Sediment Facies, Depositional Environments, and Distribution of Phytoclasts in the Recent Mahakam River Delta, Kalimantan, Indonesia

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The Mahakam River delta is a tide- and wave-dominated delta located on the edge of the Kutei basin, eastern Kalimantan, Borneo. A vibracoring program sampled the principal fine-grained depositional environments in two transects; one within the fluvially-dominated regime, one within the tidally-dominated regime. Ten sedimentary facies are distinguished and phytoclasts have been recovered from all environments of deposition. Canopy parts from the mixed tropical forest community are preserved throughout the delta, whereas dicotyledonous angiosperm mangroves are restricted to the subtidal zone and delta front. Nypa *parts are preserved in most depositional environments. In sites where there appears to be an absence of macrodetritus, dispersed cuticle is recoverable. Identifiable plant parts include wood and fibrous tissues,* Nypa *petioles and leaf laminae, dicotyledonous angiosperm leaves and isolated cuticles, fruits and seeds, roots and rootlets, and moss. Dammar is found either as dispersed resin ducts or amorphous clasts. Additional biotic components found in bedded plant litters include insects, gastropods, bivalves, sand dollars, ostracods, and crabs. Fluvial channels and depositional sites associated with these systems in the delta front can be differentiated from* Nypa *swamps and mixed tropical hardwood-palm swamps based on their phytological components and accessory biotic elements.*

INTRODUCTION

Although a large body of literature exists documenting the sedimentological aspects of deltas, our understanding of taphonomic processes responsible for the development of terrestrial plant-bearing sedimentary environments in these regimes is limited. Presently, only a rudimentary knowledge exists with regard to the phytotaphonomic processes operative in deltaic regimes of various climatic constraints. Whereas Fosberg (1964) summarizes the role of vegetation as a geological agent in tropical deltas, results from recent studies suggest that his discussion is an oversimplification. Interactive complex processes are responsible for the generation, incorporation, and ultimate preservation of plant parts as either identifiable macrodetritus or kerogen precursors. This is evidenced by the scope of plant taphonomic studies conducted in deltaic regimes within the past decade.

The most comprehensive taphonomic works on the incorporation of plant detritus into deltaic deposits have been focused on a few fluvial-dominated deltas (Mississippi delta—Kosters and Bailey, 1983; Kosters et al., 1987; Frazier River delta—Styan and Bustin, 1983; Orinoco delta—Scheihing and Pfefferkorn, 1984; Pfefferkorn et al., 1988; Niger River delta—Bustin, 1988; Mobile-Tensaw River delta—Gastaldo, 1989; Gastaldo et al., 1987, 1989). Prior to these investigations, references to the quantity, quality, systematic composition, and community contribution to the plant-bearing deposits were limited to statements such as "disseminated organic matter", "disseminated plant fragments", "wood fragments and other organic detritus", and "drifted branches, logs, seeds and comminuted leaves" (see: table I in Gastaldo, 1986). Even in more recent reports, most workers have concentrated their focus either on the sites of plant part incorporation (Scheihing and Pfefferkorn, 1984), the broad identification of the botanical components as either 'herbaceous marsh' or 'freshwater swamp' (Kosters and Bailey, 1983; Kosters et al., 1987), or the phytological components of delta plain peats

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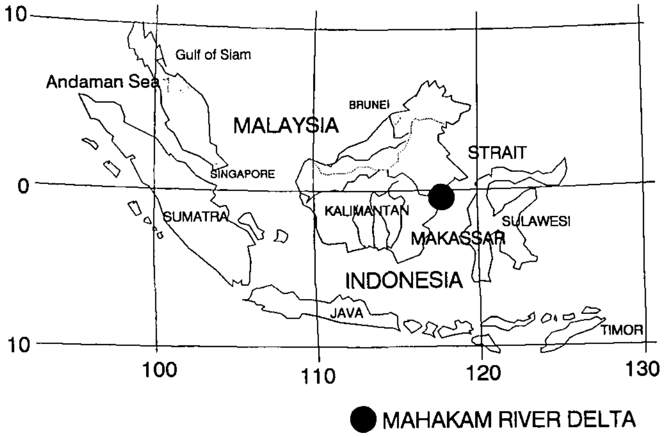

FIGURE 1—Locality map of Mahakam River delta, eastern Kalimantan, Indonesia.

as precursors to coal macerals (Styan and Bustin, 1983). Although providing a comprehensive overview of accumulation sites and mechanisms, there is little attempt at relating the recovered macrodetritus in each depositional environment to the contributing vegetational communities. The constraints of logistics, field time, and knowledge of the floral communities hampered their attempts.

The first effort to integrate the biotic and abiotic components of a deltaic regime in a comprehensive approach to develop an understanding of the relationships between original contributing plant communities, sites of plant part accumulation, and resultant macrodetrital assemblages has been undertaken in the Mobile-Tensaw River Delta, Alabama, (Gastaldo, 1985, 1989; Gastaldo et al., 1987, 1989). These studies have revealed that a variety of necrological, biostratinomic, and diagenetic processes function in the development of macrodetrital assemblages recovered from specific environments of deposition. That is, depositional sites within the upper, transitional, and lower delta plain are characterized by a unique complement of phytological canopy parts. These assemblages, in combination with the sedimentological features of the site, can be used to distinguish subenvironments in this fluvial-dominated regime.

This basic approach was employed and amplified (with the addition of geochemical analyses) to investigate the tidally-influenced Mahakam River delta, Kalimantan, Indonesia. The Mahakam Delta is a coastal deltaic sequence, Neogene to Holocene in age, from which all recoverable hydrocarbons (crude oil and natural gas) are considered to be derived from kerogen III (terrestrial plant) predecessors (Boudou, 1981; Oudin and Picard, 1982; Schoell et al., 1983; Boudou et al., 1984). Although various aspects of these oils have been researched in some detail (Hoffman et al., 1984; Monthioux et al., 1985; Durand and Oudin, 1980; Vandenbroucke et al., 1983; Durand et al., 1983), a complete understanding of the types of sediments sourcing the hydrocarbons has not been yet achieved. A vibracoring program was conducted to partially address this problem in determining the accumulation sites of terrestrial plant detritus, the type(s) of plant parts accumulating in the depositional environments of the modern delta, the vegetational communities responsible for the contribution of organic carbon, and the geochemical parameters associated with each of these sites. The purpose of this paper is to detail the sediment facies and plant-accumulating depositional environments, the variety of taphofloras and phytoclasts found within each identified environment of deposition, and to correlate the accumulated plant parts within specific depositional environments with their provenance vegetation. Geochemical data will be presented elsewhere (Gastaldo et al., in press; Huc and Gastaldo, in prep.).

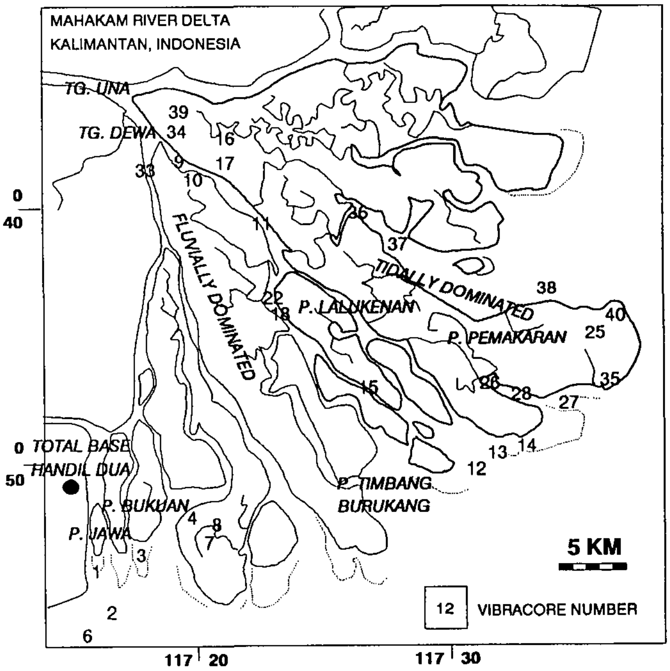

FIGURE 2—Mahakam River delta located between 0°21′ and 1°10′ South Latitude and 117°40′ East Longitude. Localities of recovered vibracores are marked by core number in the fluvially- and tidally-dominated parts of the delta. Vegetation distribution in wetlands outlined in bold are found in Figure 3. Dotted lines represent tidal flats. Scale in km.

MAHAKAM RIVER DELTA

The Mahakam River delta, Kalimantan, Indonesia, is located at the eastern edge of the island of Borneo (Fig. 1). Six major rivers drain the island, the headwaters of each originate in the central highlands of Kalimantan. The Mahakam delta is situated at the edge of the Kutei Basin, between 0°21′ and 1°10′ South Latitude and 117°40′ East Longitude (Fig. 2). Deltaic sedimentation began in the Middle Miocene (LaLouel, 1979). Since then, several major deltaic complexes have accumulated, each separated by marine transgressions (Magnier et al., 1975). The eastward prograding sedimentary sequence is between 6–8 km thick. The Pliocene-Quaternary history of the delta has recently been detailed through the interdisciplinary MISEDOR project (Pelet, 1987).

The modern Mahakam River drains a 75,000 km² area, and the sediment transported through the equatorial basin forms a tide- and wave-controlled delta complex (Combaz and De Matharel, 1978). The present Mahakam River delta is a thin sedimentary sequence, approximately 50–60 m in thickness, that overlaps the paleodeltas (Roux, 1977). Presently, it is approximately 50 km in "length", as measured from the delta front to the hinterland, and is distributed along the coast for nearly 100 km. It is composed of approximately 2000 km² of wetlands of the subaerial delta plain, and 1800 km² of delta front and prodelta.

The Mahakam has two active fluvial distributary systems directed northeast and southeast. An intervening area, termed interdistributary (Allen et al., 1979), consists of a series of tidal channels practically unconnected to the fluvial regime (Fig. 2). River depths average 7–10 m, with maximum depths of 15 m. Waters have a high suspension load of mud, whereas medium to fine sand and silt are transported in bedload. Tidal channels are similar in depth to river channels, with the base of tidal channels often at the contact with delta front sands (pers. observ. 10/88). Medium to fine-grained sand and silt are localized in the distributary channels and delta front (Allen et al., 1979; Gayet and Legigan, 1987). The remainder of the delta is characterized by mud. Identifiable plant macrodetritus accompanies organic mud and clay distributed throughout the various deltaic environments of deposition.

The interior subzone of Allen et al. (1979; equivalent to the upper delta) is characterized by a mixed hardwood and palm tropical forest (Figs. 3, 4A). No systematic botanical survey has ever been conducted in eastern Kalimantan. Based on vegetational surveys of other Southeast Asian coastal zones (Anderson, 1964, 1983; Andriesse, 1974), the vegetation is composed of Dipterocarp angiosperms, Pandans (Pandanaceae), Palms (Palmae), and other angiosperm families including the Myristicaceae, Schisandraceae, Theaceae, and Dilleniaceae. The subtidal zone of Allen et al. (1979; equivalent to the lower delta) is a monoculture swamp of *Nypa fructicans* (Figs. 3, 4B). The shoot apex of the palm is at ground level. Large erect leaves attain heights of 8 m. Coastal mangroves (*Avicennia, Rhizophora,* and *Sonneratia*) colonize newly formed tidal flats and aggradational headlands (Figs. 3, 4C). Glades of *Acrostichum* (mangrove fern) are also present. Mangrove taxa may be found adjacent to channels towards the interior of the delta where salinity gradients are generated by tides.

The delta front fringes the delta plain, and is an intertidal to subtidal platform 8 to 10 km in width (Combaz and De Matharel, 1978). Localized sand bars interrupt a monotonous mud sequence in which a marine fauna is often preserved. At the boundary of the delta front and the delta plain, laterally extensive detrital peats accumulate as beach ridges (Allen et al., 1979; Gastaldo et al., in press). These beach ridges may be up to 2.5 m in thickness, are distributed as much as 3 km inland, and may cover a total surface area of approximately 50 km² (Allen and Pizon, 1986).

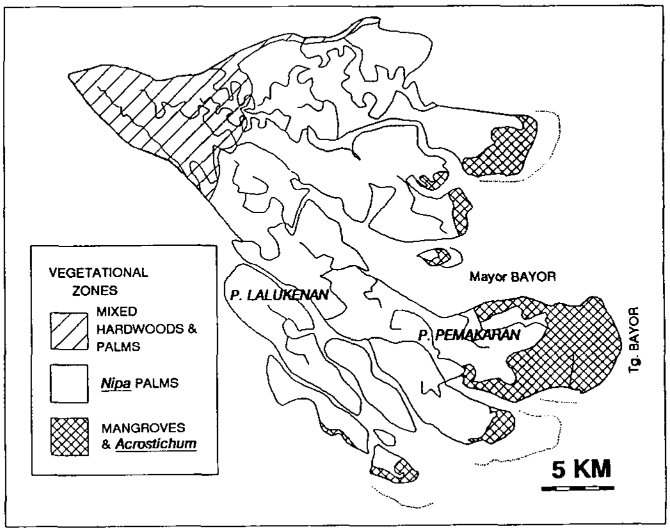

FIGURE 3—Distribution of vegetation types based upon SPOT imagery analysis. Dicotyledonous angiosperm mangroves and *Acrostichum* fern glens fringe the delta front, while *Nypa* swamps occupy the majority of the subaerial delta plain. A mixed tropical hardwood and palm forest is established in older portions of the delta where the topographic relief is slightly higher.

Prodeltaic sediments accumulate on the outer limit of the delta front where water depth begins deepening to 35 m within a kilometer of the delta front (Kartaadiputra et al., 1975). The prodelta is characterized by a homogenous massive mud in which beds of carbonaceous clay and silt occur. Although phytoplankton would be expected to accumulate within this area, none have been recovered (Combaz and De Matharel, 1978). Decayed organic debris including degraded wood fibers and other aerial plant macrodetritus has been noted to occur. Few spores and pollen have been recovered (Combaz, 1964; Bellet, 1987).

VIBRACORING PROGRAM AND METHODOLOGY

A non-random sampling strategy was devised to collect surface and shallow subsurface sample suites from the principal Holocene organic-rich depositional environments. The vibracore sampling pattern was organized in two transects. Samples from the first transect represent the environments of deposition within the fluvially-dominated distributaries (Fig. 2). The second transect was designed to sample sites from within the tidally-dominated interdistributary setting. Sites in the emergent swamps and submergent delta plain were accessible only by boat. TOTAL Indonesie provided boats including a work barge equipped with a hydraulic crane and working platform from which to conduct our sampling. Where shallow waters were encountered, prohibiting use of any of our boats, local fishing boats were hired for passage.

Aluminum irrigation pipes, 6 m in length and 7.5 cm in diameter, were imported from Singapore. The pipe length

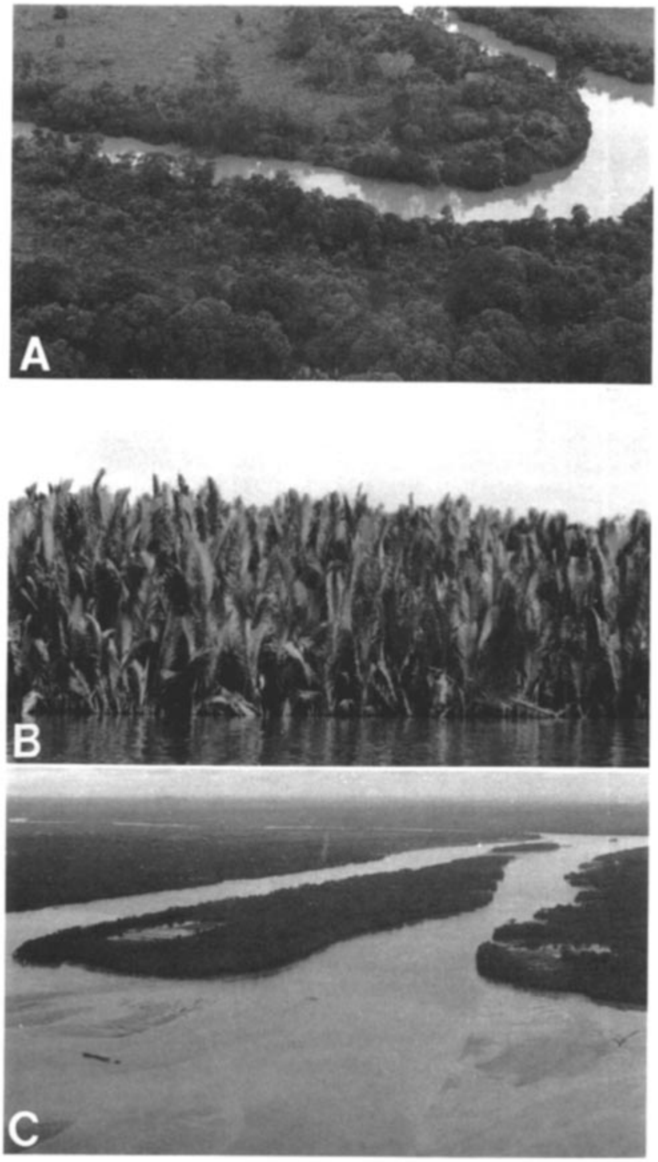

FIGURE 4—Vegetation types. **A)** Oblique aerial photograph of mixed tropical hardwood and palm swamp in the interior subzone (=upper delta). Anthropogenic disturbance may result in the establishment of herbaceous vegetation as shown in the upper portion of the photograph. **B)** *Nypa* swamp in the subtidal zone (=lower delta plain). Erect leaves are 8 m in height. **C)** Oblique aerial photograph of the delta front illustrating the fringing character of dicotyledonous angiosperm mangroves, principally *Rhizophora* and *Avicennia*. Mud flats can be seen in the shallow waters in front of headlands.

was the limiting factor on the depth from which subsurface samples could be recovered. Depending upon the depositional environment sampled, lengths of recoverable core varied from less than 3 m to greater than 5 m. At great expense, three 12 m tubes were constructed. These were used in water depths that exceeded 8 m (up to 7 m of core recovered). Thirty-seven vibracores were recovered during an 18 day field season (Fig. 2). Five Indonesian technicians assisted in recovery and processing of vibracores. Auxillary sediment sampling techniques were used on a limited basis when vibracoring was deemed infeasible. Core barrels, either PVC or aluminum, were pushed or hammered into the sediment resulting in a shortened compressed core (compression ratios of 3.5:1 to 4.0:1; cores 7, 35 and 40). Dredging of the sediment-water interface to recover plant macrodetritus was used to supplement vibracores in particularly organic-rich depositional sites. Soil sampling by excavation was employed in vegetated areas. Floristic sampling was conducted within the monotypic lower delta swamps and along the more diverse Handil River in the upper delta. Samples of leaves and wood from the flanking vegetation, those plants most prone to allochthonous transport, were recovered from the margin of the channel. Each different tree from the channel margin along a distance of 2 km was sampled.

Recovered vibracores were split longitudinally. One half of the core was used as the basis for sedimentological description, photography, and Epoxy Resin peels (housed in the core warehouse, TOTAL Indonesie, Balikpapan, Kalimantan). The other half was used for various analyses. pH and Eh were measured throughout the length of each core. The core was subsampled for subsequent phytological and geochemical analyses. Each field identified sediment facies was sampled for plant macrodetritus either from within bedded litters or from dispersed debris. The quantity of phytological sample size was consistently maintained by filling a 60 ml polyethylene sample vial. Where a thick sequence of bedded plant detritus was encountered (e.g., organic-rich channel fills), the complete interval was collected. All samples were sieved (100 μm mesh) to recover macrodetritus and to remove most of the clastic fraction. Sieving was conducted either on the barge by Indonesian assistants or at TOTAL's Handil Base. Samples were not sieved in which no visible macrodetritus occurred, but maintained for future processing to recover dispersed cuticles. All samples were dried under heat lamps at 60° C to prevent fungal growth. Detrital dammar was removed, where recognized, and selected leaf litters were taken for C^{14} dating. Bulk samples of detrital peat beach were hand-sampled at Tandjung Bayor (see Gastaldo et al., in press), as well as dredge samples from channel-infill sequences.

Phytological samples were hand-picked and segregated into 9 categories: 1) unidentifiable millimeter sized resistant phytoclasts; 2) moss; 3) woody, petiolar, and fibrous parts; 4) *Nypa* petiole; 5) angiosperm leaf laminae; 6) dispersed cuticle; 7) reproductive structures; 8) roots and rootlets; and 9) dammar (resin). Originally, the quantitative share of each plant part category was determined for each sample (5 repetitive counts of 300 randomly selected plant parts were used to determine the relative frequency of occurrence). This approach provided artificial results, increasing the quantitative share of leaf parts, due to leaf damage sustained during sieving and drying. Subsequently, the plant part segregates for each sampled horizon were weighed to provide a means to determine the contribution by weight of each plant part category to the litters. Cluster analyses were performed using the Gower general similarity coefficient and an unweighted pair grouping (Kovach, 1990). The Gower coefficient was chosen because quantitative characters can be utilized in the data matrix. In addition, Sorenson's similarity and Simple Matching coefficients were calculated using the presence/absence of plant parts and other biotic components (foram tests, insect parts, bivalves, etc.). Cluster analyses were conducted on these matrices to determine if specific environments of deposition could be identified by the composition of recovered biotic components. Several iterations were conducted randomizing the input matrix to determine if clustering of samples was affected by the order of the data matrix.

SEDIMENT FACIES

Ten sediment facies were identified during vibracore description. Although clasts may range from coarse sand near the first bifurcation of the Mahakam River (Tandjung, Una—Fig. 2; Allen et al., 1979), medium sand was the largest grain-size encountered, albeit rarely. Mud predominates the sedimentological profile. Plant parts are found in all facies and, commonly, as detrital clasts either bedded or dispersed within the cores.

Bioclastic Sand

Composed of medium-dark gray fine sand with a slight admixture of mud, this facies is characterized by the presence and incorporation of fragmented invertebrate shell debris (bivalves, echinoderms [Echinoidea], and gastropods; Fig. 5). Lamination and bidirectional small-scale cross bed structures were noted (Core 24). Only pH was recorded for this facies and it ranged from 6.67 to 7.54. Bioturbation is absent, and phytoclasts are highly fragmented. These are found either dispersed or concentrated into laminae. Finely disseminated organic matter may impart a black stain to the sand. Contacts with adjacent facies are gradational.

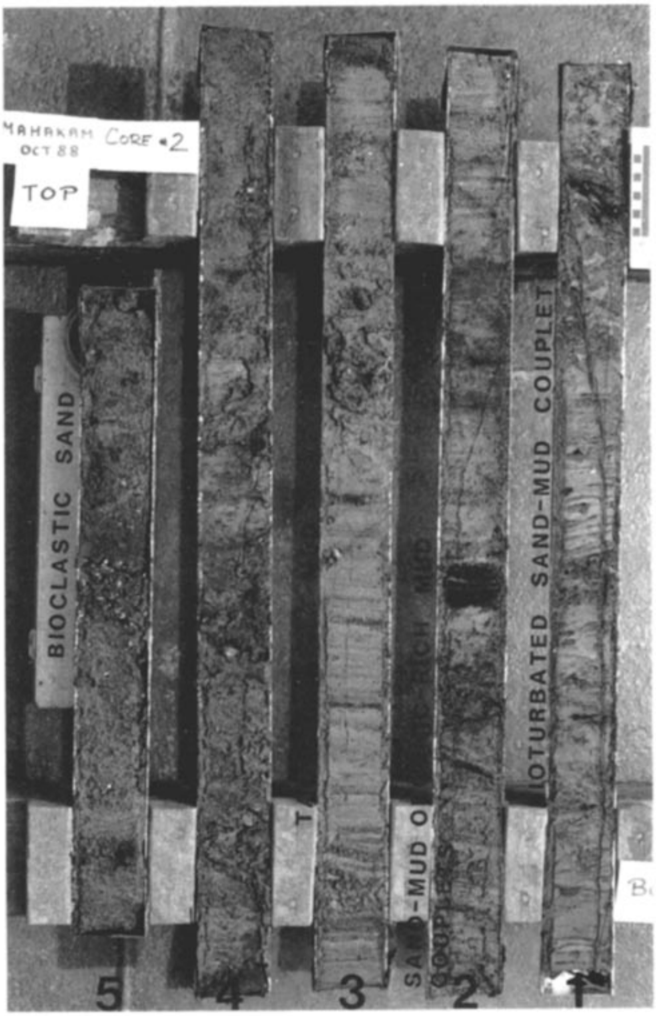

FIGURE 5—Vibracore 2 recovered from the seaward margin of the distributary mouth bar in the delta front (water depth 2.5 m; see Fig. 2). Core barrels are cut in 1 m lengths. Section 5 is the core top, section 1 is the core bottom. See text for explanation of sediment facies. Scale in cm.

Sand-Mud Couplets

Couplets of very fine- to medium-grained sand and mud are the most commonly encountered sedimentary feature within the subaqueous portion of the delta. Grain size varies from medium-grained sand that is localized in the proximal parts of the delta (Tg. Dewa—Fig. 2), to fine sand encountered in the distal parts of the system. The sand : mud ratio is variable, ranging from 9:1 to 3:7. Sand color varies from yellowish-tan to olive green-gray or gray-tan, whereas mud is gray-tan to gray-brown. Primary sedimentary structures include asymmetrical ripples and, rarely, starved ripples. Ripples, isolated or in sets, may be up to 7 cm in thickness, but most commonly average 2 cm. Ripple bases are not erosional. Ripples may be inclined upstream, downstream, or may be horizontally disposed in the same core. Within any one core, ripples may be unidirectional or bidirectional (Figs. 6, 7). Mud, up to 1 cm in thickness, overlies ripples and these drapes generally are disposed horizontally. Couplet thickness varies as a function of tidal influence, and there may be as few as 4 couplets, or as many as 12, per 10 cm of core length. Recorded pH and Eh ranged from 6.38 and −125 mv @ 30.6° C to 7.71 and −201 mv @ 33.8° C. Maximum and minimum values for Eh were −11 mv and −355 mv, respectively, and the minimum pH value recorded (without accompanying Eh and temperature data) was 5.99. Plant litter occurs as drapes over ripple structures, and accumulations may be 2 cm in thickness. Plant parts may be whole or fragmentary, reflecting their residency time in, and conditions subjected to during, transport (Gastaldo, in press). Shell detritus is rarely encountered in the distal parts of this facies, and bioturbation is isolated. Where bioturbation occurs, burrow diameters are generally less than 2 cm, U-shaped, and lined with fecal pellets. Contacts with adjacent facies may be gradational or sharp, but not erosive.

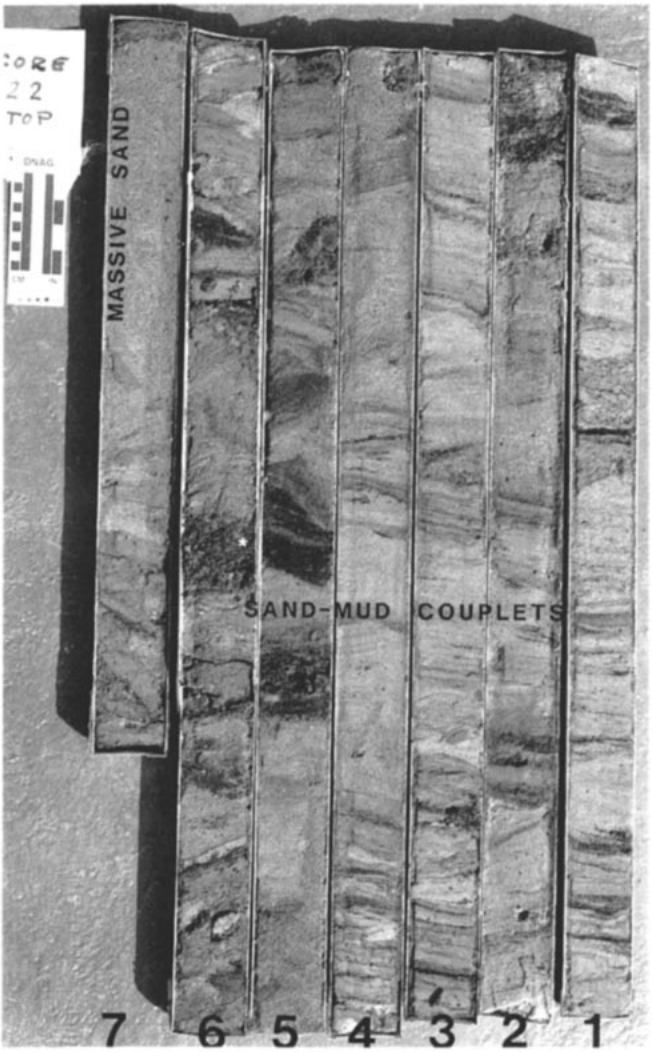

FIGURE 6—Vibracore 22 recovered from a lateral channel bar in the fluvially-dominated portion of the delta (water depth approximately 4 m; see Fig. 2). Core barrels are cut in 1 m lengths. Section 7 is the core top, section 1 is the core bottom. See text for explanation of sediment facies. Asterisk marks sample site of specimens illustrated in Figure 9. Scale in cm.

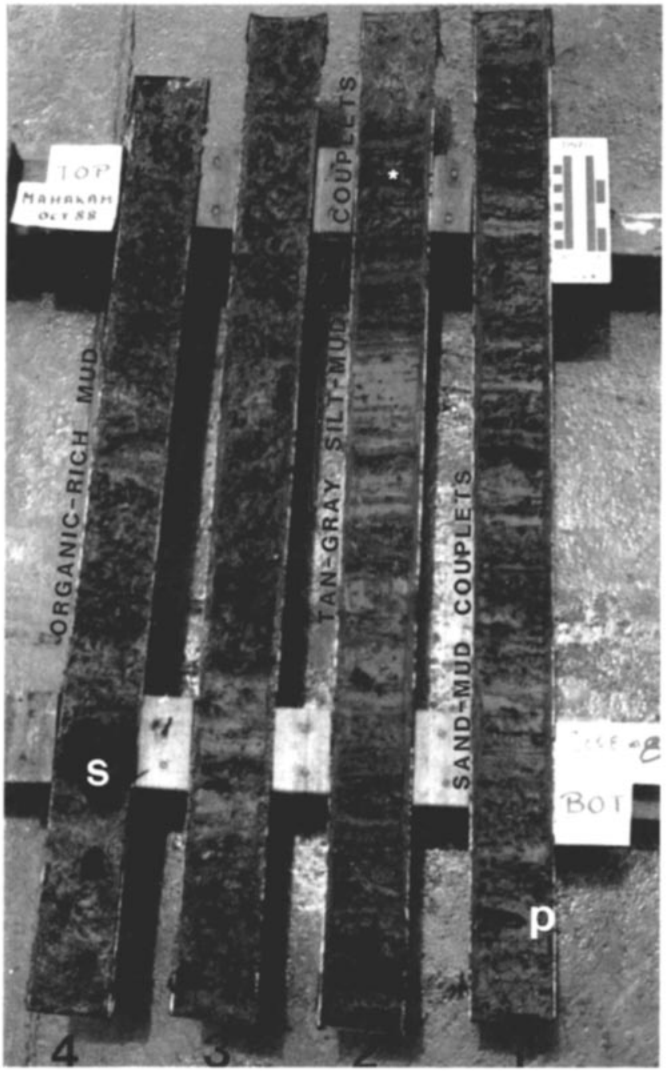

FIGURE 7—Core 8 recovered from tidal channel (water depth 2.5 m) adjacent to *Nypa* swamp. Core barrels are cut in 1 m lengths. Section 4 is the core top, section 1 is the core bottom. See text for explanation of sediment facies. A *Nypa* seed (s) marks the base of the organic-rich mud. A mud-cast *Nypa* petiole (p) is preserved near the base of the sand-mud couplet facies. Asterisk marks sample site of specimens illustrated in Figure 9. Scale in cm.

Bioturbated Sand-Mud Couplets

This is an alteration of the rhythmically bedded sand and mud facies and is characterized by the incorporation, through bioturbation, of sand ripples into the mud drapes (Fig. 5). The sediment is, generally, not completely homogenized. Sand is fine-grained, medium to dark gray, and the sand : mud ratio is variable (8:2 to 3:7) as in the previous facies. Not all primary sedimentary structures are disrupted by bioturbation. Ripples, where present, are slightly inclined and of the same character described above. Vertical and horizontal burrows, ranging from 0.4 to 2 cm in diameter, are sand-filled and may be calcite cemented.

In the delta front, fragmentary bivalve shells may occur as ripple scour lags, accretionary pebbles, or isolated valves. Recorded pH and EH ranged from 6.57 and −128 mv @ 26.7° C to 7.65 to −301 mv @ 27.8° C. Maximum and minimum values for EH were −128 mv and −366 mv, respectively, and the minimum recorded pH (without accompanying EH and temperature data) recorded was 6.39. As in the preceding facies, plant parts may be scattered, concentrated as drapes over low-angle ripples, or incorporated into the sediment. Contacts with adjacent facies may be gradational or sharp.

Mud with Sand Laminae

This facies is an extreme condition of the rhythmically bedded sand and mud facies in which the sand : mud ratio is low (1:9 to 2:9). Tan mud predominates with horizontally-disposed sand laminae or ripples. Sand is medium to fine-grained, greenish-gray, and in beds less than 5 mm in thickness. Micro-cross stratification can be seen in some sand laminae. Recorded pH and Eh ranged from 6.48 and −125 mv @ 31.6° C to 7.40 and −358 mv @ 34.4° C. These values also represent pH and Eh maxima and minima. Plant detritus is either bedded, oriented horizontally or slightly inclined, or scattered within the facies. Macroinvertebrate shells are rare and, where present, are isolated non-articulated valves. Localized bioturbation consists of horizontal sand-filled burrows. The facies contacts may be either gradational or sharp.

Tan-Gray Silt-Mud Couplets

This predominantly mud facies contains a small silt component. All sediments are tan to gray in color and it is often difficult to distinguish the silt component in a fresh core. Silt laminae, generally less than 2 mm in thickness, are inclined or horizontally disposed (Figs. 5, 7). Mud drapes, ranging between 3 mm to 15 mm, overlie the silt. Primary sedimentary structures are absent in the mud fraction. Silt-mud couplets may be as few as 6–7 or as many as 23 per 15 cm length of core. The number of couplets increases upsection, and this facies generally overlies organic-rich mud. Recorded pH and Eh ranged from 6.47 and −95 mv @ 62.1° C to 7.56 and −250 mv @ 28.5° C. Maximum and minimum values for Eh were −95 mv and −351 mv, respectively, and the minimum pH recorded (without accompanying Eh and temperature data) was 6.40. Plant detritus often is bedded, disposed horizontally or inclined, and less than 1 cm in thickness. Rarely are plant parts fragmentary and pelloidal, and mud-cast *Nypa* petioles are infrequently encountered. Organic staining and mottling is common. Bioturbation is restricted to contacts with adjacent facies, and facies contacts are commonly gradational.

Sandy Mud

Restricted to a single vibracore (top Core 15), this sediment facies consists of highly saturated gray-brown mud with a small admixture of sand. The sand : mud ratio is approximately 5:95. Sediment rapidly oxidizes to a tan color when exposed. Recorded pH and Eh ranged from 7.20 and −115 mv @ 34.4° C to 6.61 and −147 mv @ 32.2° C. Scattered plant detritus is found that is probably responsible for a mottled appearance imparted to the mud. There is no evidence of bioturbation. The basal contact is sharp. If dewatered, this facies may be equivalent to the Mud with Sand Laminae Facies.

Gray-Black Mud

Medium-gray to black mud with no apparent primary sedimentary structures is infrequently encountered. Only plant litter, composed of fragmented detritus, define horizontal bedding surfaces. When exposed, the mud often emits a sulfurous odor. Recorded pH and Eh ranged from 6.68 and −129 mv @ 30.1° C to 7.34 and −129 mv @ 30.1° C. These values represent pH and Eh maxima and minima. Contacts with adjacent facies are gradational.

Organic-rich Mud

Plant detritus occurs principally within homogeneous brown-tan to medium dark gray mud (Figs. 5, 7). Upon exposure, mud may oxidize from brown to black or black to tan. No primary sedimentary structures are visible. Recorded pH and Eh ranged from 7.05 and +8 mv @ 36.5° C to 5.86 and −115 mv @ 27.9° C. Maximum and minimum values for Eh were +8 mv and −318 mv, respectively, and the minimum recorded pH (without accompanying Eh and temperature data) was 5.68. Plant parts, composed of vegetative and reproductive aerial parts and/or rooting structures, may be horizontal, inclined, or vertically disposed depending upon the depositional environment. Plant material may be entire and concentrated, or fragmentary and dispersed. Where roots are present, an orange oxidation halo is often found surrounding each root. Degraded plant parts appear as residual fibrous materials. Bioturbation is rare and sand-filled burrows originate from suprajacent facies. Contacts with adjacent facies generally are gradational.

Peat

Excised vegetative and reproductive parts, originating from the forest canopy, are the main component of this facies. Autochthonous peat accumulations have not been identified in the Mahakam. All Recent peat appears to be *allochthonous in origin* (*Gastaldo et al., in press*). Recorded pH and Eh ranged from 5.47 near the top of the core to 7.35 and −268 mv @ 2.19° C. Plant parts may be entire (*Nypa* seeds, mangrove leaves) or fragmentary (dicotyledonous leaves, woods, petioles, etc.), and are disposed in horizontal or inclined beds. Plant parts are often size-sorted. Contacts with adjacent facies are sharp.

DEPOSITIONAL ENVIRONMENTS AND SEDIMENTARY FACIES

Vibracored sites can be separated into 4 principal depositional environments: 1) Swamps; 2) Fluvial-dominated channels; 3) Tidal dominated channels; and 4) Delta Front (Table 1). Swamps are the least sedimentologically diverse environment of deposition, where both mixed tropical forests and *Nypa* swamps are characterized exclusively by the Organic-rich Mud Facies. Cores recovered from the Fluvial-dominated channels of the upper and mid-delta plain all are dominated by the Sand-Mud Couplet Facies.

TABLE 1—Distribution of sedimentary facies.

	Bioclastic Sand	Massive-bedded Sand	Sand-Mud Couplets	Bioturbated Sand-Mud Couplets	Mud with Sand Laminae	Tan-Gray Silt-Mud Couplets	Sandy Mud	Gray-Black Mud	Organic-rich Mud	Peat
Fluvial upper delta Core 9			●						●	
Fluvial mid-delta Cores 11, 18, 22			●		●					
Fluvial lower delta Cores 15, 36			●	●		●	●			
Upper delta tidal Cores 16, 17, 34			●	●		●	●		●	
Lower delta tidal Cores 8, 25			●			●			●	
Interdistributary Cores 24, 26, 27, 28, 37, 38	●	●	●	●	●	●		●		
Mixed swamp Cores 10, 39									●	
Nipa swamp Cores 4, 7									●	
DMB Cores 2, 12, 13, 14	●		●	●						
Headlands w/peat Cores 35, 40								●	●	●
Delta front Cores 1, 2, 6	●	●	●	●	●	●	●		●	

TABLE 2—Sedimentary facies characteristic of depositional environments.

Sediment facies	Depositional environment
Bioclastic Sand	Delta front
Massive-bedded Sand	Delta front
Sand-Mud Couplets	Fluvial channels
Bioturbated Sand-Mud	Tidal-influenced channels; delta front
Mud with Sand	Tidal-influenced channels; delta front
Tan-Gray Silt-Mud	Tidal flats, tidal and fluvial channels
Sandy Mud	Fluvial channels
Gray-Black Mud	Tidal flats; headlands with peat
Organic-rich Mud	Swamps, tidal channels; tidal flats
Peat	Headlands; tidal flats

Facies diversity increases in Fluvial-dominated channels in the lower delta plain where tidal influence plays a major role in deposition. Tidal-dominated channels located in the upper delta plain show a more diverse range of sedimentary facies than those situated in the lower delta. Fluvial channels that have been abandoned and subjected to increased marine processes possess a wide diversity of sediment facies and are very similar to those encountered in vibracores from the Delta Front. The Delta Front is the depositional environment with the most sediment facies diversity. Depositional environments, correlated with characteristic sediment facies (Table 2), are described below.

Swamps

Swamps of the interior subzone (mixed hardwood and palm tropical forest) and subtidal zone (mangroves and monoculture of *Nypa*) are characterized by the Organic-rich Mud Facies. Mangrove swamps rapidly become established on Delta Front tidal flats (see below) and colonization by *Nypa* soon follows. Mixed tropical forest replaces palm swamps as slight increases in topography are established through accretion. Accretion occurs via tidal deposition and not flooding, as flood events have not been recorded within the past century. *Nypa* may occur within the mixed tropical forest, but is restricted to tidal channel margins. Fruits of the palm are transported to the delta interior via tides. Swamp deposits are characterized by the presence of vertical rooting structures with a small amount of incorporated canopy detritus. Sediment colonized by mixed forests can be differentiated from *Nypa* swamp sediment only by the phytological component.

Fluvial-dominated Channels

Fluvial sedimentology is greatly influenced by tides operating within the delta. During the field season, Spring tidal displacement was greater than 2 m as far west as Tandjung Dewa (Fig. 2), nearly 50 km inland. Lateral channel bars and distributary mouth bars were sampled. The Sand-Mud Couplet Facies characterizes both environments (Fig. 6). Rippled sand is the result of bedload transport with the overlying mud and plant detrital drape deposited in response to the reverse in the tidal bore operating within the channel. Lateral channel bars are thickest adjacent to the channel margins and slope down towards the thalweg (reconstructed echo sounding traverses, 10/88). Sediment facies are more characteristic of tidal environments (Gray-Black or Organic-rich Mud) in the shallow-water areas. Either of these facies might dominate the sequence depending upon the degree of tidal influence during development of the bar. Fluvial channels in the lower delta plain tend to have thicker accumulations of mud facies than do sites in the interior subzone (Allen et al., 1979). It is interesting to note that when compacted and dewatered, lateral channel bar deposits appear homologous to what are generally interpreted as tidal flats (pers. observ. TOTAL Core Warehouse, Bordeaux, 2/89). Lateral channel bar deposits overlie Gray-Black Mud or Bioclastic Sand of the Delta Front. The sequence terminates in either a saturated mud drape of the Sand-Mud Couplet Facies or in the Bioturbated Sand-Mud Couplet Facies.

Three Distributary Mouth Bars (Mayor Jawa, Tandjung Bukan, and Mayor Bujit) were sampled and sediment facies in all three are similar to those of the lateral channel bars. The Sand-Mud Couplet Facies overlies Bioclastic Sand of the Delta Front (Fig. 5). The DMB can be differentiated from the lateral channel bars by the presence of fragmented shell debris incorporated with bedded plant parts. Bivalves, gastropods, and echinoids are allochthonous, transported into the site via waves and tides. Burrowing is more commonly encountered in the DMB and in only one instance (part of Core 13) were primary sedimentary structures completely homogenized. Distributary Mouth Bar deposits are generally overlain by Gray-Black or Organic-rich Mud Facies of tidal origin. These facies accumulate along the margins of the DMB in response to shallowing and water velocity reduction in these sites. Sulfur reduction may proceed locally in these muddy areas.

Tidal-dominated Channels

Two types of tidal-influenced channels are differentiated. Tidal channels that develop within the Delta Front early are maintained as the delta progrades onto the shelf. These primary tidal channels can be traced into the interior subzone and can be distinguished from former fluvial channels, mostly abandoned, that have been reworked by tidal activity. These latter channels are found within the "interdistributary" area of Allen et al. (1979).

A variety of sedimentary facies exist within primary tidal channels. This is dependent upon channel depth and whether or not flow of tidal waters through the channel is free or restricted. Tidal channels of less than 10 m width in the interior subzone may be at least 5 m in depth, and commonly tidal channel depth may be up to 7.5 m (as determined from echo soundings). Tidal channels of the interior subzone and subtidal zone are similar depositionally. Sediment facies reflect the fluctuating water conditions with the Sand-Mud Couplet and Bioturbated Sand-Mud Couplet Facies common at the base of channels. As flow is restricted, either in response to position within the delta plain or the presence of obstacles (fallen trees and logs) hindering flow, a fining-upward sequence is deposited. This includes the Tan-Gray Silt-Mud Couplet Facies generally overlain by an Organic-Rich Mud. Both facies preserve horizontally bedded plant litter (Fig. 7).

Fluvial channels modified by tidal processes are sedimentologically complex. Limited data from a minimum of vibracores lends some insight into these sites. Characteristic fluvial facies (Sand-Mud Couplets) overlie Delta Front Facies (Bioclastic Sand), and the presence of fragmented macroinvertebrates and bioturbation reflects initial marine influence. Reworking of fluvial deposits by tidal processes varies depending upon the position (proximal or distal) within the interdistributary area. Sand-Mud Couplet Facies may be reworked resulting in the winnowing of the fine clastics and the development of Massive-bedded Sand. Mudflats (Tan-Gray Silt-Mud Couplet and Gray-Black Mud Facies) are deposited under shallowing water conditions and reduced velocity. Bedded plant parts are also reworked and mechanically fragmented into millimeter-sized, mostly unidentifiable, organic debris.

Delta Front

The largest number of sedimentary facies coexist in this setting, and the facies sequencing is complex. The rapid change in facies within any particular core is in response to fluctuations in either fluvial or marine influence. The Bioclastic Sand Facies is most ubiquitous, characterizing this environment (Fig. 5). The position of this facies in any one core is variable. Intercalated facies within the sequence occur with no particular order, as far as can be determined from our small sample, and include: the Massive-bedded Sand, restricted to the vicinity of the Handil River DMB; the Bioturbated Sand-Mud Couplet and the Sand-Mud Couplet Facies found proximal to the Handil River DMB; Mud with Sand Laminae, Tan-Gray Silt-Mud

Couplet, and Organic-rich Mud Facies in shallow water tidal flats. Sampled tidal flats do not have any coarse clastic fraction. Bedded plant litter, either composed of entire or mechanically fragmented plant parts, are encountered throughout the delta front.

Plant parts transported to the delta front may be reworked by tides and waves into shallow water areas and onto tidal flats resulting in Peat deposits. Organic-rich Mud Facies underlie detrital Peat beaches. Aggradational headlands in the interdistributary zone are characterized by these two facies alternating during progradation (Gastaldo et al., in press). Peat deposits are bedded and exhibit sedimentary structures characteristic of beach facies. Gray-Black Mud may be interbedded with Peat, and reflects a topographic-low area within the headland (pers. observ. 10/88). Flanks of headlands may have a thin accumulation of detrital peat overlain by tidal flats composed of the Gray-Black Mud Facies.

PHYTOCLASTS AND OTHER BIOTIC COMPONENTS

Phytoclasts were recovered from 44 samples, taken from 19 cores, representing all depositional environments. Over 14,000 fragments have been assessed. Plant beds are composed of either whole or fragmented phytoclasts and are predominated by leaves, fibrous and woody detritus, except in root-rich swamp entisols. Most macrodetritus residing in the water, either at the sediment-water interface or in the shallow subsurface, had undergone some degree of degradation. Most leaf material is blackened. Wood and fibrous components, moss, seeds and fruits, root and dispersed leaf cuticle retain a color similar to their original coloration. Dammar may retain its original golden-orange color or may be altered to a tannish-white. Mechanical processes operating in the system are ultimately responsible for the fragmentation of all plant parts. Transport in suspension load is not a factor in the development of "comminuted" plant parts (Gastaldo, in press).

Leaves

These are encountered in a variety of states reflecting varied residency times in the water column. Leaves range from being recently dehisced and fresh (tannish and turgid) to degraded (blackened and flaccid). Leaves that have been transported offshore and have acted as a substrate for macroinvertebrate colonization may be reworked into the delta front (Gastaldo, in press). Pore waters surrounding these subfossils are slightly acidic to neutral and Eh values are negative. Accumulations are recent in origin. *Nypa* leaves recovered from a channel-fill sequence were C^{14}-dated at ages from 385 ± 105 (at a depth of -2.1 m) to 1280 ± 210 (at a depth of 3.9 m) C-14 years BP (Krueger Sample Nos. GX-14769–14770).

Dicotyledonous angiosperms dominate most assemblages. Degradation of these leaves may result in one of several conditions. In general, the parenchymatous mesophyll tissues undergo decay probably through bacterial colonization. Degraded dicotyledonous leaves examined utilizing SEM show little evidence of fungal degradation (Fig. 8A). Fungal colonization appears to be most common in leaves that had been partially eaten by insects prior to their introduction into an aqueous environment (Gastaldo, in press). Arthropods are the vector for the introduction of fungal spores. Hyphae, when present, are restricted to the cells directly adjacent to the damaged area. Additionally, it is within these insect-damaged leaves that early-formed framboidal pyrite occurs (Fig. 8B).

Degradation in leaves and leaf fragments appears to begin in cells adjacent to the conducting tissues, without specificity to the level of vein architecture. Deterioration results in the separation of the intervein lamina, imparting an irregular aspect to the leaf (Fig. 8C). It is interesting to note that this not only affects the parenchymatous mesophyll tissues but also some cuticles. Mesophyll loss results in a leaf comprised of xylary elements surrounded by a cuticular sheath (Fig. 8D). In some cases where mesophyll cells have not been degraded, the cuticle may be separated from the underlyng epidermis. This results in isolated thick cuticular fragments within plant-rich beds. Isolated petioles may be found when leaf laminae have been degraded either through biological or physical processes (Gastaldo, in press).

Dicotyledonous leaves are virtually absent in sites within the *Nypa* monoculture. Where *Nypa* fringes channel margins of the upper delta plain, it may play a major contributing role to the subfossil assemblage. Fibrous petioles are more commonly encountered than laminae in these sites. Where laminae do occur, they can be easily distinguished by their characteristic cellular pattern and stomatal distribution (thick cuticle with cutinized hypodermis, deeply sunken stomata 2–3 times as long as unspecialized cells, strong cuticular thickening of the guard cells, and a ring of strongly specialized cells surrounding the sunken stomata; Upchurch, written comm. 6/91). The typical fate of laminae in the swamp is to degrade while still attached to the erect or semi-erect petiole after the leaf has become non-functional. Only after extensive aerial degradation, including decay of all parenchymatous tissues, does the petiole break and fall over. Often, even when broken, the petiole remains above ground or water level and decay proceeds. Hollowed petioles may be infilled with mud when introduced onto the swamp floor or into subaqueous sites (Fig. 7), and remain at the sediment-water interface for some period of time before burial. In addition, they may act as substrates for encrusting worms, as calcareous worm tubes are commonly found on petioles recovered from subaqueous sites (Gastaldo, in press).

Dispersed cuticle is the most conspicuous leaf element in all depositional environments, those in which bedded leaf litters occur and those that appear to be void of plant parts. Cuticle may be pristine or show degradational structures (G. Upchurch, written comm. 6/91). These degradational structures include crystal marks on cuticle surfaces, selective destruction of the stomatal apparatus, and irregularly-shaped thinned areas. At least one sample (Core 35) yielded cuticle with pocket domatia (specialized dwell-

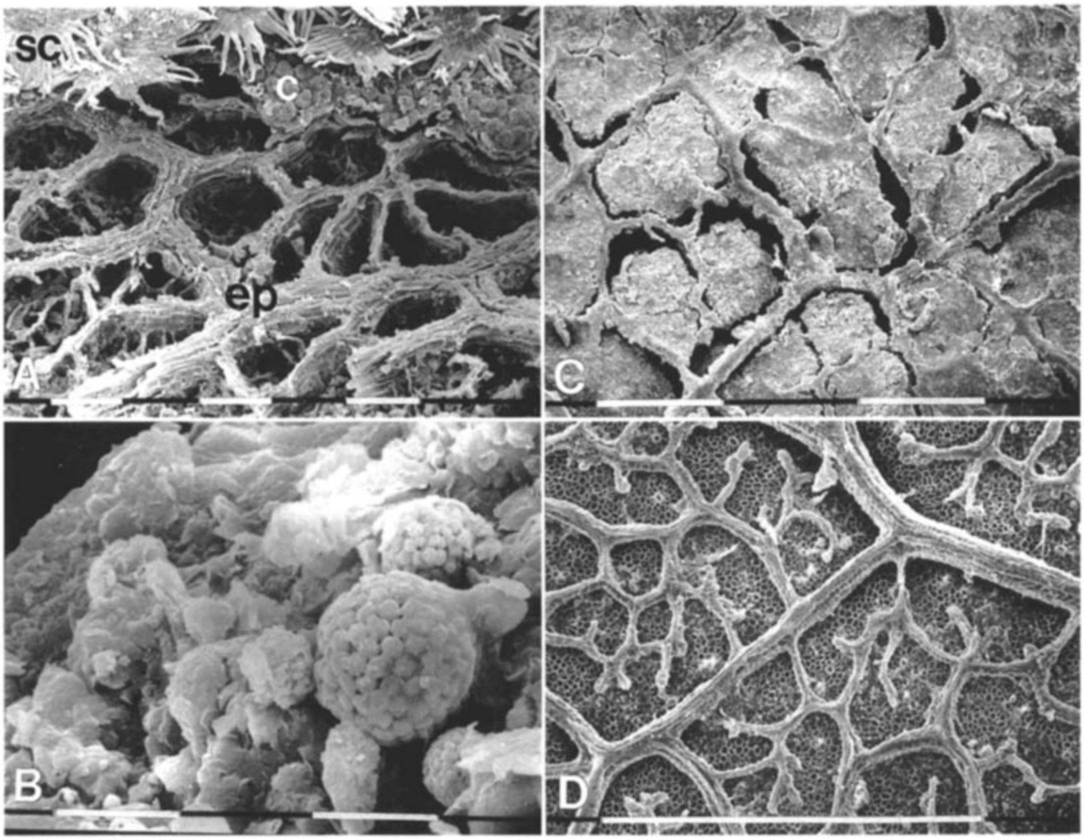

FIGURE 8—SEM micrographs of recovered leaf materials. **A)** Degraded dicotyledonous angiosperm leaf with epidermal scales (sc) overlying a papillate cuticle (c). Epidermal cell walls (ep) remain but no evidence for fungal degradation exists. Core 34, abandoned tidal channel mixed tropical forest. Scale 100 μm. **B)** Framboidal pyrite in leaf directly adjacent to insect-damage. Note that pyrite crystals are incompletely formed. Upper delta plain. Scale 10 μm. **C)** Dicotyledonous angiosperm leaf showing parenchymatous intervein laminar areas partially detached from venation. No evidence of fungal degradation. Core 35, detrital peat beach. Scale 10 μm. **D)** Mangrove leaf in which all parenchymatous tissues have been degraded leaving only the venation surrounded by a cuticular sheath. Few fungal hyphae have been noted in any of these specimens. Detrital peat beach. Scale 1 mm.

ing structures used by mites). Cuticle diversity is extremely high. In only six slides examined (representing six different depositional environments), more than 80 different dispersed cuticle species have been recognized (G. Upchurch, written comm. 6/91). Cuticle species represent parautochthonous or allochthonous elements. Most cuticles are robust (>2–3 μm thick) and characteristic of coriaceous-leaved evergreens, reflecting the physiognomy of the source vegetation, which is broadleaved evergreen.

Wood

Wood clasts are generally flattened and rounded near their ends and are similar to those reported in other coastal regimes (Gastaldo et al., 1987). Most recovered clasts are less than 1 cm in maximum dimension, and clast size is similar to that for recovered leaf fragments in the same plant-bearing bed. Where mixed litters had been reworked by tidal processes, woody components are more common as they are more resistant. SEM examination of wood clasts (both exterior and interior) reveals little colonization by fungi. Degradation of xylem cell walls is mechanical, and cell walls appear fractured (Fig. 9A). The physical abrasion of the exterior cells of wood clasts moved in bedload mechanically breaks portions of saturated cell walls from the phytoclast. This results in progressive rounding during transport, and may be a relative indicator of residency time in bedload. Alteration of size and shape appears to be in response to bedload transport after sinking and reworking rather than through biotic-induced decay. At a depth of −2.15 m in Core 8 (estuarine conditions; pH 7.12, Eh −350 @ 30.7° C), early diagenetic framboidal pyrite had formed within a hollowed cavity (Fig. 9B). Dammar-bearing woods retain crystallized resin-rodlets within xylary elements (Fig. 9C). These resin-rodlets are approximately 1 mm in diameter and easily distinguished from amorphous dammar. Wood clasts are older than other plant parts. A sample of wood recovered at depth from a lateral channel bar was C^{14}-dated at 5950 ± 255 C-14 years BP, whereas leaves C^{14}-dated from the same core at −2 m greater depth were C^{14}-dated at 765 ± 200 C-14 years BP.

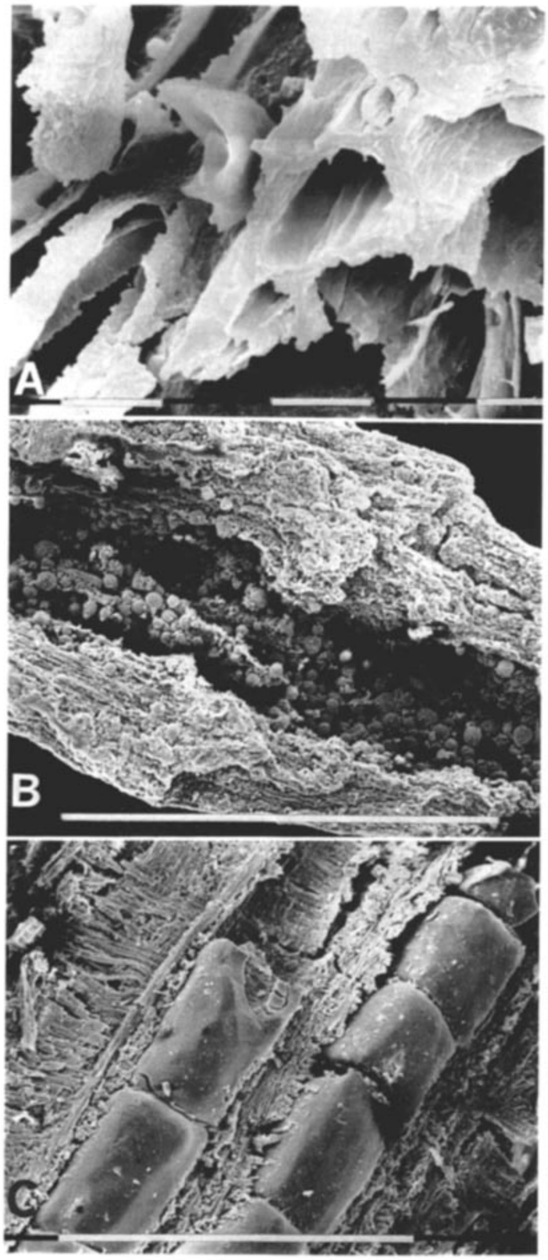

FIGURE 9—SEM micrographs of recovered wood. **A**) End of a wood clast demonstrating the fractured nature of wood elements. Note the absence of fungal hyphae. Core 22, section 6, −55 cm depth (see Fig. 6). Scale 1 mm. **B**) Wood with early diagenetic framboidal pyrite forming within a cavity. Core 8, section 2, −15 cm depth (see Fig. 7). Scale 1 mm. **C**) Resin ducts in wood recovered from lateral channel bar sediments. Core 22, section 6, −55 cm depth (see Fig. 6). Scale 1 mm.

Dammar

Resins are plant secretions that solidify when exposed to air, and approximately 10% of extant plant families living in temperate and tropical climates synthesize them (Langenheim, 1990). Resins are common in certain gymnosperms and angiosperms, and resins from plants of different systematic affinity commonly have been given distinct appellations. Coniferous terpenoid resins are generally referred to as resins or ambers. The production of resins in angiosperms is limited to a few families. Members of the tropical Burseraceae and Dipterocarpaceae produce resins that contain triterpenoids and have been termed dammars (an Indo-Malay word for resin).

Dammar is infrequently encountered as isolated small rodlets or filling ducts within wood clasts. Most commonly, dammars are found as isolated, amorphous to cylindrical masses of polymerized resin in high energy depositional environments. Dammar is heavier than water and, therefore, is transported in bedload. Clast lengths may be up to several centimeters, and diameters may exceed 1 cm. Individual irregularly-shaped pieces of dammar show features acquired during transport including rounding and fracturing. Most pieces are not angular. In addition, they may show signs of macroinvertebrate interactions that include boring and utilization as a firm substrate (Gastaldo, in press). Coloration, translucence/opacity, and friability of the dammar do not appear to be characteristics that can be used to infer age of individual clasts. C^{14} dates for two dammars recovered from a detrital peat beach demonstrate this fact (Gastaldo et al., in press). One piece appeared to be "young" based on its amber coloration (dark yellowish-orange, Munsell 10 YR 6/6) and translucent appearance; another piece appeared to be "older" based on its "weathered" opaque appearance (bluish-white coloration Munsell 5 B 9/1). The C^{14} age of the translucent specimen is 2645 ± 215, whereas the opaque specimen has yielded an age date of 930 ± 205 C-14 years BP (Krueger Sample Nos. GX 14808 and 14809).

Fruits and Seeds

Small, whole fruits and seeds, or fragmentary sclerotesta (hard outer seed coats) were encountered infrequently in some sample sites (Table 3). Although low in number, the diversity of seed types is high (36 taxa). Only one seed type was found in two or more samples. The most commonly encountered large seed is that of *Nypa*. It is found not only buried at depth (Fig. 7), but more often as an allochthonous component incorporated within detrital peat beaches. The presence of *Nypa* along upper reaches of tidal channel margins in the mixed tropical forest (10's of kilometers inland) attests to the transportability of the seed by tides. One *Nypa* seed recovered from an abandoned channel fill sequence (at a depth of −1 m; Core 16) was C^{14}-dated at 380 ± 155 C-14 years BP (Krueger Sample No. GX-14771).

Roots

Roots and rootlets are the predominant component in entisols, although rootlets have also been identified as allochthonous elements in other depositional settings. Woody roots are common in soil profiles of the mixed tropical forest, whereas non-woody roots are the main component

TABLE 3—Phytoclast samples used in cluster analyses. Sample number 3.4/45 read as Core 3, section 4, sample recovered from −45 cm from top of section. Weight in grams except for fractions that were too small to be weighed. Those fractions were assigned a weight of 0.001 g for calculation purposes. Additional biotic components are either present (P) or absent (0). All data used for cluster analysis presented in Figure 10.

Number	3.4/45	2.2/60	3.5/60	1.4/35	1.1/68	Core 34	Peat Beach	22.2/10	22.1/80	8.3/60	10.1/13	8.1/80
Weight leaves	0.31	0.16	0.34	0.41	0.13	0.37	0.21	0.13	0.14	0.25	0.01	0.17
Weight petioles	0.22	0.12	0.14	0.19	0.02	0.44	1.17	0.27	0.27	0.33	0	0.62
Weight roots	0.001	0.001	0	0.001	0.001	0.13	0.04	0	0	0.001	0	0.001
Weight cuticle	0.001	0.001	0.01	0.02	0.001	0	0.01	0.001	0.001	0.001	0	0.001
Weight dammar	0.001	0.02	0.001	0.001	0.01	0.001	0.64	0.01	0.02	0	0	0.001
Weight fr & seed	0	0	0	0	0	0.001	0.06	0.001	0.001	0	0	0.001
Weight misc	0	0	0.001	0.02	0	0	0	0.001	0	0	0	0
Insect	P	P	P	P	P	P	P	P	P	P	P	P
Forams	P	0	0	0	0	0	0	0	P	P	0	P
Bivalve	0	P	0	P	P	0	0	0	0	0	0	P
Gastropods	0	0	0	0	0	0	P	0	0	P	0	0
Crabs	0	0	0	0	0	0	0	0	0	0	0	P
Vertebrates	0	0	0	0	0	0	0	0	0	P	0	0
Mosses	P	0	P	P	0	0	P	P	P	0	P	0

Number	7/60–70	8.2/75	13.5/5	8.3/85	22.6/20	26.2/52	26.3/75	Core 39/0–20	13.5/80	22.5/65	22.3/79	13.5/80
Weight leaves	0.08	0.22	0.33	0.19	0.27	0.02	0.02	0.05	0.18	0.2	0.15	0
Weight petioles	0.58	0.5	0.13	0.34	0.1	0.36	0	0.46	0.23	0.59	0.21	0
Weight roots	0.02	0.01	0.001	0.001	0	0	0	0.37	0	0	0	0.001
Weight cuticle	0.001	0	0	0.01	0.01	0.001	0.001	0	0.001	0	0	0
Weight dammar	0.001	0	0.18	0	0.001	0.001	0.52	0	0.001	0	0.001	0
Weight fr & seed	0	0	0	0.001	0.001	0.001	0.001	0.001	0	0.01	0	0
Weight misc	0	0	0	0	0.001	0	0	0	0.001	0	0	0
Insect	P	P	P	P	P	P	P	P	P	P	P	P
Forams	0	0	0	P	0	0	P	0	0	0	0	0
Bivalve	P	0	P	0	0	P	0	0	0	0	0	P
Gastropods	0	0	0	0	0	P	0	0	P	0	0	P
Crabs	0	0	0	0	0	0	0	0	P	0	0	0

of *Nypa* swamps. The majority of rooting structures occur as cuticular sheaths without stomata.

Moss

Non-vascular plants are a component of bedded plant detritus in high energy environments. Moss has been recovered from several samples, and each specimen is composed of a central axis with laterally-disposed leaves. The achlorophyllous leaves are entire and show no signs of chemical or physical degradation.

Other Biotic Components

Biotic components in litter assemblages are not restricted to plant parts, although these are the most common subfossil. A wide range of insect parts are found within plant-bearing beds throughout the various depositional environments. Pieces identifiable to systematic position are relatively rare. Insect parts consist predominantly of ant head capsules, beetle elytra and prothoraces, and various mandibles (W. Shear, written comm. 6/90). One spider carapace has been found. Other invertebrates include ostracods and foraminifera, bryozoa (attached to leaf laminae; Gastaldo, in press), gastropods, bivalves, sand dollars, and a variety of crab parts. Vertebrate remains are minor components and consist of small vertebrae, presumably of fish.

TAPHOFLORAS AND DEPOSITIONAL ENVIRONMENTS

Plant detrital beds in the delta are dominated by canopy parts. Leaves quantitatively overshadow phytoclast assemblages. When assessed on the basis of weight contribution, though, leaves and wood are similar in assemblage contribution (Table 3). Different systematic suites of leaves are encountered depending upon the depositional site samples. Dicotyledonous angiosperm leaves are the most conspicuous and represent the quantitative share in most fluvial- and tidally-dominated sites. The exception is found within sites of the *Nypa* swamp monoculture. Here, *Nypa* leaves (laminae and particularly petioles) overshadow all other plant components. *Nypa* laminae are rarely encountered outside of inhabited zones, but they are not restricted solely to the monoculture swamps. As previously indicated, *Nypa* may grow in mudflats associated with mixed tropical forests of the interior subzone. In these sites, it may contribute significant quantities of detritus to channel-fill assemblages (e.g., Core 16). When recovered from depositional sites outside of these principal growth areas, though, *Nypa* leaves represent a small share of the assemblage. For example, only three fragments were recovered from 304 parts assessed in two fluvial samples representing a lateral channel bar and the DMB (samples 22.1/80 and 13.5/80, respectively). *Nypa* petioles are more commonly found in distributary mouth bars and stranded on headlands, the result of transport from swamps to the delta front. Dispersed cuticle assemblages, albeit, do not mimic the monospecificity of macrodetritus in *Nypa* swamps (G. Upchurch, written comm. 6/91). Although *Nypa* cuticle is a common element, other non-mangrove cuticles are also routinely found (e.g., *Knema* of the Myristicaceae, G. Upchurch, written comm. 6/91). *Nypa* cuticle, then, may be useful in mapping the limits of tidal influence on vegetation and sedimentation within the delta.

Dicotyledonous angiosperm leaves are either parautochthonous, buried close to the original contributing community in tidal channels adjacent to vegetation, or allochthonous, transported distances >0.5 km and deposited in fluvial or delta-front environments. Mangrove swamps are easily recognized from recovered macrodetritus as these assemblages are characterized by a low species diversity of mangal taxa. Again, this is not reflected in dispersed cuticle assemblages (G. Upchurch, written comm. 6/91). Although the presence of specific cuticular physiognomies found in dicotyledonous mangrove cuticle (Rhizophoraceae, Sonneratiaceae) along with *Nypa* appear to segregate the mangrove swamp assemblage from other depositional sites, the highest dispersed cuticle taxonomic diversity occurs in the sample examined from a black water tidal channel in the mangrove community (Core 25). This condition indicates a mixing of mangrove and non-mangrove cuticles, the latter being transported into the channels by tides. The mechanism is equivalent to the processes responsible for redistribution of phytoclasts onto headland in the form of peat beaches (Gastaldo et al., in press). It is this reworking of leaves by waves and tides that is responsible for mechanical fragmentation into, ultimately, organic components of the same clast size as the enclosing sediment.

Most other recovered phytoclasts do not appear to have any specificity to a particular depositional environment. Wood clasts are found throughout all sampled plant-bearing beds, as are fruits and/or seeds. Most plant-bearing beds also preserve small root cuticle. This is introduced into the fluvial system by erosion of channel margins within forested wetlands. The presence of older wood (C^{14}-dated at 5950 ± 255 C-14 years BP) stratigraphically higher than young leaves (C^{14}-dated at 765 ± 200 C-14 years BP) in lateral channel bar deposits may either be the result of such soil excavation or reworking. All entisols investigated in this study are dominated by these small root cuticles. More resistant wood and fibrous petiole parts complement the root-dominated assemblage. Dammar is a component mainly of fluvial environments, and small isolated amorphous bodies are commonly encountered. Larger pieces of dammar are reworked onto the detrital peat beaches where they are incorporated (Gastaldo et al., in press). Clast density appears to be responsible for concentration of dammar in beds that have been reworked, as they were more frequently encountered in the tide-influenced interdistributary area. Isolated rodlets, being liberated from degraded and fractured wood during transport, are infrequently found.

It is interesting to note that mosses are a component of some litter. It appears to be restricted to fluvial-dominated depositional sites, occurring in lateral channel and distributary mouth bars, and delta front environments. These may have originally been epiphyllous or may have been established in the canopy. Their introduction to the fluvial regime as a consequence of animal activity in the forest can not be ruled out.

Cluster analyses of plant-bearing beds in which only the contribution by weight of individual plant part categories were used (Gower general similarity coefficient) and those in which all recovered biotic components were used (presence/absence data used for Sorenson's similarity coefficient, Fig. 10) provide similar results. Mixed tropical forests can be differentiated from all other sites primarily due to the high quantitative share (Gower's) or nearly exclusive presence of roots and rootlets. A soil can be recognized for what it is by the predominance of subterranean plant parts. All samples recovered from the *Nypa* swamp cluster together, with the exception of one sample (760-70) which represents the base of a core recovered in the margin of a tidal channel traversing a palm swamp. This organic-rich mud sample incorporates amorphous dammar, providing the correlation linkage with other fluvial-dominated sites. All samples recovered from fluvial-dominated sites cluster, essentially, together. It would be difficult to distinguish most subenvironments based solely upon the presence or absence of a specific biotic component. Those sites of the subtidal zone and delta front (=lower delta plain) clustered together and this is due to the presence of a variety of macroinvertebrates incorporated within the litter.

CONCLUSIONS

Phytoclasts are an integral component in coastal sedimentary regimes and can be used in conjunction with other data to refine interpretations concerning depositional environments. Megascopic assemblages consisting of a single plant type are indicative of monocultures, and reflect contribution from a plant community adapted to stressed environments. Higher diversity assemblages must be treated more cautiously as they may reflect litter from one (parautochthonous accumulations) or more (allochthonous accumulations) communities. Depositional context and an understanding of lateral facies relationships are necessary to interpret and utilize these assemblages.

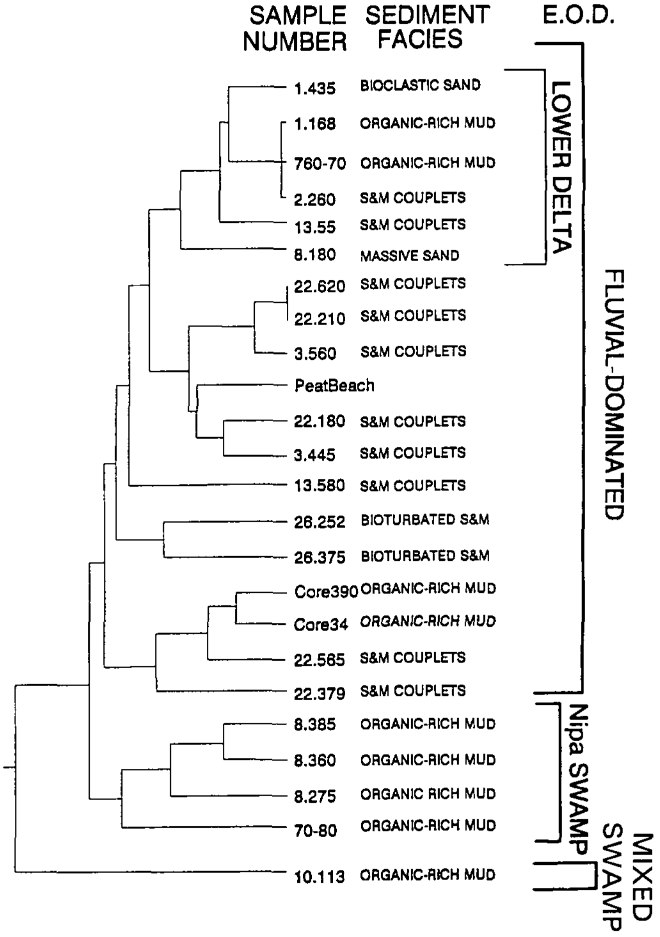

FIGURE 10—Unweighted pair cluster analysis of presence/absence data (Table 3) for all biotic components using Sorensen's coefficient of similarity (Kovach, 1990). Mixed tropical swamps cluster separately from samples recovered from *Nypa* swamp. Lower delta plain samples cluster within the fluvial-dominated samples because of the added presence of a variety of macroinvertebrates.

In the present study, ten sedimentary facies have been distinguished within the vibracore sample suite. Specific facies characterize one or more depositional environments. Bioclastic Sand and Massive-bedded Sand Facies are found exclusively in the delta front. Fluvial channels are characterized by the Sand-Mud Couplet and Sandy Mud Facies. The Bioturbated Sand-Mud Couplet Facies and the Mud with Sand Laminae Facies are modifications of the Sand-Mud Couplet Facies. These are also found in the delta front and restricted to all tidally-influenced channels. Tidal flats and headlands are characterized by Gray-Black Mud and the Tan-Gray Silt-Mud Couplet Facies, although this latter facies is also present in tidal and fluvial channels. Organic-rich Mud is most common in swamps, tidal-channel infills, and tidal flats, whereas Peat is restricted to the delta front headlands.

Identifiable phytoclasts occur in all depositional settings, either as recoverable macrodetritus or dispersed cuticle. Plant-bearing beds are composed of excised canopy parts, predominantly leaves, that are parautochthothonous or allochthonous in origin. The size of phytoclasts reflects mechanical processes operating during transport and/or reentrainment before final burial. Plant parts include wood and fibrous tissues, *Nypa* petioles and leaf laminae, dicotyledonous leaves and isolated cuticle, fruits and seeds, roots and rootlets, and moss. Isolated resin ducts may be recovered but, in most instances, dammar is found as rounded amorphous clasts.

Fluvial channels and depositional environments associated with these systems in the delta front preserve bedded litter as drapes, reflecting flow reduction either in shallow water areas or in response to the reverse in tidal bore. Rarely are plant parts found incorporated into sand. Dicotyledonous angiosperms are derived from the mixed tropical forest of the interior subzone or are extrabasinal, originating from vegetation to the interior of the island. Other biotic components that occur in the lower reaches of these settings include a variety of macroinvertebrate parts (gastropods, bivalves, Echinoidea). The entire biotic complement allows the delta front settings to be separated from other fluvial depositional sites, although these sites cluster within the samples derived from fluvial-dominated localities.

Nypa swamps and tidal channels traversing these wetlands are easily distinguished by a monotypic macrodetrital assemblage dominated by palm leaves. Few other phytological components have been found in the megafloral sample, although the dispersed cuticle suite demonstrates that extrabasinal elements are easily transported into swamp interiors. This is particularly true in the sample recovered from a black water tidal channel traversing mangrove swamp. Although little identifiable macrodetritus is found, a plethora of dispersed cuticles is present. Tidal channels in the mixed tropical forest of the interior subzone may appear similar to those of the subtidal zone, particularly if *Nypa* is growing in shallow water along channel margins. A higher proportion of dicotyledonous angiosperm leaves mixed with palm leaves would allow one to identify this setting. Based solely upon recoverable plant part categories, these sites could not be differentiated from fluvial environments. Accessory biotic components indicative of marine influence (foraminifera, bivalves, decapods) would be additional evidence to differentiate subtidal sites from deposition in the interior subzone.

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