under mesotidal influence, which may be a function of sample number.

Although *Rhizophora* pollen dominates across mangrove pollen spectra in the delta, a diversity of taxa is encountered at each sampling site (Fig. 11). These include *Avicennia, Brownlowia, Ceriops, Acrostichum, Casuarina,* and *Nypa* in all macrotidal (Lassa, Paloh, Belawai, Rajang) sites under salt-water influence, with an alpha diversity of 4 taxa per sample (minimum $\alpha = 1$; maximum $\alpha = 8$; see Supplementary Data Table 6). Systematic diversity averages 4 taxa per site in the fresh-water samples, with *Brownlowia* and *Casuarina* common in the Rajang River deposits but absent in the Igan site. The concentration of *Brownlowia* pollen in the sediment-water grab samples of the Rajang River is related directly to the presence of this taxon in the area, and either an absence or low percentage of this taxon at all other collection sites is a function of transport (Fig. 11).

DISCUSSION

The way in which palynomorphs are introduced to surface waters in river systems is either directly as airborne (wind-borne) particles and through precipitation (McCully et al., 1956; McDonald, 1962), or from canopy runoff or drainage from across the land surface (e.g., Pelgar, 1993). Grain density, generally slightly >1.0 (Brush and Brush, 1994; Holmes, 1994), plays a role in their settling through the water column, as uptake of fluid occurs through germinal apertures following degradation of protoplasm, resulting in a change of density (Davis and Brubaker, 1973). Some pollen types, such as those found in the gymnosperms where air is trapped in sacci, float longer before beginning their descent through the water column. Hopkins (1950) notes that temperate, arboreal pollen sinks in beakers of still water within 5–10 minutes, and different pollen types sink at different rates (Holmes, 1990). Where pollen is suspended in water at velocities >20cm/sec^2 (Holmes, 1994), however, they will be retained in suspension load and transported until flow velocities are reduced that allow for settling. In natural systems where river discharge velocities fluctuate in response to rainfall, or coastal deltaic systems that are influenced by both fluvial and tidal activity of various magnitudes, palynomorph response is not well understood.

The current models for the incorporation of palynomorphs in Holocene coastal deltaic regimes are based on a small number of studies that include both experimental and empirical data. Experimental results, such as those of Hopkins (1950), Brush and Brush (1972), and Holmes (1990, 1994), provide inferences into how palynomorphs of various morphotypes settle from suspension load and may be incorporated in the sediment record. Empirical data range from studies centered on pollen concentration in water-column and sediment-water interface studies, with inference about the resultant pollen spectrum in the sediment. In coastal settings under the influence of fluctuating salinity and various tidal regimes, however, palynomorph deposition may be more a function of their encapsulation in macro- and micro-floccules (Chmura and Eisma, 1995; unstructured heterogenous aggregates of Gastaldo et al., 1996, fig. 5F) and/or fecal pellets (Chmura et al., 1999) than direct settling through the water column. Although there is a wide array of modern deltas (e.g., Sidi et al., 2003), few of these have been sampled to assess the palynological relationship with the sedimentary record. Most studies are in the temperate to subtropical zones, with a focus on the Mississippi delta (Chmura and Liu, 1990; Chmura et al., 1999; Smirnov et al., 1996) and the Rhone delta (Cambon et al., 1997), although studies on tropical deltas have been conducted by Muller (1959) and Hofmann (2002) in the Orinoco delta, Wang et al. (1982) in the Yangtze River delta, Somboon (1990) in the Gulf of Thailand mangroves, Ayyad et al. (1992) in the Nile Delta, and Hardy and Wrenn (2009) in the Mahakam Delta. Each system has a unique set of physical parameters controlling delta geometry, size, and sedimentation patterns of both siliciclastic and biogenic clasts. The current study examines the relationship of palynomorph assemblage attributes in deltas, where tidal influence ranges from microtidal to macrotidal, in an attempt to discern potential taphonomic bias in the resultant pollen record.

The Mobile-Tensaw River Delta located at the head of Mobile Bay, Alabama, experiences a microtidal influence which, at spring tide, extends to the confluence of the Alabama and Tombigbee Rivers, nearly 60 km inland from the terminus of the delta (Fig. 1). Pollen concentrations range from values as low as 404/ l to as high as 115,379/ l, and parallel those reported by Campbell and Chmura (1994) and others for rivers and delta distributaries in the southeastern United States. Pollen concentrations at all sampled positions in the water column (surface and deep waters, and sediment-water interface) vary seasonally; this is a pattern similar to that reported by Chmura and Liu

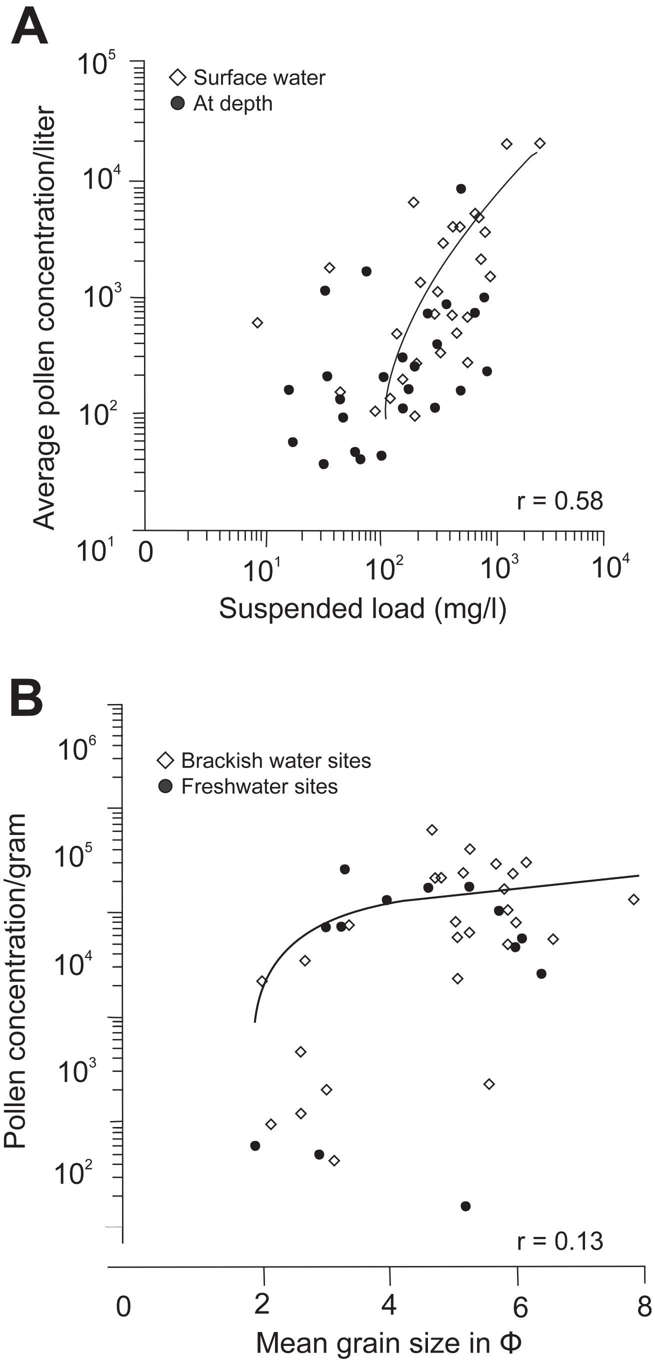

FIGURE 9—Plots showing the relationship between pollen concentration and water-column and grab-sample parameters. A) Average pollen concentration per liter plotted against mg/l of suspended sediment load. Pollen concentrations from surface water (open diamonds) and those recovered at depth (circle) display similar patterns. B) Pollen concentration per gram of bottom sediment plotted against mean grain size (Φ). Higher concentrations are found in brackish (open diamond) than in fresh-water (circle) sites.

(1990) for their seven-month study in the microtidally influenced, fluvial-dominated Mississippi Delta. Pollen concentration is lowest in surface waters, with increasing concentrations at depth at all sampling sites, regardless of the time of year. The same trend is seen experimentally (Brush and Brush, 1972; Holmes, 1990, 1994), and also has been reported for the distributary channels in the Mississippi River (Smirnov et al., 1996) and temperate microtidal estuaries (Trinity-Galveston Bay, Texas; Traverse, 1990, 1994; Chesapeake Bay, Maryland; Groot, 1966; Brush, 1989) in the United States. This positive relationship between pollen concentration and suspended sediment load conforms to reports of other fluvial regimes (e.g., Brown, 1985; Matsushita, 1985), and may reflect pollen concentration by gravity through sinking.

All sediment-water interface samples in the Mobile-Tensaw River Delta are statistically similar in their palynomorph concentrations when sites are compared at a single collection time during the year. But, when pollen concentrations are assessed spatially over the 13-month sampling interval, there is a statistically significant difference between the upper, middle, and lower delta sites. Collectively, lower delta sites have a higher concentration of palynomorphs/g of sediment than either the middle or upper delta regions. Lindley et al. (2000) report that the palynofacies suite in estuarine-influenced, lower delta regions is dominated by Unstructured Organic Matter (OM; particles with form but without structure, Gastaldo et al., 1996). Both Heterogeneous Granular and Heterogenous Aggregate OM categories are encountered, with palynological components often acting as a nucleating agent for the aggregate. Isolated spore-and-pollen grains, though, also are found in these palynological preparations apart from Heterogenous Aggregates and represent $<3.6\%$ of assemblages. A statistically significant increase in palynomorph concentration in the lower delta sites indicates that either: (1) the aggregation of organic matter into floccules in response to saline influence changes their settling rate; (2) even microtidal influence at the interface between fresh and brackish waters affects palynomorph concentration in bottom sediment, allowing for settling at low flow velocities (generally >20 cm/s for saturated pollen; Holmes, 1994) or during stillstand prior to the reversal of the tidal bore; or (3) that both factors influence palynomorph deposition in this setting. The highest pollen concentration values occur in the Mobile, Raft, and Spanish Rivers (sites 1–3; Fig. 5), the distributary channel system with the highest suspension load (McPherson et al., 2003); these data conform to previously published reports.

The Rajang River Delta, located on the western coast of Sarawak debouching into the South China Sea, is under the influence of mesotidal amplitudes in the Igan River and macrotidal amplitudes throughout the remainder of the regime (Fig. 2). Tides affect localities as far inland as Kanowit in the alluvial valley where amplitudes may reach 2 m displacement (Staub et al., 2000). Pollen concentrations of water-column samples recovered during the 1992 dry season exhibit a range of values similar to those found in the Mobile-Tensaw River system (Figs. 3, 4, 8A, B) and in northern Australia (Moss et al., 2005). Low concentrations range from 0 in both samples taken at the surface and at depth, to high surficial values of 8,102 grains/l and 22,028 grains/l at depth. The same relationship of increasing pollen concentration with depth, and the fact that this is related to increased sediment load (Fig. 9A), occurs in this coastal regime; it is reported above and elsewhere (Groot, 1966; Brown, 1985; Matsushita, 1985; Chmura and Liu, 1990). Although the low calculated value of 42 grains/g at the sediment-water interface is a similar value reported in other regimes, these samples originate from sites along the coast directly adjacent to river mouths and reflect winnowing by wave activity (Fig. 8C). When only collection sites in distributary channels are considered, the lowest pollen concentrations at the sediment-water interface occur where rivers debouch into the South China Sea near the mouth bars. These sites are sand dominated where low pollen concentrations are expected (Fig. 9B). Pollen concentrations at all other sites range from a low of 13,580 grains/g to a high of 178,500 grains/g, and are up to 50% higher than the highest concentration recorded in the Mobile-Tensaw River delta. Concentrations are highest in bottom sediments of distributaries where little active sediment transport occurs and tidal range is highest (Fig. 8C); conversely, suspension load concentrations are highest in distributaries with greatest sediment transport without regard to tidal influence (Fig. 8B; Staub and Esterle, 1993; Staub et al., 2000).

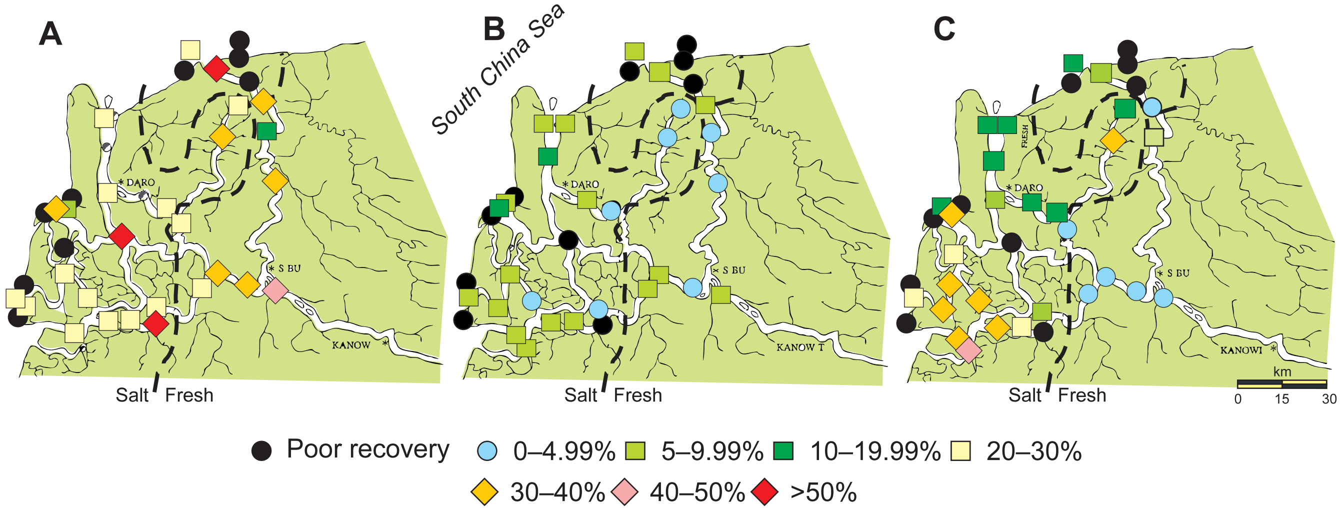

FIGURE 10—Distribution of selected across the delta as a proportion of the pollen count. The demarcation between fresh-water and salt-water (estuarine) areas in the delta marks the landward limit of mangrove taxa. A) Distribution of monolete spore taxa showing high frequencies in nearly all sampling sites. B) Distribution of trilete spore taxa showing low frequencies throughout the delta. C) Distribution of mangrove pollen showing high frequencies in the mangrove-dominated areas surrounding the Rajang and Belawai distributary channels, sites of no active sedimentation. Note that mangrove pollen accounts for up to 5% of assemblages to the interior of the delta, and can be found as far inland as alluvial valley sediments southeast of Sibu. Low palynomorph percentages are indicated by circles; moderate pollen percentages are indicated by squares; high pollen percentages are indicated by diamonds.

Similar to the Mobile-Tensaw Delta, palynofacies assemblages in the Rajang River Delta are dominated by Heterogenous OM categories (Gastaldo et al., 1996; Gastaldo and Staub, 1997). Isolated palynomorphs represent a very low percentage of all processed samples, with more pollen-and-spore grains found within aggregates (=floccules; Chmura and Eisma, 1995). Gastaldo et al. (1996) identify three clusters of assemblages from vibracores recovered from distributary channel bars, two of which delimit fresh-water sites (Clusters 1) from those in the inactive, salt-water flushed, macrotidally influenced sites in the Belawai and Paloh distributaries (Cluster 2). Cluster 1 assemblages are characterized by a high proportion of Structured OM and Homogenous Unstructured OM (dammar), whereas the estuarine sites of Cluster 2 record the highest quantities of Heterogenous Aggregate OM. Gastaldo and Staub (1997) also report a higher proportion of Black Indeterminate (pyrite) in sites representing Cluster 2 than elsewhere, a function of

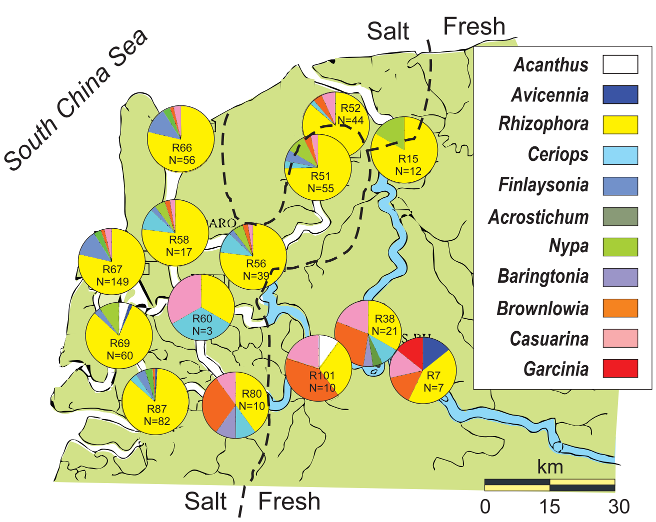

FIGURE 11—Proportion of mangrove taxa identified in sediment samples in the brackish and fresh-water collection sites in the Rajang River Delta during the dry season. Collection sites are labeled as R*; N in the each pie diagram represents the number of mangrove pollen grains and spores counted in the sample.

early burial diagenesis. It is in these estuarine regions, however, that the highest palynomorph concentrations are found at the sediment-water interface, and are up to an order of magnitude higher than in the fresh-water sites (Fig. 8C). Hence, these saline-influenced areas that are most prone to the generation of floccules (Dyer, 1995) also are the sites in which palynomorphs are concentrated. This probably is a function of higher settling rates for larger aggregate clasts during tidal stillstand than individual phytoclasts, alone (Chmura and Eisma, 1995).

The relationship between palynomorphs and the fine clastic fraction identified by others (e.g., Muller, 1959; Cross et al., 1966; Chen, 1987) is reconfirmed in the current study in both the Mobile-Tensaw River and Rajang River deltas. In both instances, there is a trend of increasing concentration with decreasing clast size (Figs. 6, 9B) until the hydrodynamic equivalency of pollen is reached. This is ~6.25 Φ in the former and 6.30 Φ (medium-fine silt) for sediments collected at depth, and conforms to those reported by Matsushita (1985) for the Kako River, Japan, where most pollen occurs with suspended sediment in the size range 5.0–6.5 Φ. These results also conform to Brush and Brush's (1994) Chesapeake Bay estuarine study where they found the hydrodynamic equivalents of several pollen types to be medium to very fine, silt-sized, quartz grains (6–8 Φ).

The results from the Mobile-Tensaw River and Rajang River deltas demonstrate a physical control on pollen concentration that, to date, is unreported. In general, the highest pollen concentrations occur in the distal delta plains where tidal influence is greatest, regardless of tidal displacement or salinity values, and palynofacies assemblages are dominated by Heterogenous Aggregate OM (Gastaldo et al., 1996; Lindley et al., 2000) in which palynomorphs may act as aggregating nuclei. Tidal displacement in the former reaches a maximum of <1.5 m, whereas displacements of >6 m occur in the latter. Salinity values in the lower delta plain of the Mobile-Tensaw River Delta are very low during peak discharge (1‰–2‰), but increase during summer base flow (25‰; Chadwick and Feminella, 2001). In contrast, areas that effectively act as estuaries of the Rajang and Belawai Rivers are fully mixed and tidal channels in this region have the highest salinities (Staub et al., 2000; >10‰ wet season, >25‰ dry season). The slowing of fluvial discharge by the tidal bore apparently brings flow velocities below those needed to maintain palynomorphs in suspension (Holmes, 1994), allowing for their settling in the water column. These may come to rest at the sediment-water interface as isolated grains, depending upon their position in the water column at the time of prolonged tidal bore stillstand (e.g., during king tidal cycles), or act as nucleation sites for aggregates or floccules at depth depending upon the salinity which, in turn, controls surficial ionic charge and floccule genesis (Dyer, 1995). Regardless, settling to the sediment-water interface in the distal regions of the delta results in significantly higher palynomorph concentrations than in other parts of either system.

There is no doubt that the magnitude of tidal displacement impacts the distribution of palynomorphs in the Rajang River delta. This is demonstrated by the distribution of trilete and monolete spore types and mangrove pollen, although the former may be a function of anthropogenic disturbance and the pioneering taxa that overtake the landscape, the time of sampling, or both. Monolete spores systematically comprise a large percentage of palynomorph assemblages at river-mouth bars and in the inactive delta plain, which may be a function of their density when compared to trilete spores. If monolete spore densities are slightly higher, they would settle in greater numbers during slack tide than their trilete counterparts. Also, if there is a difference between spore densities, a high percentage of monoletes in any deep time sample from a coastal deltaic regime could be more a function of their hydrodynamic equivalents than provenance. This is a hypothesis that needs to be tested.

A hypothesis that does not need testing, and is evident from the data presented here, is that mangrove pollen occurs in considerable percentages and in moderate diversities some tens of kilometers inland from where mangroves grow when the coastal system is meso- to macrotidally influenced. Mangrove taxa occupy the distal regions in the Rajang River Delta and dominate in areas influenced by brackish waters along margins of distributary channels (Scott, 1985). They dominate the northeastern delta plain and adjacent coastal plain, and fringe fluvial and tidal channels inland to the limit of salt-water incursion (Fig. 7; Staub and Gastaldo, 2003). The proportion of mangrove pollen in these areas is high, with some sites exhibiting ≥40% of its pollen assemblage (Fig. 10C). Mangrove taxa, however, are found in low percentages (<5%) still further inland, east of Sibu, in the alluvial valley (Fig. 11). Here, Heterogenous Aggregate OM is a minimal component of palynofacies assemblages, reducing the probability that mangrove pollen was transported as flocculate nuclei. The physical process responsible for their redistribution this far inland, some 30 km from the salt-water–fresh-water interface and ~120 km from the sites where specific taxa now grow, is most likely the magnitude of the tidal bore, and duration of stillstand associated with it, found during king tidal cycles of this meso- to macrotidal regime. This may be particularly the case during the dry season when most sedimentation occurs (Staub et al., 2000). Such findings have implications for coastal plain reconstructions in the more recent, and deep, time because often the proportion of a systematic group in a pollen assemblage is used to infer ecologies.

The Mobile-Tensaw and Rajang delta data demonstrate the importance in understanding the coastal tidal regime under which the sediments and pollen assemblages were deposited. There are many factors that influence the resultant palynomorph assemblage in coastal settings, and these must be accounted for before vegetational reconstructions or their climate inference are developed.

CONCLUSIONS

A comparative study of actualistic pollen-and-spore taphonomy in two coastal deltaic regimes is reported for the microtidally influenced Mobile-Tensaw River Delta, United States, and the meso- to macrotidally influenced Rajang River Delta, Sarawak, East Malaysia. Data from the subtropical Mobile-Tensaw Delta were collected over the duration of 13 months, whereas Rajang River Delta samples were collected prior to the onset of winter monsoons. Water-column and sediment-water interface samples were processed using standard protocols for total palynomorph concentration and palynomorphs were systematically identified. Grain-size distribution data were gathered and elemental analysis for TOC was performed on all grab samples.

Similar taphonomic trends are identified in all tidally influenced environments. Pollen-and-spore concentrations are lowest in surficial waters; these increase at depth in the water column, and are highest at the sediment-water interface. A positive relationship also exists between total palynomorphs and mean Φ, best defined by the natural log (ln), with the highest concentrations found in the medium-fine silt fraction (6.3 Φ), which appears to be the palynomorph hydrodynamic equivalent as reported elsewhere. There is no statistically significant difference in palynomorph concentration at the sediment-water interface in the microtidally influenced Mobile-Tensaw Delta at any one collection time during the year, but concentration varies seasonally as reported by other workers. Absolute pollen concentrations, however, are statistically higher in the lower delta sites than in other parts of the system over the sampling period. This can be accounted for by sedimentation of Heterogenous OM floccules or aggregates, formed in response to changing salinity, which comprise the majority of palynofacies clasts in both deltaic regimes (Gastaldo et al., 1996; Gastaldo and Staub, 1997; Lindley et al., 2000). In contrast, a statistically significant difference exists between mesotidally and macrotidally influenced sites in the Rajang Delta, with the highest pollen-and-spore concentrations found in channels located in the southwestern part of the delta where little active sedimentation occurs and tidal displacement is greatest.

The pattern of palynomorph distribution at the sediment-water interface in the Rajang Delta is influenced by the magnitude of tidal displacement. Both mangrove and fern palynomorphs, representing taxa growing under saline influence in the lower delta plain, are not confined to channel deposits in the immediate vicinity of their habitat. Rather, mangrove pollen is found throughout the delta and alluvial plain bottom sediments, and encountered as far inland as Sibu (~75 km inland from the mouth of the Igan and Rajang Rivers) in frequencies of 5% of the pollen spectra. Although *Rhizophora* pollen is the most common mangrove, samples with an α-diversity of 8 mangrove taxa are encountered (averaging 4 taxa/sample), and these inland, fresh-water assemblages are likely the result of tidal bore transport and settling rather than aggregate formation and flocculation. In contrast, monolete spores comprise a high percentage of palynomorph assemblages in mouth-bar deposits and in the inactive delta plain, and may be a function of their density when compared to trilete taxa. Hence, it is imperative to understand the depositional context and physical processes that operated therein before deltaic palynological assemblages can be used for deep time paleoecological interpretations.

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