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Geo-Pedological Study of the Mekong Delta

NGUYEN HUU CHIEM*

Abstract

The Mekong delta is divided into five landform units, namely, the floodplain, the coastal complex, the broad depression, the old alluvial terrace, and the hills-mountains, and some of them are further subdivided (Fig. 2). These landform units are discernible from LANDSAT imageries, topography, properties of sediment and agroecology. Except for the old alluvial soil, which was formed during the Tertiary to late Pleistocene period, the landforms were shaped by transgression and regression in the Holocene period. Stratigraphic properties of sediments were examined in terms of chemical characteristics and pollen content, and seven depositional environments were ascertained: fan wash-out into littoral, transitional, marine, lagoonal, tidal flat, intertidal, and riverine.

I Introduction

The Mekong delta is the southernmost region of Vietnam. It is bounded by the South China Sea in the east, the gulf of Thailand in the southwest and Cambodia in the northwest. Except for minor areas of hills and mountains where hard rocks are exposed, the delta is occupied by unconsolidated sediments. Evidently, the sediments were controlled throughout most of Tertiary and Quaternary by a combination of tectonic movements. But the majority of the landforms were shaped by transgression and regression in the Holocene period. Today, the process which created the delta continues, with silt deposits extending the shoreline at the mouths of rivers and topsoil layer accretion in riverine area. Therefore, the landform of the delta is continuously changing.

Although the micro-relief is not large, it greatly influences agricultural production through differences in water regime and quality of soil. To distinguish these differences and to establish a base for land use planning, landform units and their characteristics have to be studied.

II Materials and Method

A. *Materials*

To classify the landforms of the delta, the following documents were consulted: false-color LANDSAT imageries of 1 : 250,000 scale and the physiographic division map of Takaya were used for mapping. Soil maps and land use maps of 1 : 250,000 scale were used for

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determining sampling sites. A six-meter hand auger was used to take soil samples. Five representative soil profiles out of 38 collected profiles were analyzed in the laboratory. The sampling sites are shown in Fig. 1.

B. Methodology

Sampling sites were determined after reconnaissance mapping of the landform. Soil samples were taken at different horizons, depending on such characteristics of soil as color,

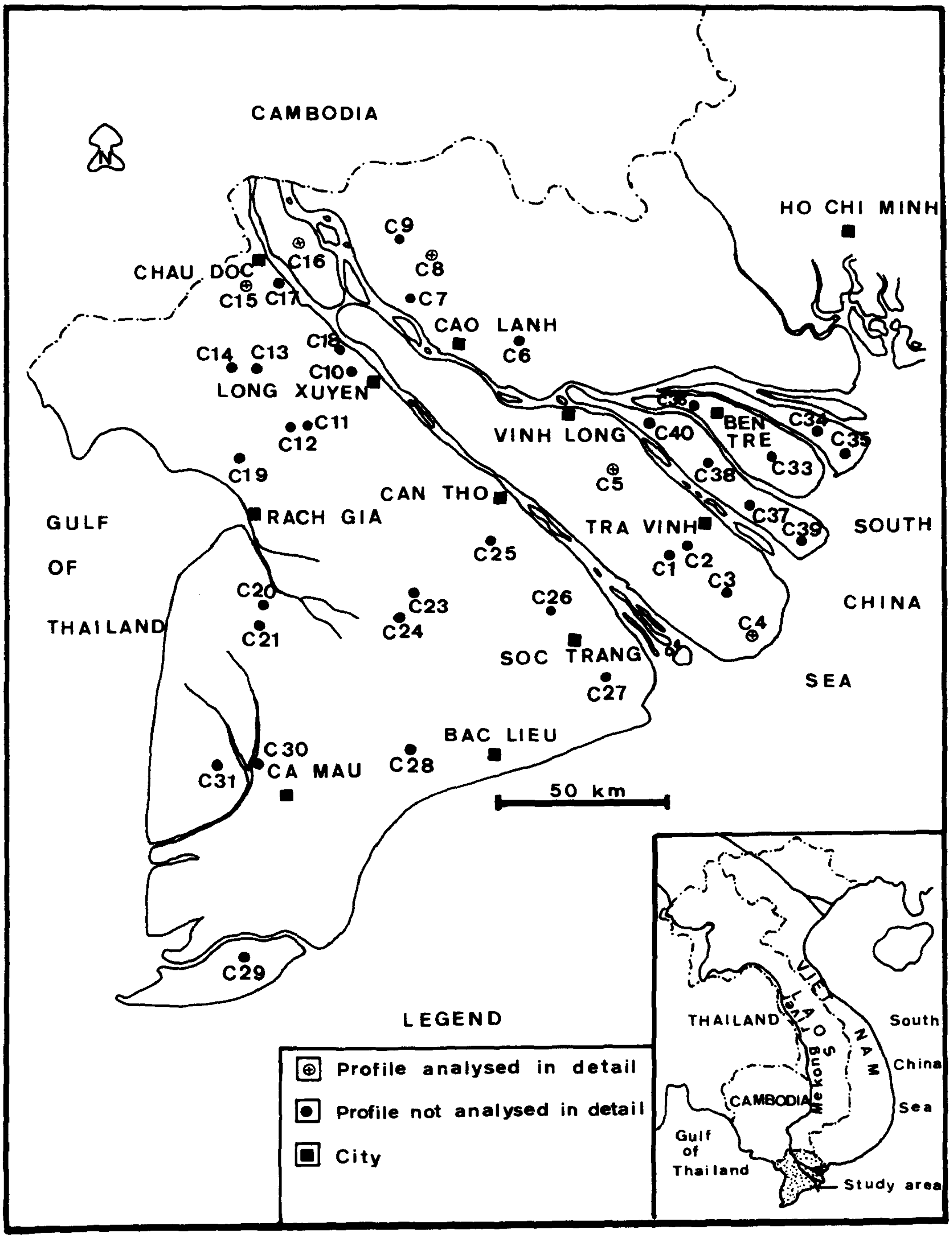

Fig. 1 A Location Map of 38 Auger-Drilled Sites in the Mekong Delta

organic matter content, texture, and pH.

Soil analyses consisted of pH of soil suspended in water ; pH after oxidation with H_2O_2 (scale 1 : 5) ; electric conductivity (scale 1 : 5) ; soil texture after removing calcium carbonate with hydrochloric acid and organic matter with H_2O_2 ; and pyrite, jarosite, water-soluble sulfate and total sulfur contents, which were analyzed by the method of Begheijin [1989 : 25-39].

To identify clay mineral, two oriented specimens were prepared [Jackson 1969 : 895] for X-ray diffraction analysis.

To count pollen grains, the method of Faegri, K. and Iversen, J. [1989 : 70-89] was used. Pollen grains were observed under a microscope at magnifications of 40, 100 and 400. Pollen species were classified into 3 main environmental types : mangrove, brackish water, and freshwater ; the remainder were spores and unidentified pollens (Figs. 4, 7, 9, 11 and 13).

Field investigation also included interviews of old, experienced farmers living in each area studied. The interviews concentrated on such natural conditions as water regime, vegetation, and topography.

III Results and Discussion

1. Landform Division

The various landform units of the delta were formed by processes of accretion and erosion under different environmental conditions. Each landform unit has different hydrographic and pedological conditions and, therefore, each form's a special agro-ecological environment. Based on these concepts, the delta was divided into five landform units and several subunits. These are illustrated on the map in Fig. 2.

- Floodplain (1)
  - High floodplain (1.1)
    - Natural levee (1.1.1)
    - Sandbar (1.1.2)
    - Backswamp (1.1.3)
    - Closed floodplain (1.1.4)
    - Open floodplain (1.1.5)
  - Tide-affected floodplain (1.2)
    - Natural levee (1.2.1)
    - Backswamp (1.2.2)
    - Broad depression floodplain (1.2.3)
- Coastal complex (2)
  - Sand ridge (2.1)
  - Coastal flat (2.2)
  - Inter-ridge (2.3)
  - Mangrove swamp (2.4)

Broad depression (3)
  Broad depression (3.1)

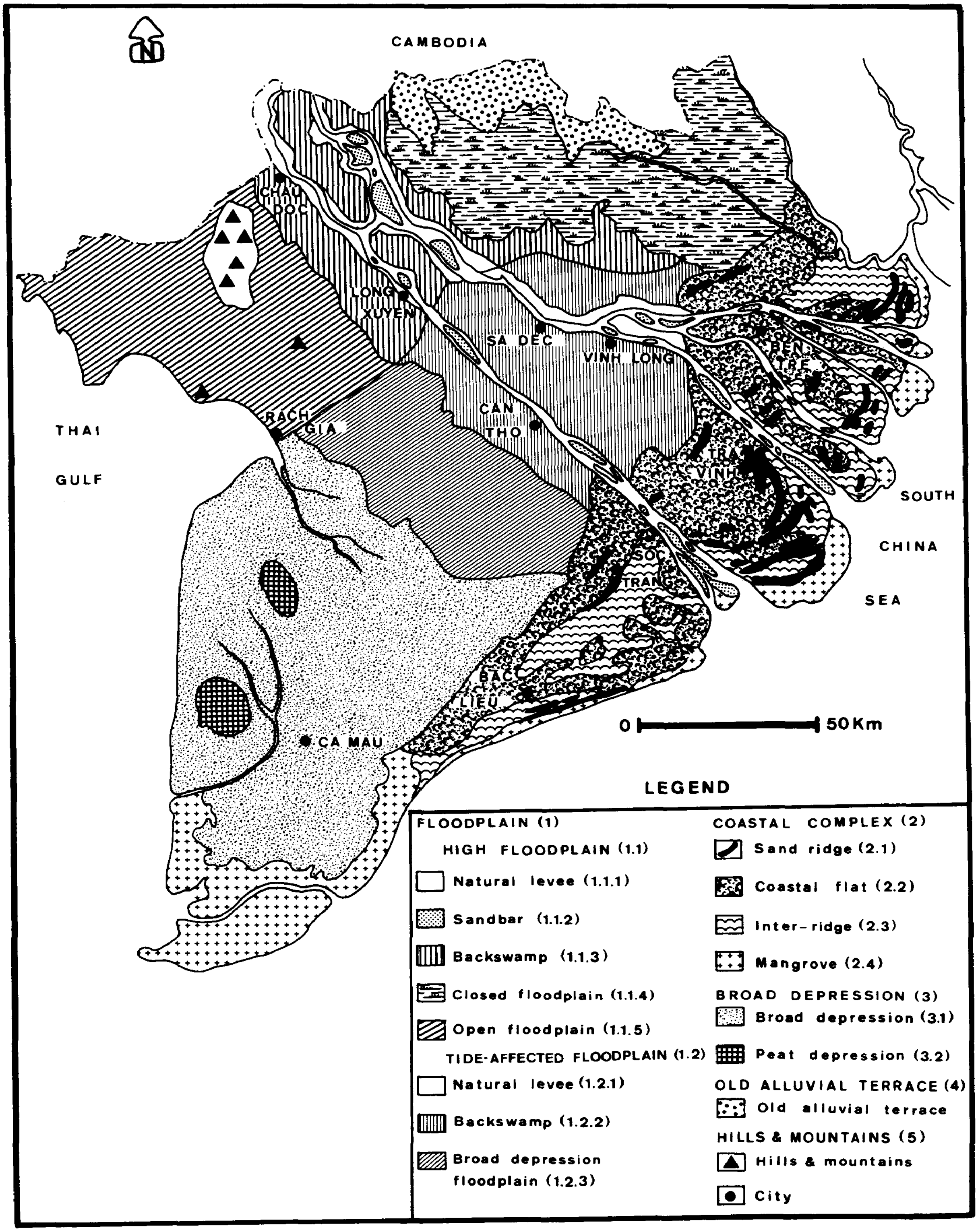

Fig. 2 Landform of the Mekong Delta

Peat depression (3.2)
Old alluvial terrace (4)
Hills and mountains (5)

2. General Description of Landform Units

Floodplain (1)

The high floodplain (1.1) is located in the northwest of the delta. It is named as the high floodplain because it has the greatest depth of inundation (2 to 3 meters) in the flood season. This unit consists of the following subunits.

Natural levees (1.1.1) run parallel to the banks of the Mekong and Bassac rivers. They stand out clearly on LANDSAT imageries, occupying the highest position in the floodplain (3 to 4 meters above sea level) and showing a gradual decrease in elevation away from the river banks. They vary in width from 0.5 to several kilometers. River water reaches their surface only during the highest flood, which normally occurs at the end of September or in October.

Sandbars (1.1.2) lie between branches of rivers. They look like natural levees on LANDSAT imageries, but their soil texture is coarser in deeper soil layers than that of the natural levees. In particular, the shape and surface of the sandbars are not smooth as are those of natural levees. Some sandbars have small areas (5 to 10 hectares) but others are very large, having the same area as a village several hundred hectares.

Backswamps (1.1.3) lie behind the natural levees. They are low and often inundated from the beginning of the rainy season in May until the end of February. The maximum inundation can reach as deep as 2 to 3 meters at the end of September. Several kinds of acid sulfate soils are found here.

In addition to these subunits, the high floodplain includes a closed floodplain (1.1.4) and an open floodplain (1.1.5), both of considerable area.

The closed floodplain (1.1.4) is a plain of reeds enclosed by sand ridges in the east at Tan An, Tan Hiep, Cay Lay and My Tho (between Cantho and Saigon), the natural levee of the Tien river (Mekong River) in the southwest, and the old alluvial terrace in the north. During the flood season, the closed floodplain resembles a big shallow lake. The water level can rise up to 3 meters, and the drainage through the Vam Co Dong and the My Tho river is very difficult and slow. Today, more than 60 percent of the area is under cultivation and the remainder is covered by *Melaleuca* and *Eleocharis*, which can tolerate the strongly acid sulfate soils.

The open floodplain (1.1.5) is quite different from the closed floodplain. It slopes gently from the Bassac river to the gulf of Thailand, forming a fan-like terrain from which floodwater easily drains. The maximum inundation depth is only about 1.5 to 2 meters in September. Strong acid sulfate soils are also found there.

The tide-affected floodplain (1.2) occupies the center of the delta. It is strongly influenced by the daily tides of the Hau and Tien rivers. The maximum inundation depth varies from 0.5 to 1 meter from the end of September to mid-October. Freshwater flows perennially in the rivers and canals, and it rises into the fields during the full moon and new moon. The ground surface is always moist to wet, providing a good environment for the vigorous growth of perennial weeds, mainly of *Cyperus* and *Scirpus*. Acid sulfate soils are also present here but their effects are less serious because toxicity is readily washed away by the tidal rivers. Therefore, the soil quality is constantly improving, and the tide-affected floodplain has the highest potential for agricultural production in the delta.

The tide-affected floodplain can also be divided into the following subunits.

Natural levees (1.2.1) along the Tien and Hau rivers and their branches. These levees are narrow and low compared to those of the high floodplain. Nowadays, fruit orchards occupy almost all of these levees.

Backswamps (1.2.2). These are the same as the backswamps in the high floodplain, but the water regime is quite different, being strongly influenced by the diurnal tides of the Tien and Hau rivers. At high tide, these areas are inundated, the depth of the water depending on the phase of the moon.

Broad depression floodplain (1.2.3). This area is situated between the tide-affected floodplain (1.2) and the broad depression (3) and is low-lying and poorly drained. It consists of Vi Thanh, Long My and Phung Hiep districts of Hau Giang province. Except in the flood season, only a limited volume of freshwater enters from the Hau river. Tidal influx and rainfall volume determine the depth of water in the area. The maximum inundation varies from 0.7 to 1 meter in October. Several kinds of acid sulfate soils can be found there.

Coastal Complex (2)

The coastal complex (2) is influenced by marine and riverine environments. Its topography varies from place to place, and it can be divided into four subunits:

Sand ridges (2.1) run parallel with the coastline. They have the highest position in the area (from 2 to 5 meters above mean sea level). The width and length of the ridges range from 0.5 to 2 km and from 5 to 40 km, respectively.

Coastal flats (2.2). These have moderate relief of about 1 to 1.5 meters above sea level. Seawater cannot intrude directly but it can enter by capillary movement from the subsoil to the topsoil layer during the dry season. The maximum inundation depth is very shallow (0.2 to 0.5 meter) even during the flood season (October).

Inter-ridges (2.3). These are located between the ridges and are low-lying, being at or below mean sea level. The tides of the South China Sea determine the water regime of these areas. They are covered by saltwater during the dry season (November to April), and by freshwater during the rainy season. Actual and potential acid sulfate soils are also common in these areas but they pose no serious effect, because toxicity is washed away by tidal action and fresh sediments are deposited on the soil surface every year. On the other hand, they are always submerged under alternately brackish or freshwater in the dry and rainy seasons, respectively.

Mangrove swamps (2.4). These are dominant along the coast, the mouth of the Mekong river and the point of Ca Mau (Mui Ca Mau). Potential acid sulfate soils are found in these swamps, and a sulfidic horizon lies very close to the topsoil. Many species of mangrove thrive in these swamps, of which the dominants are *Avicennia* and *Rhizophora*. Every year the mangrove continues to extend seaward, especially in the Ca Mau point and the mouth of Mekong River.

Broad Depression (3)

The broad depression (3) occupies a large area in the south of the delta. It is very flat and low (about 0.5 to 1 meter above sea level), and it encompasses Minh Hai province and parts of Hau Giang and Kien Giang province. Depending on the topography, soil and vegetation, the broad depression is divided into two subunits.

The broad depression (3.1) is nearly isolated from the delta system; water of the Bassac (Hau) river cannot reach this area. Although there are some artificial canals, these are only used for drainage and transportation, because the broad depression is so far from the river. As a result, the soil is influenced by saltwater and acidity in the dry season.

Peat depressions (3.2) are the two lowest areas of the broad depression. Located at U Minh Thuong and U Minh Ha, they have a lot of peat soil on which *Phragmites* and *Melaleuca* are dominant. The maximum inundation can reach up to 1 or 1.5 meters due to rain water in the rainy season (October), because these areas have the highest precipitation in the delta (nearly 3,000 mm). They resemble two large natural big lakes, and they provide supplementary irrigation water for the surrounding areas during the dry season.

Old Alluvial Terraces (4)

Old alluvial terraces (4) occupy small areas (about 150,000 hectares) in the northeast of the delta, along the Cambodia—Vietnam border. The soil is very compact, containing a lot of gravel, Fe-oxide and brown mottles.

Hills and Mountains (5)

Hills and mountains (5) consist of large and small separate ranges in the west of the delta. The highest mountain is the Cam Mountain (710 meters). All of these hills and mountains are composed of granitic rock, except for some small mountains in Kien Luong, Ha Tien district, where the dominant component is limestone.

3. *Characteristics of Landform and Some Properties of Recent Holocene Sediments*

To investigate the characteristics of landform and the history of soil formation, 66 soil samples of the five representative profiles, namely C4, C5, C8, C15 and C16, were analyzed in detail. The sampling sites are shown in Fig. 1.

Profile C8

Profile C8 is located in the closed floodplain at Tram Chim Village, Tam Nong District, Dong Thap Province. A description of the profile and the results of chemical and pollen analyses are shown in Figs. 3 and 4.

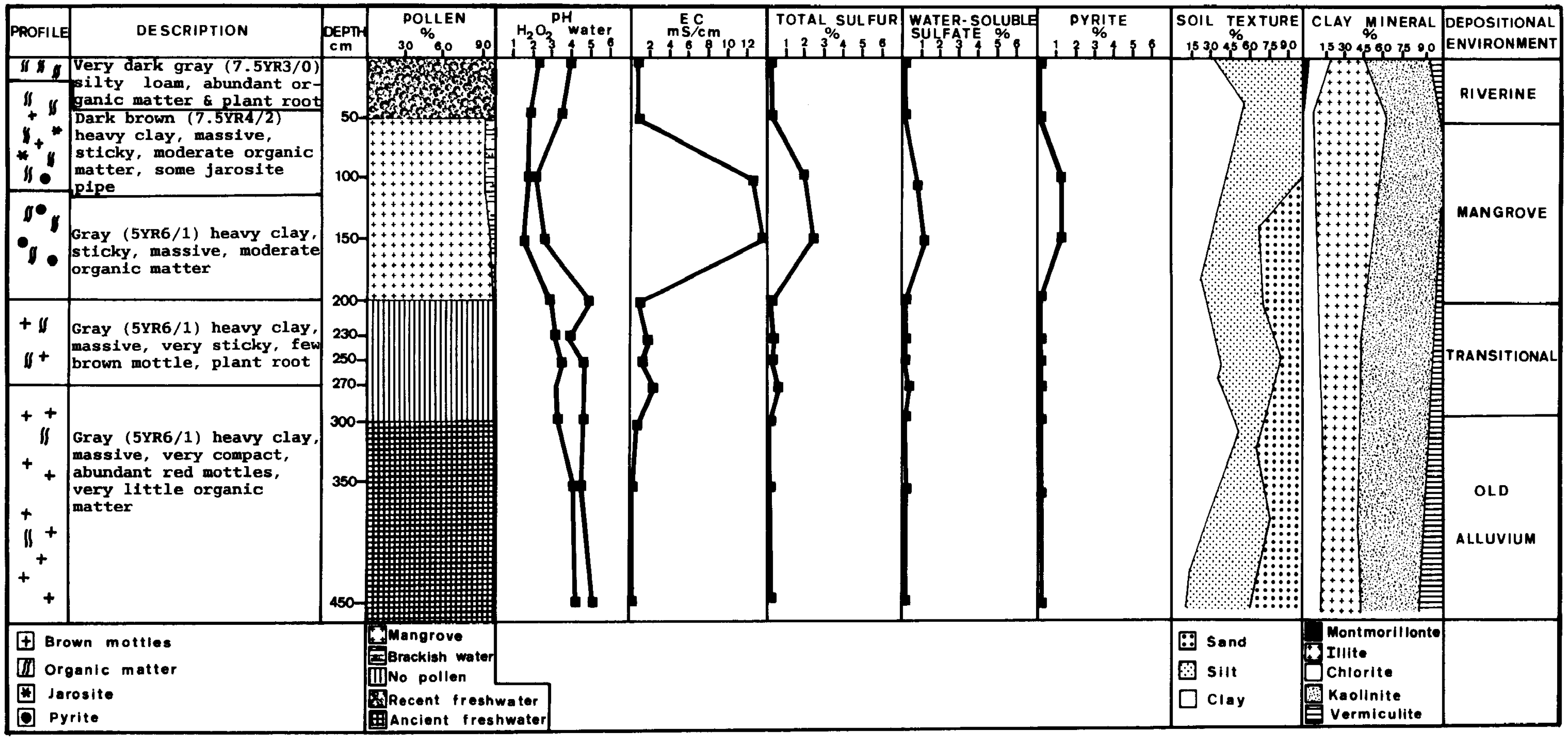

Fig. 3 Soil Profile, Chemical and Pollen Analyses, and Depositional Environment of Profile C8

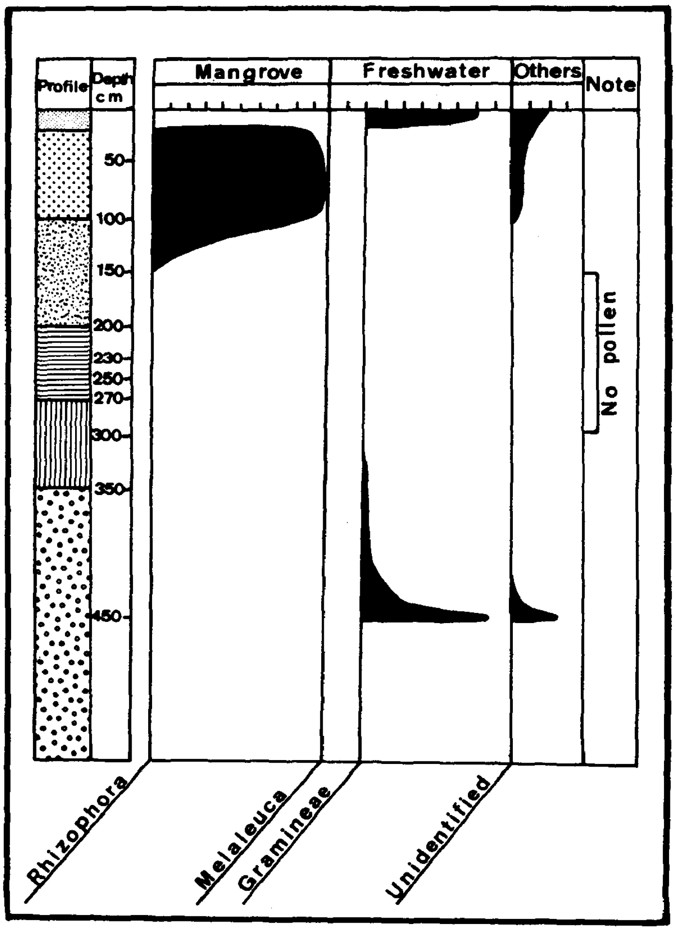

Fig. 4 Distribution of Arboreal Pollen in Profile C8

A very dark gray (7.5YR3/0) silty loam layer at 0-50 cm depth contained abundant organic matter. More than 60% of the pollens were *Gramineae* and 10 to 15% were *Melaleuca*. Brackish water and mangrove pollen species were not present. Pyrite was not detected but pH_{OX} value was low. This is probably due to a high content of organic matter, which is also oxidized by H_2O_2 to form acid. The value of pH_W was also relatively low (around 4). This is probably due to the influence of acidic water, because the soil was sampled in the dry season. Water-soluble sulfate and total sulfur were detected in negligible amounts. Clay mineralogical components consisted of 35% illite ($K[Al_2(Si_3Al)O_{10}(OH)_2]$), 30% kaolinite ($[Al_2Si_2O_5(OH)_4]$), 5 to 15% chlorite ($[AlMg_2(OH)_6]_X[Mg_3(Si_{4X}Al_X)O_{10}(OH)_2]$), 5% vermiculite ($[Mg(H_2O)_6]_n[(Mg, Fe)_3(Si_{4n}, Al_n)O_{10}(OH)_2]$) and less than 5% montmorillonite ($Na_X[(Al_{2X}Mg_X)Si_4O_{10}(OH)_2]$). The results indicate the illite to be dominant component of the riverine deposit.

Dark brown (7.5YR4/2) heavy clay layer at 50-200 cm depth contained moderate organic matter and jarosite pipes. pH_{OX} and pH_W values were low (1.8 and 3). Total sulfur, water-soluble sulfate and pyrite contents were 2-3%, 1-2% and 1%, respectively. EC (electric conductivity) value was as high as 12-13 mS/cm, probably due to the high content of soluble sulfate. Clay mineralogical components showed that illite content had increased to 60% but decreased again with the depth of the horizon. Kaolinite and vermiculite contents increased in parallel with the depth of the horizon from 35% to 50% and none to 10%, respectively.

Pollen analysis showed that *Rhizophora* were the dominant species, representing more than 95% of total pollen count. These findings indicate that this layer is a mangrove (lagoonal) deposit.

A gray (5YR6/1) heavy clay layer at 200-300 cm depth had an EC value of 2 mS/cm. Total sulfur and water-soluble sulfate contents were less than 0.5 and 0.2%, respectively. Pyrite and jarosite were not present. Mineralogical analysis showed that kaolinite was the dominant component (60%), while illite decreased to 15%. Chlorite and vermiculite were relatively sparse, with values of 15% and 10%, respectively. The predominance of kaolinite is due to the influence of terrestrial weathering, by which illite is transformed to vermiculite and kaolinite. This layer contained no pollen species. pH_W and pH_{OX} values were slightly low, perhaps due to the downward movement of acid sulfate through the jarosite pipes during the dry season. The past history of the layer revealed that it is a transitional layer between old alluvium and brackish environment. This can be seen clearly by the predominance of kaolinite.

A gray (5YR6/1) heavy clay layer at 300-450 cm depth was very compact and contained abundant red mottles and saprolitic gravels. More than 60% of the pollen were *Gramineae* species and the rest were not identified. The pH_W and pH_{OX} values were

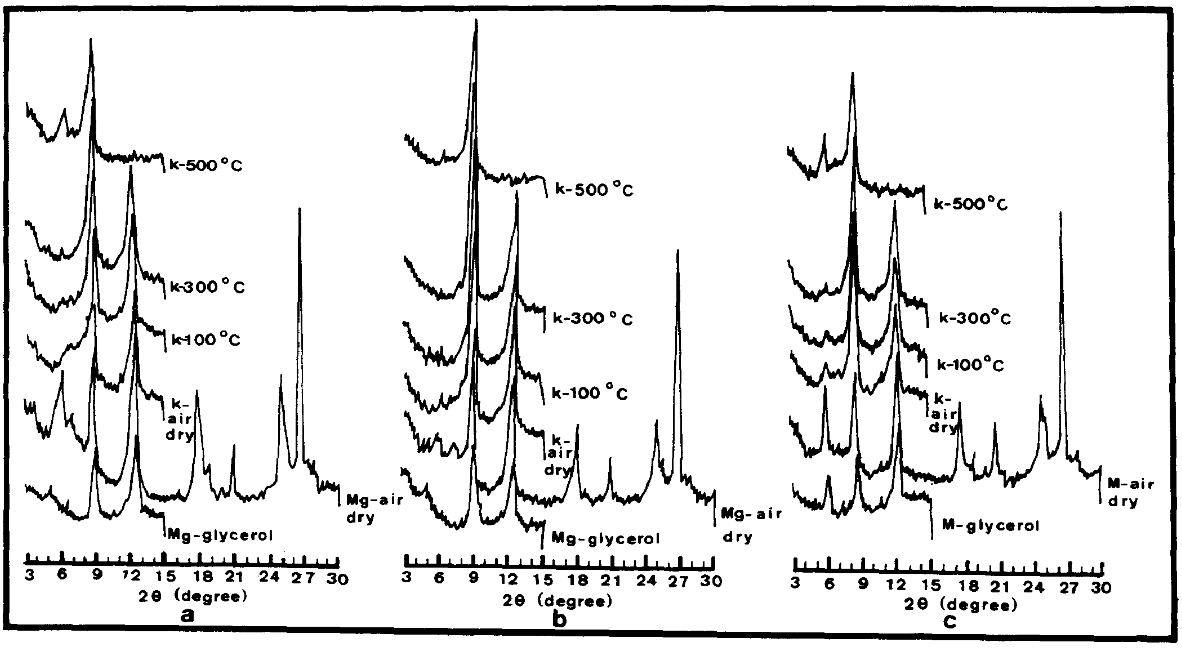

Fig. 5 X-Ray Diffractogram of Representative Profiles with Various Treatments

a. Profile C16 at 300 cm Depth | b. Profile C8 at 450 cm Depth | c. Profile C16 at 50 cm Depth relatively high (4.5 and 5). Total sulfur content was nearly zero. Mineralogical components consisted of montmorillonite, illite, chlorite, vermiculite and kaolinite. Kaolinite was the dominant component with a total value of 50%, followed by illite (20%), which was very stable in the whole layer. Vermiculite and montmorillonite were only 10% and 5%, respectively and their values increased with the depth of the layer. Chlorite was relatively stable in the whole layer with a value of about 10%. The predominance of kaolinite is relevant to the highly weathered appearance of the old alluvium soil. An X-ray diffractogram of representative profile is shown in Fig. 5. The result showed that the layer consists of old alluvium deposits.

Profile C15

Profile C15 was bored in a field of *Eleocharis* at Tay Hung Village, Tinh Bien District, 5 km from Vinh Te canal. The soil profile and the results of chemical and pollen analyses are illustrated in Figs. 6 and 7.

A dark (10YR2/1) heavy clay layer, at 0-40 cm, did not contain brackish water or mangrove pollen species; only *Gramineae* pollens were found. The pH_W and pH_{OX} values were rather low (less than 4). The EC value (1.6 mS/cm), total sulfur (0.5%) and water-soluble sulfate (0.1%) contents were relatively high. This is probably due to the capillary movement of acid sulfate from the subsoil to the topsoil, because the soil sample was taken during the dry season. Pyrite was completely absent. Mineral analysis showed that the most abundant components were kaolinite (45%) and illite (30%), and the minor components were chlorite and vermiculite, with relatively equal contents of 15% each. This layer was interpreted as being a freshwater (riverine) deposit.

A dark reddish gray (5YR4/2) to dark gray (10YR4/1) heavy clay at 40-450 cm was interpreted as being from a mangrove (lagoonal) deposit, because it had the following characteristics. pH_{OX} was always lower than 2. EC value was high, varying from 8 mS/cm to 10 mS/cm, and this was correlated to high content of water-soluble sulfate (1.5-4%). Total sulfur and pyrite contents were very high, varying from 3% to 6% and 1% to 2% respectively. Mineralogical components were very stable in content and the type of mineral. Kaolinite and illite were predominant and relatively equal in content of 40% until the depth of 400 cm. Then illite content decreased sharply from 400 to 450 cm. This is explained by the acid environment resulting from organic matter decomposition and pyrite oxidation; some illite minerals were transformed to kaolinite or vermiculite, because this layer has very high contents of organic matter and pyrite. This also coincided with increasing of vermiculite and kaolinite. Chlorite was only 10% and was stable in content. Pollen analysis showed that the population of *Rhizophora* was very high (70-95%), *Sonneratia* was minor (5-15%), and the rest were unidentified pollens.

A very dark brown (10YR2/2) peat layer at 400-450 cm was also interpreted as being from a mangrove (lagoonal) deposit, because it had very high contents of total sulfur and pyrite (5% and 2.5%) which coincided with the very high content of *Rhizophora* (75%) and *Sonneratia* (30%) pollen. EC value and water-soluble sulfate contents were very high, at

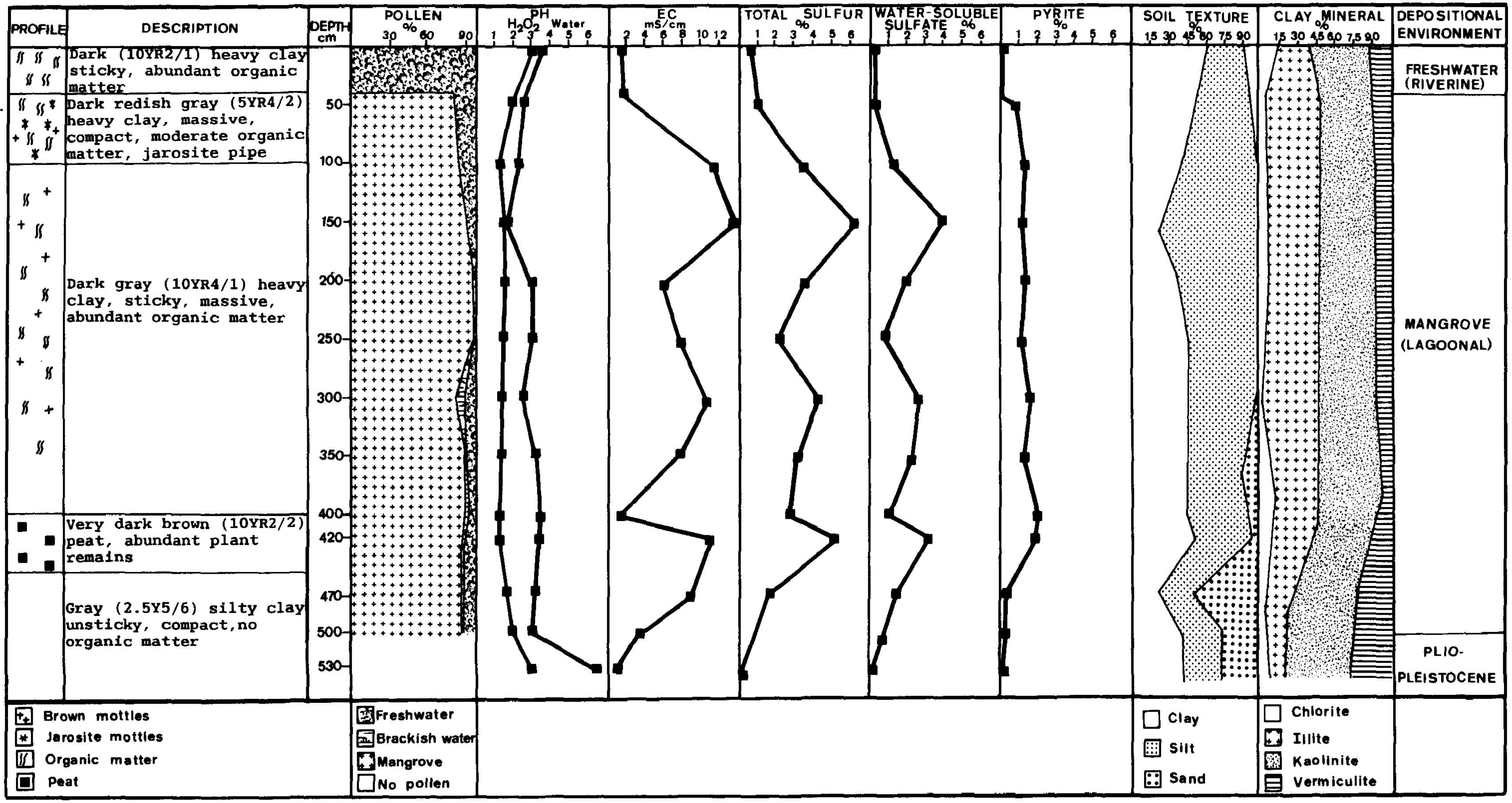

Fig. 6 Soil Profile, Chemical and Pollen Analyses, and Depositional Environment of Profile C15

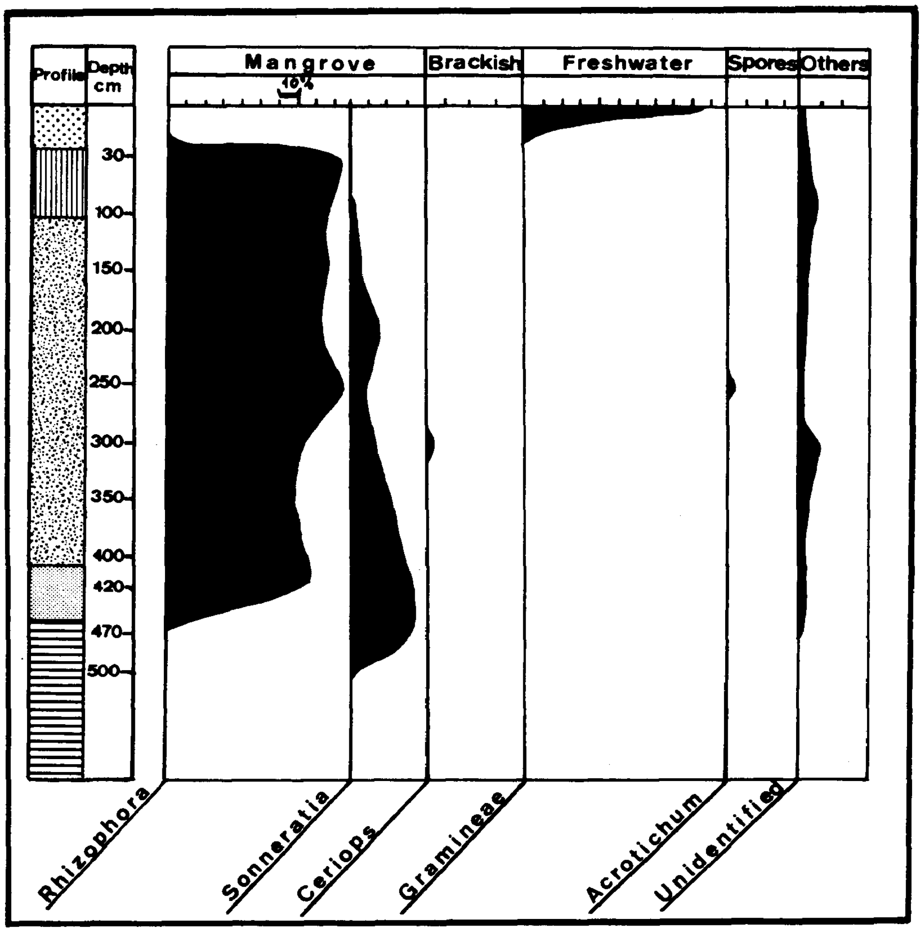

Fig. 7 Distribution of Arboreal Pollen in Profile C15

10mS/cm and 3%. These values were slightly lower at 400 cm depth, and this is attributed to the washing away or infiltration of soluble sulfates from the top layer to the lower one. This was possible because the sample was taken on top of the peat layer, and the bulk density and porosity of peat soil were very high. Consequently, its hydraulic conductivity and infiltration were also very high.

A gray (2.5Y5/6) silty clay, very compact at 450-530 cm was interpreted as being a Plio-Pleistocene deposit. This depositional environment was probably in a high energy condition because the soil texture of the layer was coarse (30% to 50% sand). Moreover, pollen species were not present. Mineralogical components showed that kaolinite predominated at 50%, vermiculite increased in content to 30%, while illite decreased sharply from 35% to 10%. This may indicate the weathering of illite to vermiculite or kaolinite. Chlorite was stable in content at about 5%. The layer is assumed to be a reworked sediment, fan wash-out into littoral, during the Holocene transgression. This can be seen by the sharp increase of kaolinite. This indicates that the sediment inherits the kaolinite of the old alluvium. Chemical analysis showed that EC value at the top of the layer (470cm) was very high (10 mS/cm), while it was only 1 mS/cm at 530 cm.

Profile C16

Profile C16 was located between the Bassac and Mekong rivers, at Phu Vinh Village, Chau Thanh District, An Giang Province, about 200 meters from the Vinh An canal. A description of the profile and the results of soil analysis are illustrated in Figs. 8 and 9.

A dark brown (7.5YR3/4) clayey silt layer at 0-90 cm contained more than 95% freshwater pollen species, mainly *Gramineae*, but their population was not dense. This was probably due to the influence of annual flooding, and the fact that some vegetation could not grow in deep inundation (2 to 3 meters). The result of analysis showed that the layer contained less than 0.1% of total sulfur; water-soluble sulfate content was negligible, while pyrite was completely absent. The values of pH_W and pH_{OX} were mostly higher than 4, except in the cultivated topsoil layer, where pH_{OX} was low (2.6). This is probably due to the influence of such acidic fertilizers as diammonium phosphate [$(NH_4)_2HPO_4$] or ammonium sulphate [$(NH4)_2SO_4$], which are widely used by farmers in cultivating rice. The EC value of the topsoil layer was also relatively high (0.32 mS/cm), and this could also be explained by acidic fertilizers. Mineralogical analysis showed that kaolinite, illite and chlorite components were very stable. They varied from 40% to 45%, 45% to 50% and around 10% respectively. Montmorillonite tended to increase in content from 0 to 8% in proportion to the depth of the layer. Vermiculite always varied in content from around 5 to 15%. Depending on soil color and the stability of clay mineral components, it showed that the soil here had just been deposited from the river, because the transformation of clay mineral components after deposition is negligible. From these data, the layer is interpreted as being from a freshwater environment (riverine).

A dark gray (10YR4/1) to very dark grayish brown (10YR3/2) heavy clay at 190-450 cm is interpreted as being from a transitional environment between brackish water and freshwater because it had the following characteristics. Three groups of pollen were found : freshwater (*Gramineae*, *Parkia* and *Podocarpus*), brackish water (*Nypa* and *Acanthus*) and mangrove (*Avicennia*, *Rhizophora*, *Bruguiera* and *Sonneratia*) ; and the percentage of each group ranged from 30 to 40%, 10 to 20% and 20 to 40%, respectively. However, the populations was very small, each soil sample containing only from 5 to 40 pollen grains in total. This showed that the original vegetation was not dense and uniform in species. Total sulfur content was low and water-soluble sulfate content was almost negligible. Pyrite was completely absent. pH_{OX} was mostly higher than 3.5 and pH_W was neutral (6-7). EC value varied from 0.2 to 0.6 mS/cm. Mineralogical components were also stable and their quantities were similar to those in the upper layer, described above.

A very dark grayish brown (10YR3/2) fine sandy clay at 450-550 cm contained three groups of pollen species, namely, mangrove, brackish water and freshwater pollen. Mangrove pollen consisted of *Avicennia*, *Rhizophora*, *Bruguiera* and *Sonneratia*, which composed 60-80% of the total pollen. Brackish water species were much less common (5-15%) and they consisted of *Nypa* and *Acanthus*. Freshwater pollen species such as *Parkia*, *Podocarpus*, and *Gramineae* were also found and they occupied 15-25% of total

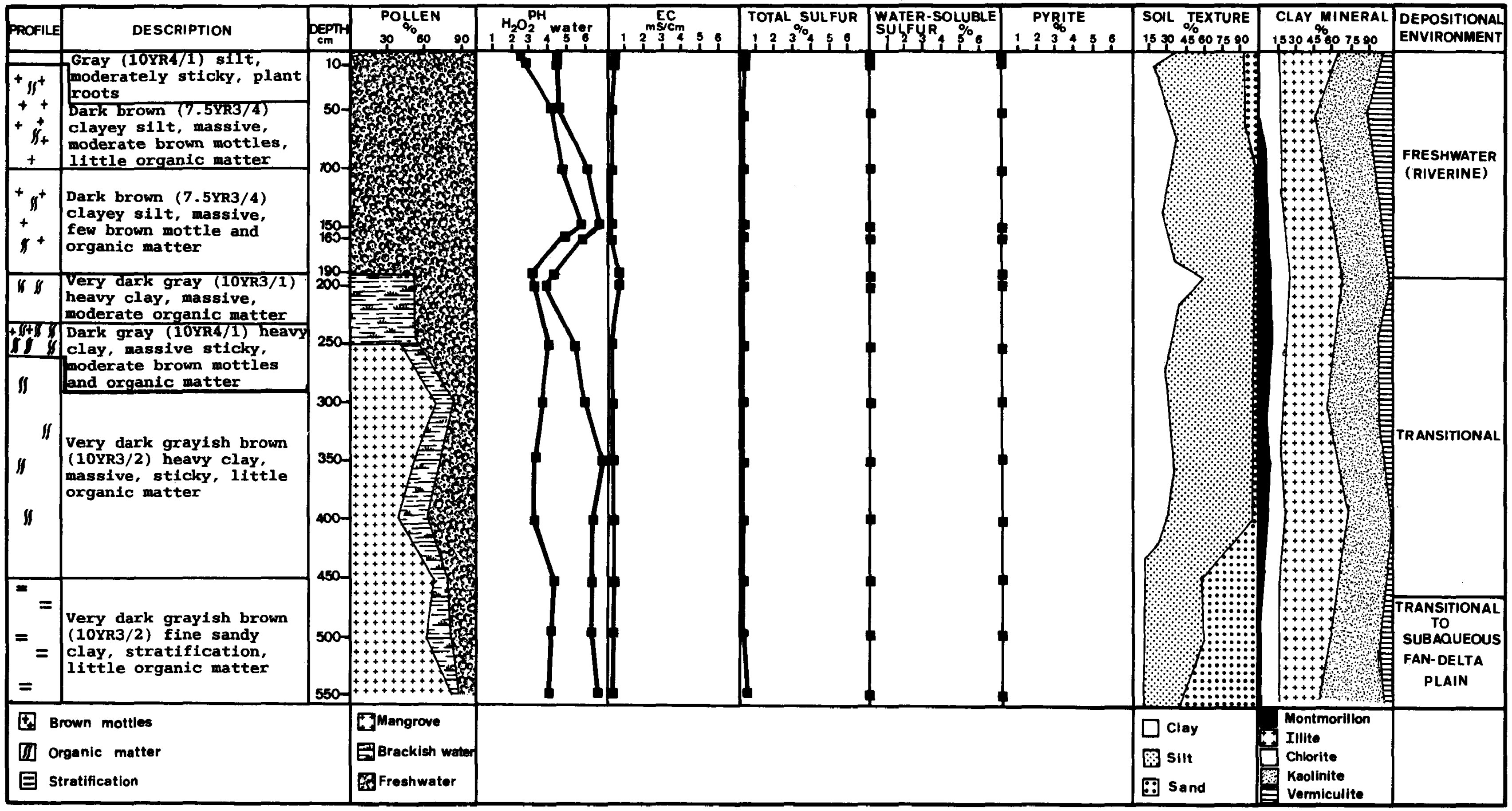

Fig. 8 Soil Profile, Chemical and Pollen Analyses, and Depositional Environment of Profile C16

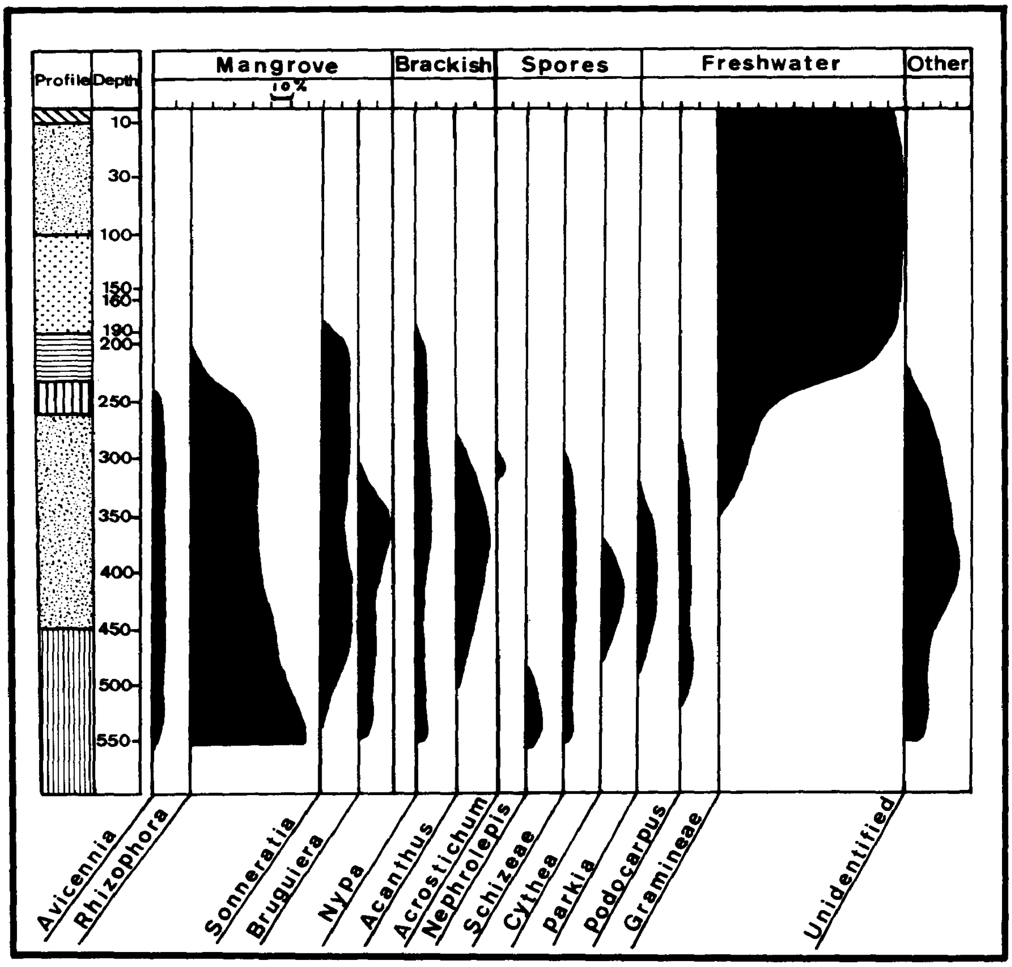

Fig. 9 Distribution of Arboreal Pollen in Profile C16

pollen. Aside from pollens, some spores of *Acrostichum*, *Nephrolepis*, *Schizeae* and *Cythea* were also found in small quantity. Although mangrove, brackish water and freshwater pollens were present in the layer, their numbers were very low. One interpretation of this is that these pollens were transported by tide and river currents to the sampling site. A second one is that they were produced on the spot by a low density of vegetation. This is supported by the absence of pyrite. Pyrite is formed by a process involving the reduction of sulfate ions to sulfides by sulfate-reducing bacteria decomposing organic matter [Dent 1986 : 74-93]. The absence of pyrite was also correlated to the rather high pH_{OX} value (more than 4). pH_W was neutral and tended to increase with the depth of the profile. EC value was constant at 0.3 mS/cm. Total sulfur varied from 0.04 to 0.19 % and water- soluble sulfate was negligible. Mineralogical components were the same at the top of the layer as in the layer above, but they varied with the depth : kaolinite increased in content from 40 to 45%, and chlorite was constant at 10%, while illite and montmorillonite decreased from 45% to 30% and 8% to 2%, respectively. This is explained by the action of the brackish water environment, in which some illite is transformed to kaolinite. The data showed that the past environment of this layer was a transitional to subaqueous fan-delta plain (turbulent riverine flow and calm marine conditions).

Profile C5

Profile C5 was bored in a rice field at Hieu Phung Village, Vung Liem District, about 2 km from the Man Thich river. A description of the soil profile and the results of chemical and pollen analyses are illustrated in Figs. 10 and 11.

A very dark gray (10YR3/1) heavy clay layer at 0–15 cm contained more than 90% of freshwater pollen species, mostly *Gramineae*. Total sulfur, water-soluble sulfate and EC values were rather high, around 0.3%, 0.1% and 1 mS/cm respectively. Pyrite was very low but enough to make pH_{OX} drop to 2. The presence of pyrite is probably due to the mixing of topsoil with the pyritic layer below through ploughing, since the pyritic layer lies very close to the topsoil. Mineralogical components consisted of kaolinite, illite, chlorite, and small amounts of montmorillonite and vermiculite. The most abundant component was kaolinite with more than 50%, followed by illite and chlorite with 30% and 15% each respectively. Montmorillonite and vermiculite had less than 3% and 5% respectively. Thus, the percentage of kaolinite in the layer was relatively high, probably due to transformation of illite to kaolinite through the action of acidity. The data showed that the layer was a riverine deposit.

A black (10YR2/1) silty clay at 15–30 cm depth contained a very high content of 4.5% total sulfur, 1% water-soluble sulfate and 3% pyrite. The pH_{OX} and pH_W value were very low. EC value reached 12m S/cm. Mineralogical components were the same as in the upper layer. Pollen analyses showed that more than 85% of pollens were *Rhizophora* and *Sonneratia*. The rest were freshwater pollens (*Gramineae*) and unidentified pollens. Their populations were very small. The past environment of the layer is interpreted as being lagoonal.

A very dark grayish brown (10YR3/2) silty clay loam at 30–240 cm contained from 40 to 50% *Rhizophora*, 5 to 30% *Sonneratia*, 5 to 20% *Bruguiera* and very few *Avicennia* pollens. Brackish water pollens such as *Nypa*, *Ceriops*, *Phoenix*, *Acanthus* and *Oncosperma* were present with low density of 3% to 20%. Freshwater pollens consisted of *Gramineae* (3%) and *Melaleuca* (35%), which were only found at depths of 130–160 cm. This showed that the depositional environment sometimes changed from wet to dry; and from salt water to brackish or freshwater. Therefore, pyrite was probably oxidized, lowering the pH value of soil, and creating favorable conditions for growth of *Melaleuca*. Mineralogical components consisted of kaolinite, illite, chlorite, vermiculite and montmorillonite. Kaolinite and chlorite were stable at 40% and 10%, respectively, while illite and montmorillonite tended to decrease with depth from 60% to 40% and 5% to 0%, respectively. This is probably due to the influence of the acid environment resulting from organic matter decomposition and pyrite oxidation, by which some illite is transformed to vermiculite; this can be seen in the increase of vermiculite from 0% to 10%. Chemical analysis showed a high EC value of from 1 to 6 mS/cm, probably due to the influence of

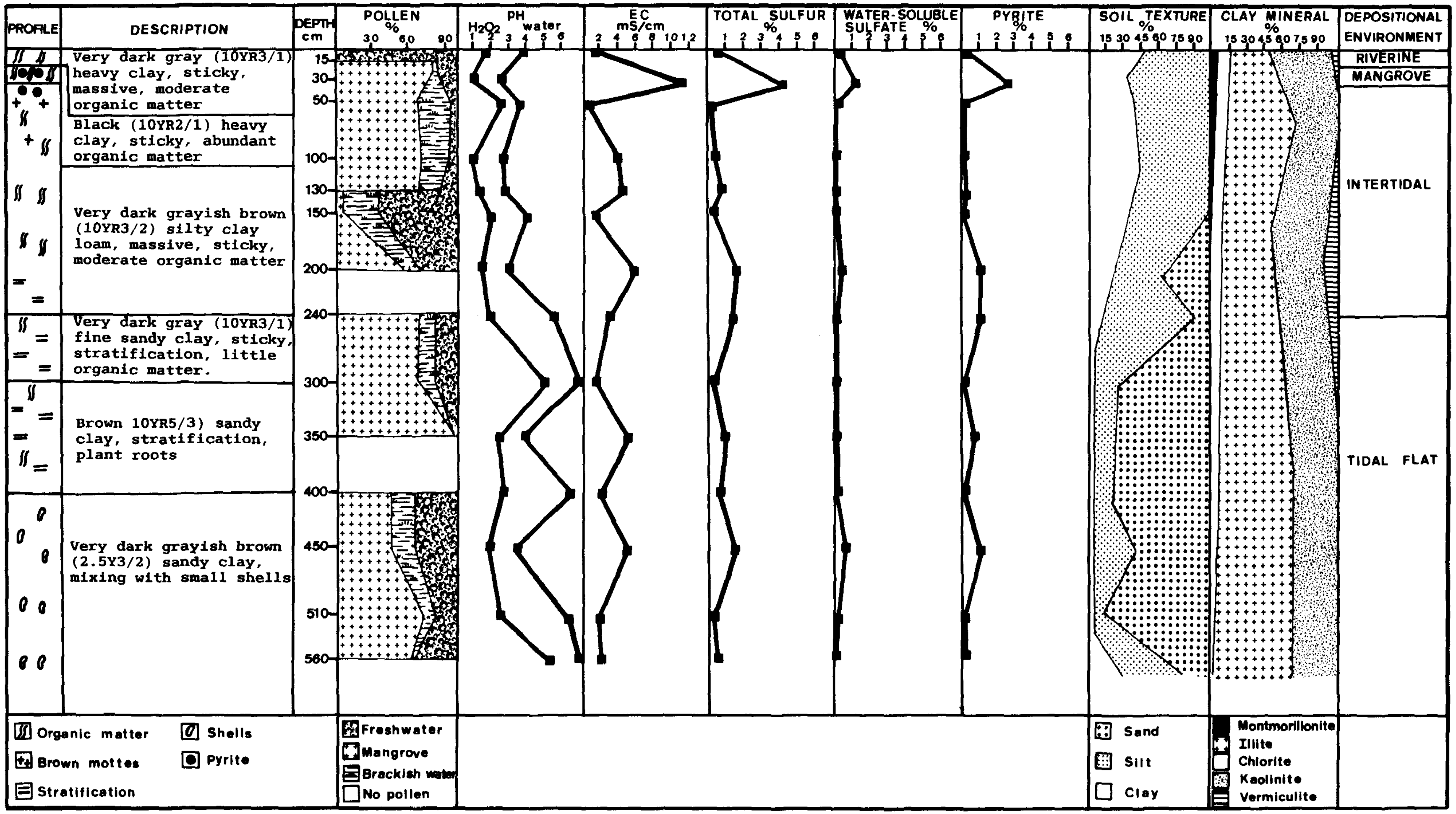

Fig. 10 Soil Profile, Chemical and Pollen Analyses, and Depositional Environment of Profile C5

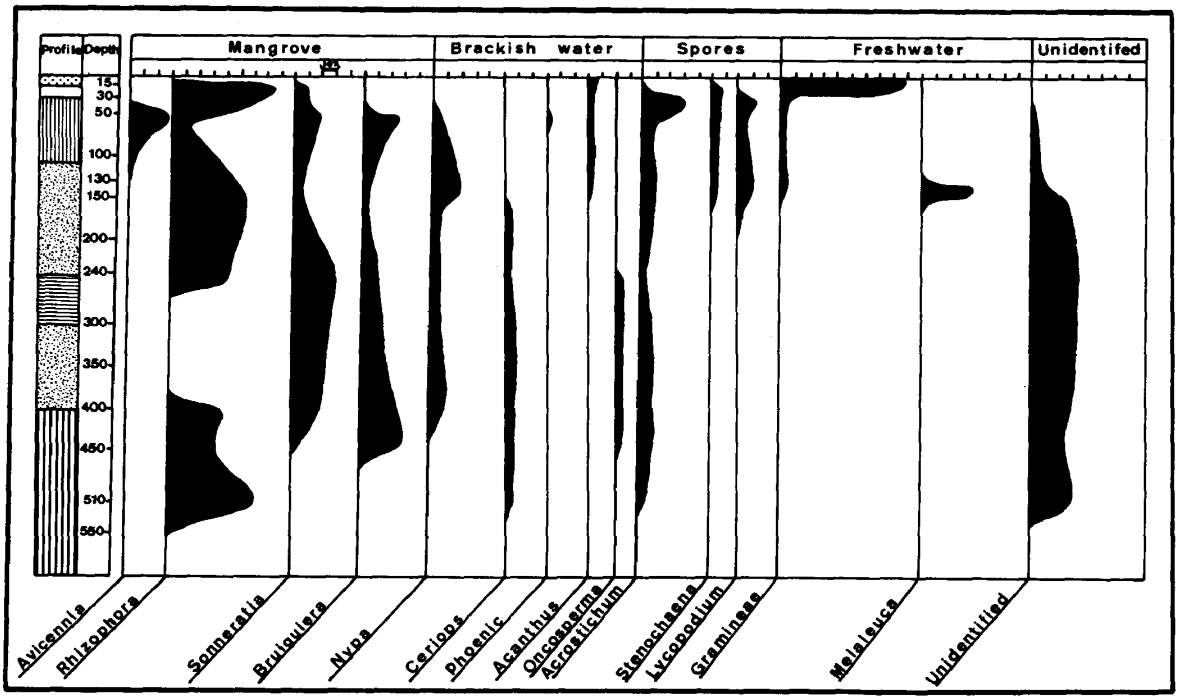

Fig. 11 Distribution of Arboreal Pollen in Profile C5

saltwater. Total sulfur content was relatively high, varying from 0.5 to 2%. Water-soluble sulfate content varied from 0 to 0.5%. Pyrite was also present with a content of 0.1-1%, and this was also correlated with a low value of pH_{ox} (less than 2). The past environment of this layer is interpreted as being intertidal to mangrove.

A black (10YR2/1) clay to very dark grayish brown (10YR3/2) silty clay loam and brown (10YR5/3) sandy clay, laminated structure layer at 240-560 cm had the same mineralogical components as the upper layer described above. Their percentages may not be representative, however, because this soil layer contained more than 70% of very coarse, fine sand, the remainder being silt and clay, and clay content being only 5%. The percentages of mineralogical components are thus not discussed here. Pollen analysis showed that mangrove pollen species such as *Rhizophora*, *Sonneratia*, *Bruguiera* and brackish pollen species such as *Nypa* and *Ceriops* were poor to moderate in number, which correlated closely with the soil texture and chemical characteristics of soil. This is indicated as follows: if the soil is silty or clay, the number of pollens is relatively high, as are the EC value, pyrite, total sulfur and water-soluble sulfate content. This is in contrast to the layers which have a high content of sand. This is probably because the layers with a lot of sand were deposited in a high-energy water environment, where clay and silt could not be deposited in large amounts and where vegetation could also not easily grow. So very little organic matter can be accumulated to form pyrite and sulfur. In contrast, in low-energy water environments, clay and silt are deposited easily, and vegetation also has a good environment for growth. Their pollens are thus found in abundance. The data show that the past environment of the layer is a tidal flat.

Profile C4

Profile C4 was bored on the Thong Nhat shrimp farm, Duyen Hai District, Cuu Long Province, about 5 km from the South China Sea. The chemical characteristics and pollen analysis of the profile are illustrated in Figs. 12 and 13.

A dark gray (2.5Y4/0) heavy clay at 0-50 cm contained 45% illite, 35% kaolinite, 10% chlorite, 5% montmorillonite and very little vermiculite. The data showed that clay mineral components of the layer are very uniform compared with the other soil profiles. Transformation between clay mineral components is not clear, because the depositional environment is very recent. The pH H_2O_2 value dropped to 1.5, which correlates closely with a high content of pyrite (1.8%). This leads to a high content of total sulfur (2.15%), while water-soluble sulfate content was rather low (0.2%). These results showed that the soil layer had always been submerged by water; in other words, it was a potential acid sulfate soil. EC value reached 8 mS/cm, as a result of the direct influence of saltwater. Pollen analysis showed that more than 50% pollens were mangrove species of *Rhizophora, Avicennia* and *Bruguiera*. The other pollens identified were of brackish water species, *Nypa, Ceriops, Phoenix, Pluchea, Acanthus, Moraceae, Pandanus* and *Amoora*, each of which accounted for from 3% to 10%. Freshwater pollen species such as *Ilex, Palmae* and *Parkia* were also found, but their populations were very small. From these results, the layer is interpreted as deriving from a mangrove environment.

A dark brown (10YR4/1) heavy clay to dark gray (10YR4/1) silty clay loam layer at 50-200 cm contained moderate organic matter. Pollen content was not high, and very different species were represented. For each species, only from 1 to 5 pollen grains were found on the slide sample, except for the sample at the depth 150 cm, where the pollen content was high. These consisted of 40% mangrove pollens (*Rhizophora, Avicennia, Bruguiera* and *Sonneratia*), 35% brackish water pollens (*Nypa, Ceriops, Phoenix, Pluchea, Acanthus, Moraceae, Pandanus* and *Amoora*) and 25% freshwater pollens (*Palmae, Parkia,* and *Gramineae*), but their populations were still low compared with the mangrove deposits mentioned above. Pyrite was present in the whole layer but not in large amount (around 0.3%). Even so, it was enough to lower pH_{ox} from 7 to 2. Total sulfur content ranged from 0.2 to 0.5%, and water-soluble sulfate content was negligible. EC value was moderately high (3.5 to 4.5), probably due to the influence of saltwater. Mineralogical analysis showed that mineral components were the same as in the upper layer, except that montmorillonite was absent. Kaolinite and chlorite were very stable, with contents of 45% to 10%, respectively. Illite content tended to decrease from 45% to 30% with increasing depth of the layer, while vermiculite content increased to about 10%. From above results, the layer is interpreted as being intertidal to mangrove deposits.

A dark gray (10YR4/1) silt clay loam to very dark gray (10YR3/1) loam layer at 200-400 cm depth contained moderate organic matter. Soil had a laminated structure, showing that sediments were probably deposited in a high-energy environment. Vegeta-

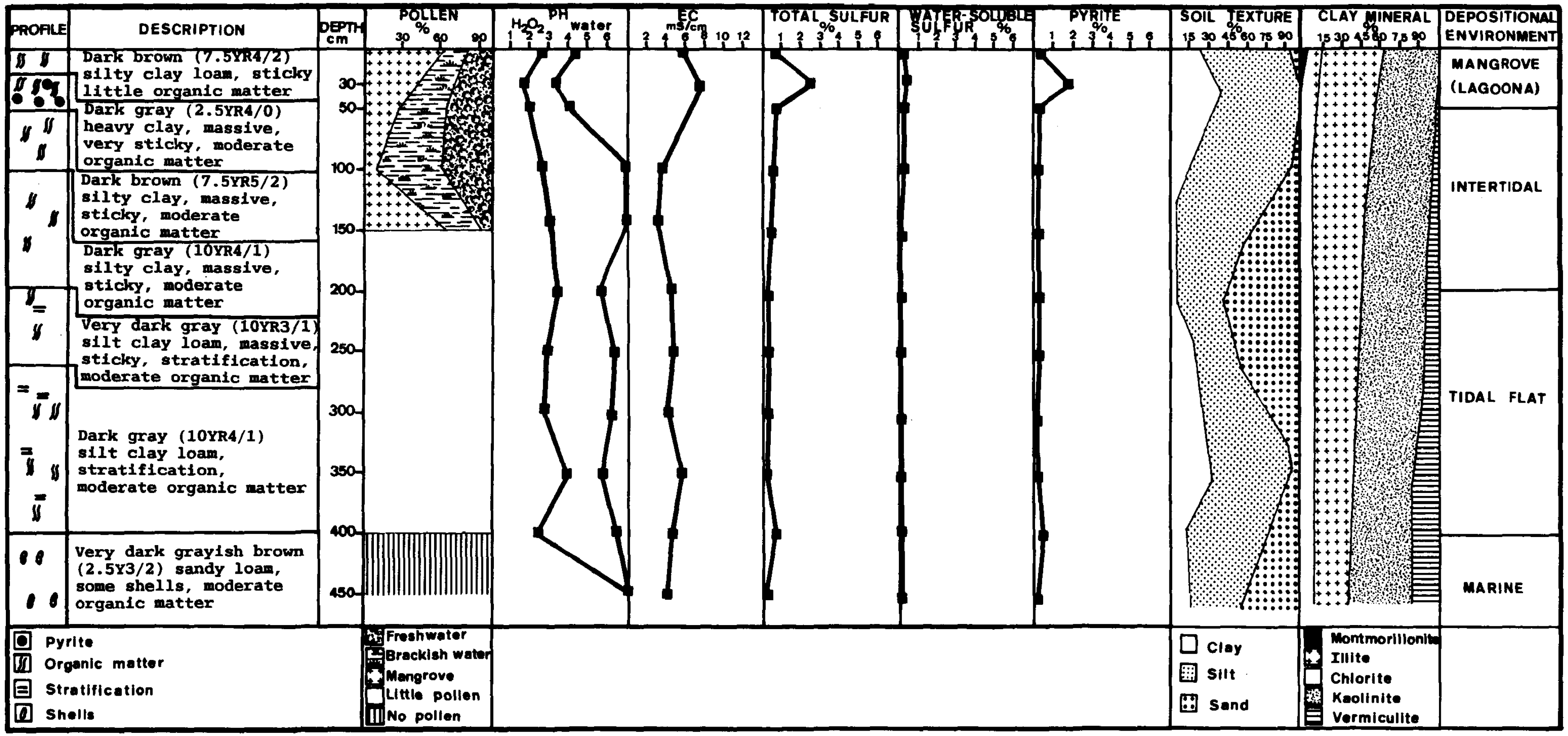

Fig. 12 Soil Profile, Chemical and Pollen Analyses, and Depositional Environment of Profile C4

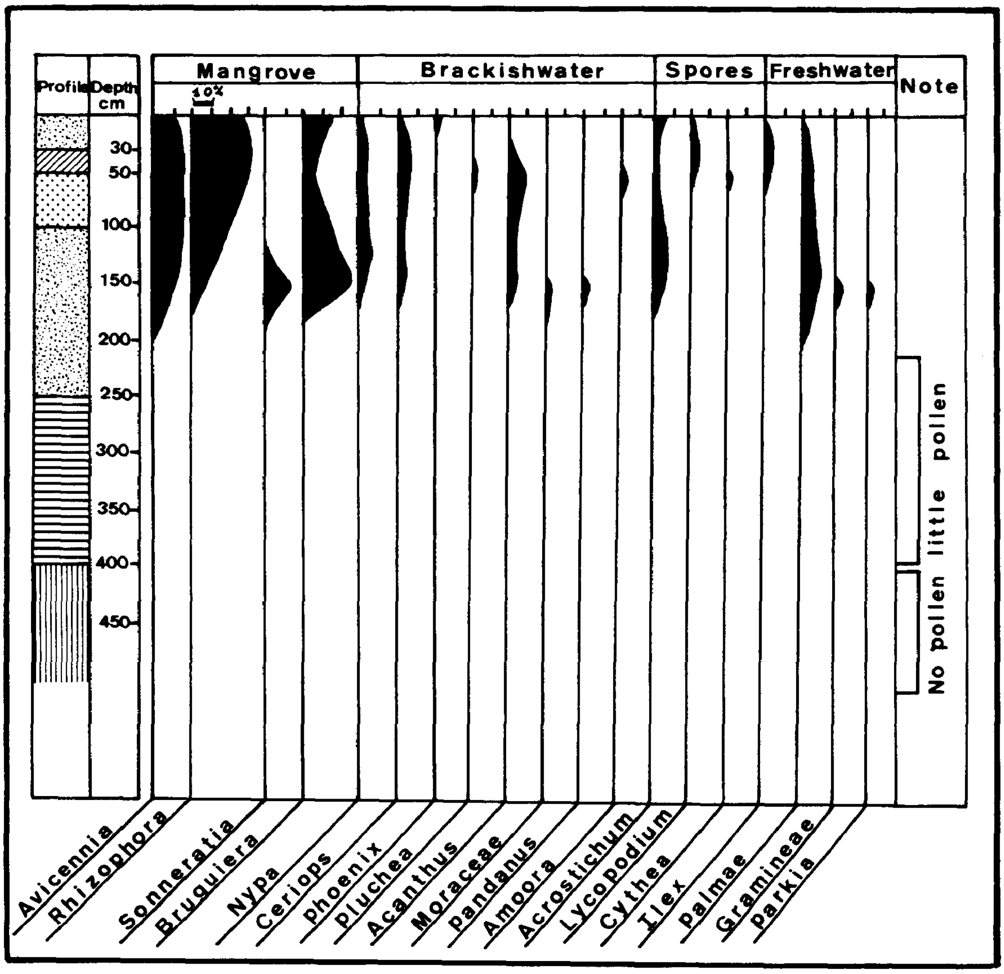

Fig. 13 Distribution of Arboreal Pollen in Profile C4

tion was, therefore, probably not dense, and this coincided with the small content of pollen species found in the layer, with each species represented by only from 1 or 2 pollen grains on the slide sample. Pyrite was present in the layer but its content was lower than in the upper layer. However, it was still enough to lower pH from 6 to 3. Total sulfur content varied from 0.2% to 0.6% and water-soluble sulfate content was negligible. EC value was higher than in the upper layer, also due to influence of saltwater. Mineralogical components were the same as in the upper layer. Kaolinite and chlorite were quite stable, with contents of 45% and 10%, while illite tended to decrease in content from 35% to 20% with depth, and in contrast, vermiculite increased from 10% to 20%. The results showed that the layer represents tidal flat deposits.

A very dark grayish brown (2.5Y3/2) sandy loam at 400-450 cm contained some small shells. The value of pH_{OX} and pH_W were mostly higher than 7, and this coincided with the absence of pyrite. EC value was relatively high (4 mS/cm), because soil was influenced by saltwater. Total sulfur was negligible (0.09%). No pollen was present in the layer. Mineralogical components were very stable and the same as in the upper layer. They consisted of 45% kaolinite, 25% illite, 10% chlorite and 20% vermiculite. The past environment of the layer can be interpreted as being marine.

4. History of Formation of the Recent Holocene Sediments and Their Stratigraphy

Formation of the recent Holocene sediments of the delta began about 11,000 years B.P. As for older sediments, Bosum *et al.* [1971 : 93-102] have interpreted an aeromagnetic map covering the Mekong delta as suggesting that the metamorphosed lower Paleozoic deposits found in the plateau area northeast of the delta and in Cambodia to the northwest of the delta constitute the basement of the delta. The thickness of 3 to 5 km of the sediments suggested by magnetic interpretation means that they could include any parts of the section ranging from the Permian limestones to the Quaternary alluvium. According to Tran Kim Thach [1980], during the Tertiary, the delta was covered by a thick layer of old sediments consisting of marine, brackish and alluvial sediments. Especially during the late Pleistocene era, when the sea fell to 68 meters below its present level [Biswas 1973 : 229-256], sediments of the Mekong river covered all the delta. This sediment layer outcrops in the north and northwest of Dong Thap Province. Nowadays, it is called old alluvial soil. Deep borings to find oil and groundwater showed that the old alluvial soil layer is about 400 meters thick at Long Xuyen and more than 2,000 meters at Tra Cu, Cuu Long Province [Tran Kim Thach 1980]. Thus, a thick layer of old Tertiary and late

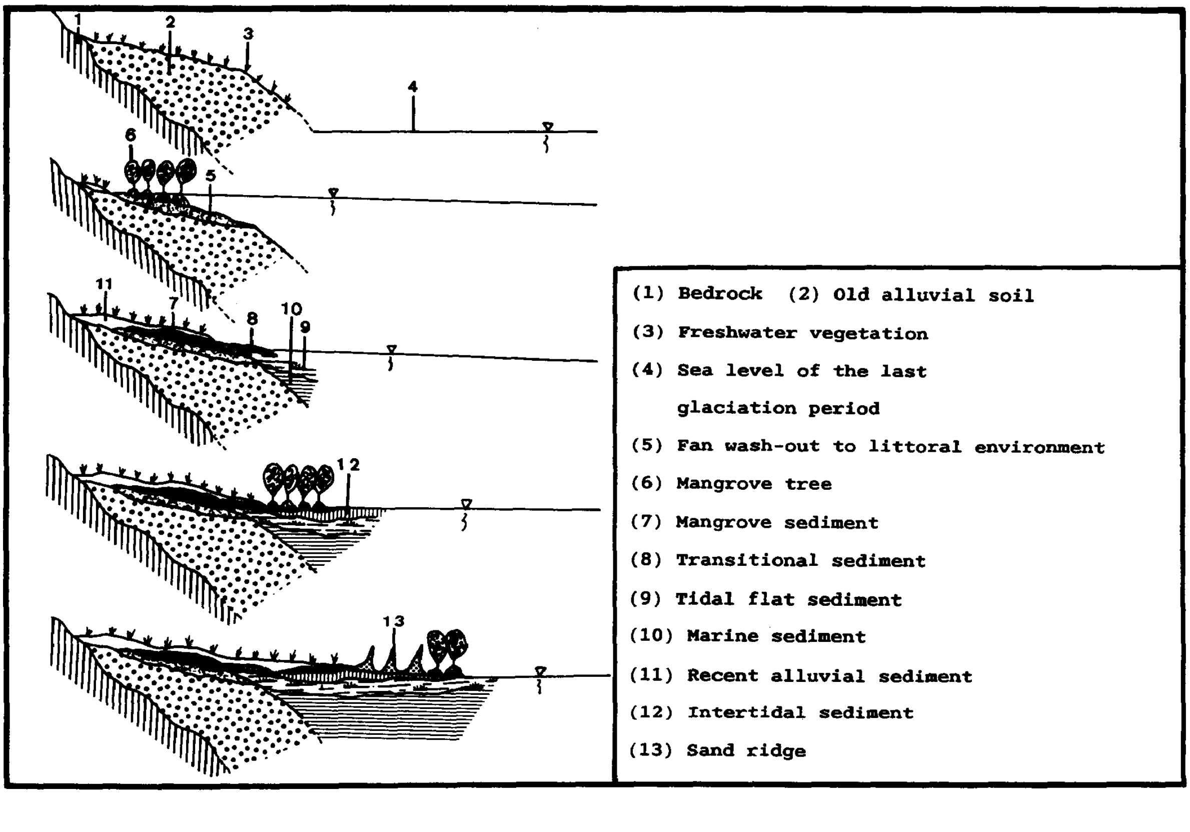

Fig. 14 Formation of Recent Sediments in the Holocene

Pleistocene sediments lying under the delta is considered to form an inter-layer between the bedrock and the recent Holocene sediments.

Based on the characteristics of the five soil profiles discussed above, the history of formation of recent sediments in the Holocene and their stratigraphy (see Figs. 14, 15 and 16) are summarized as follow.

A gray (5YR6/1) heavy clay layer, very compact, containing abundant red mottles and saprolitic gravels is a relict of the Pleistocene ground surface. More than 60% of pollens

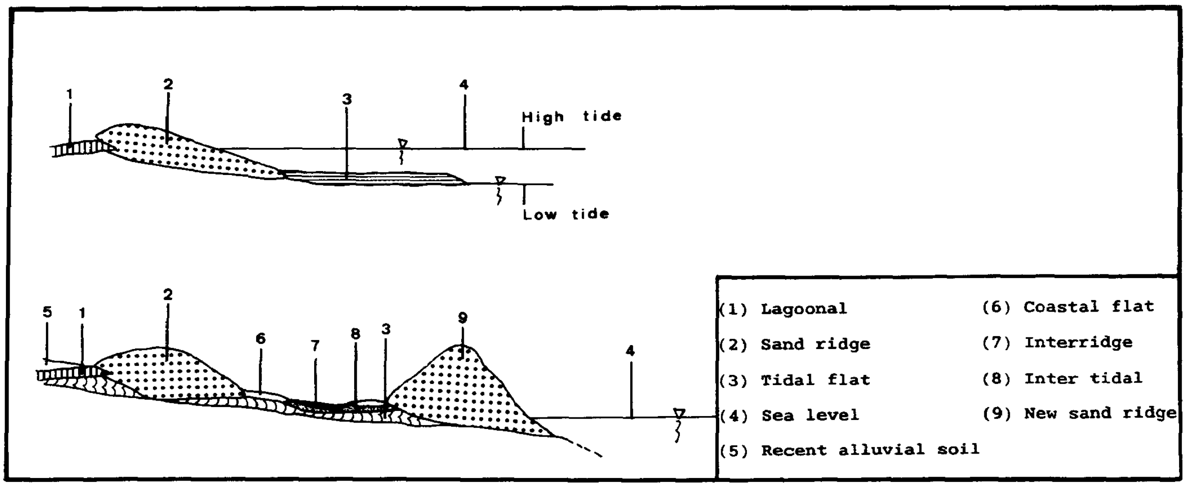

Fig. 15 Formation of Coastal Complex during the Holocene Regression

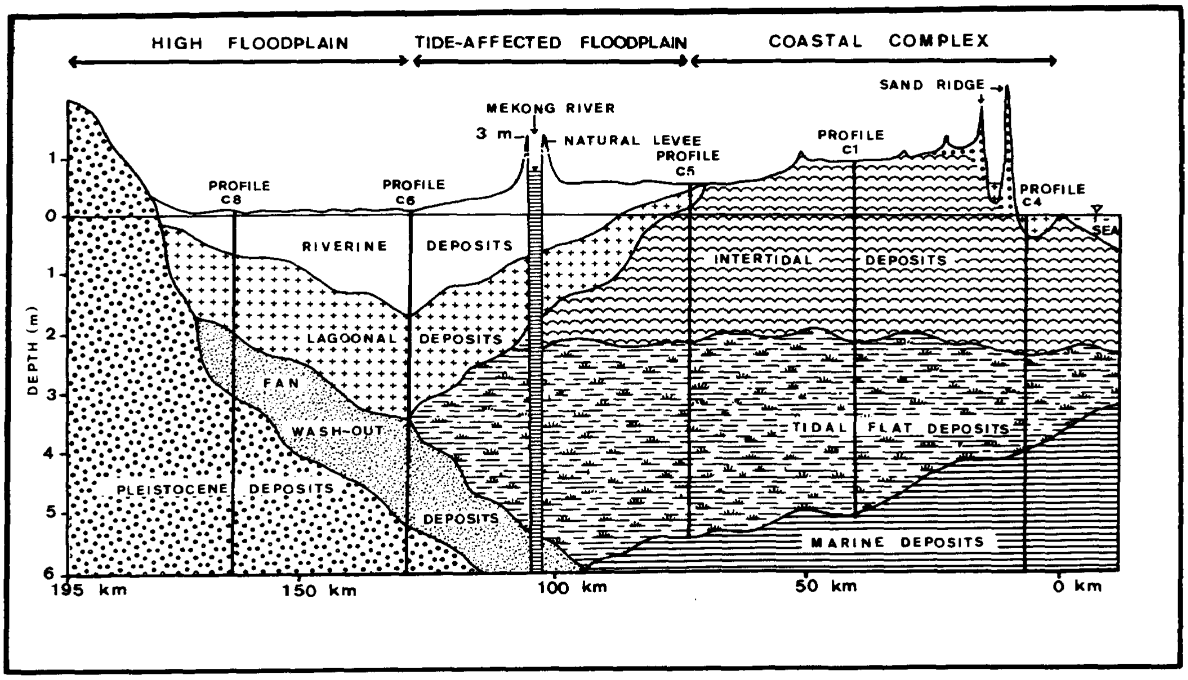

Fig. 16 Stratigraphy of Sediments on a Transect from the South China Sea to Vietnam-Cambodia Border

contained are *Gramineae*, it has high pH, very low content of total sulfur and water-soluble sulfate, and very high content of kaolinite at the depth of 300 cm in profile C8 and 500 cm in profile C5. This is the result of terrestrial weathering of the old alluvial terrace, under a rather dry steppe landscape, which is evidenced by dominance of *Gramineae* pollen. With the change to a more humid climate in the Holocene, reworking of soil surface was activated; and with the rise of sea level, fan wash-out was deposited into a littoral environment. It formed transitional deposits between old alluvium and brackish water environment at 200-300 cm depth in profile C8 and 450-530 cm depth of profile C15. With the Holocene transgression, the former terrace was submerged by brackish water, and mangrove developed on it. This produced a dark brown (7.5YR4/2) heavy clay layer at 50-200 cm depth of profile C8 and 40-450 cm depth of profile C15, which contained very high contents of pyrite, total sulfur, water-soluble sulfate and kaolinite. More than 90% of the pollen count is accounted for by *Rhizophora*.

In the Holocene regression, the sea gradually receded. Sediments of a transitional to subaqueous fan-delta were formed. These sediments contain relatively few pollens (either freshwater, mangrove or brackish). Total sulfur and water-soluble sulfate contents are low. EC value varies from 0.2 to 0.6 mS/cm. pH_{ox} and pH_w are mostly above 3.5. Toward the sea, the Holocene sediments become thicker. The deepest layer of Holocene sediments contains small shells. The pH_w and pH_{ox} are mostly above 7. EC value is high (4 mS/cm). Pollen is completely absent. These indicators show that the layer represents a marine environment and was deposited during the Holocene transgression. In the subsequent marine regression, sandy clay layer with laminated structure, relatively high EC value (2-4 mS/cm), low contents of total sulfur, water-soluble sulfate, pyrite, and pollen, in which illite mineral was transformation to vermiculite or kaolinite, was deposited on the marine sediments. This layer represents a tidal flat environment. On this was deposited another layer with the same chemical characteristics and pollen content as the tidal flat but without the laminated structure of soil texture, namely, an inter-tidal flat to mangrove layer. The continuation of the marine regression toward the South China Sea subsequently led to the development of a coastal landform (see Fig. 15). The coastal complex consists of many sand ridges, coastal flats, inter-ridges and mangrove swamps. The sand ridges run parallel to the coastline, most of them have an arched or fan shape, and the distance between ridges varies from 0.5 to 5 km. These ridges are the highest ground in the coastal area and their height gradually decreases inland. Coastal flats have moderate relief, lying about 1 to 1.5 meters above mean sea level. They are very flat and well-drained. The maximum inundation depth is only 20-50 cm, even during the flood season. In contrast, the inter-ridges are very low-lying, being at or below the mean sea level. They are thus influenced almost perennially by saltwater, except for the months of flood season. Soil texture is heavy clay, and potential acid sulfate soils are common. Mangroves are distributed along the coastline and the mouth of the Mekong river. Many kinds of mangrove species thrive in these swamps. Very new potential acid sulfate soils have formed there.

The coastal complex has a special landform, as mentioned above, because it was formed through the interaction between sea and river during the marine regression. Its formation can be explained as follows:

Every year, during the flood season, huge volumes of sediments were carried to the mouth of the Mekong river on the South China Sea. At high tide, these sediments were carried back inland and deposited there. The coarse sediments such as sand and silt were deposited first and the finer ones later. These formed the coastal flat. When the environment became stable, the sediments with sand, silt and clay were deposited near the sea shore. At high tides, waves brought the sand, silt and clay to the water surface. When tide receded, only the sand and silt were deposited to form sand dunes by wind action, while the clay and mud went out with the tide and were deposited in the lower areas to form the inter-ridges. Because these inter-ridges were low, they favored the growth of mangrove and brackish vegetation, which were one of the main factors in the formation of potential acid sulfate soil. Today, the coastal complex is still progressing seaward, although sea level is been to be rising, the mangrove forests which work to trap sediment and thereby promote land build-up.

When sea receded far from the former coast, the recent alluvial sediments were drained. In the high floodplain and the tide-affected floodplain, a large amount of recent sediments were deposited. The coarse sediments such as sand and silt were carried by violent plug-flow and deposited along the river banks, forming natural levees, while clay was deposited behind the levees and formed the backswamps. Three areas, namely, the open floodplain, the closed floodplain and the broad depression are located far from the river and received only small quantities of new accretion. There, the mangrove sediment layer can be found very close to the topsoil.

Two depressional areas, U Minh Thuong and U Minh Ha, contain peat soil, which was probably formed in the same way as the peat soil in the coastal wetlands of Indonesia, as explained by Furukawa [1992 : 57-58]. The process began during the Holocene transgression, when pluvialization of the climate and a rise in the base level of erosion caused part of the terrace surface to become freshwater swamp. The freshwater swamp was covered by forests with many tree species, which formed thick peat. Later, (in case of the Mekong delta) after repeated disturbance, these were replaced by *Melaleuca* forest.

The stratigraphy of sediments on a transect from the South China Sea to the Vietnam-Cambodia border is shown in Fig. 16. The transect crosses the high floodplain, tide-affected floodplain, the Mekong River at Vinh Long city and the coastal complex. There are six stratigraphic units, namely, old alluvial soil, fan wash-out (transitional), marine, lagoonal, tidal flat, intertidal and riverine deposits. The old alluvial soil layer is considered to be an interlayer between the bedrock and recent Holocene sediments. This layer is exposed toward the Cambodia-Vietnam border and goes down deeper toward the South China Sea. The fan wash-out layer covers the old alluvial soil with a thickness of about

Table 1 Characteristics of Sedimental Environments in the Mekong Delta

Depositional Environment	Variety of Pollen	Total Sulfur (%)	Water Soluble Sulfate (%)	Pyrite (%)	EC (mS/cm)	pH		Soil Texture	Clay Mineral Component
						water	ox		
Riverine	Dominant Gramineae	0.1-0.4	0.0-0.1	None	0.1-1.6	3.5-5.0	3.0-3.5	Dark brown (7.5YR3/4) clayey loam	Abundant kaolinite (40%) and illite (35%): others: monmorillonite, Vermiculite and chlorite(5 to 10% each)
Mangrove	Dominant Rhizophora (>90%)	2.0-6.0	0.5-3.5	1.0-3.0	6.0-13	2.5-4.5	1.0-2.0	Dark gray (5YR4/2), heavy clay	Abundant kaolinite and illite (45% each), vermiculite (15%) and little chlorite (5%)
Fan Wash-Out	No pollen	0.0-2.0	0.0-1.0	0.0-0.2	1.0-8.0	1.5-4.0	3.0-7.0	Gray (2.5Y5/6) silty clay	Dominant kaolinite (55%), abundant vermiculite and illite (20-25% each), little chlorite
Old Alluvium	Dominant Gramineae	0.0-0.05	None	None	0.1-0.5	5.0-6.0	3.0-4.0	Gray (5YR6/1) Heavy clay, abundant red mottles, very compact	Dominant kaolinite (55%), abundant illite (25%), vermiculite (15%) and little montmorillonite and chlorite
Transitional	Very few pollens: mangrove, brackish & freshwater	0.1-0.5	0.0-0.2	None	1.5-2.0	4.0-6.0	3.0-4.0	Gray (5YR6/1) heavy clay	Abundant kaolinite and illite (40-45% each): others: montmorillonite chlorite and vermiculite (5-10% each)
Intertidal	〃	0.3-1.5	0.1-0.5	0.1-1.0	1.0-4.0	3.0-7.0	1.0-3.0	Very dark grayish brown (10YR3/1) fine sandy clay	Abundant kaolinite and illite (45% each), little montmorillonite, chlorite and vermiculite
Tidal Flat	〃	〃	〃	〃	〃	4.0-7.0	2.0-3.0	Very dark grayish brown (10YR3/1) laminated fine sandy clay	Dominant kaolinite (50%), abundant illite (25%), vermiculite (15%) and chlorite (10%)
Marine	No pollen	0.0-0.1	None	None	4.0	>7.0	7.0	Very dark grayish (2.5YR3/2) sandy loam, some small shells	The same as tidal flat

1 meter at profile C8. The lagoonal depositional layer covers and runs parallel to the fan wash-out layer until profile C6, then it becomes thinner and lies shallower toward the sea. The tidal flat depositional layer is found in profile C5 and C4 at a depth of 2 to 5 meters. It is shaped like a sweet potato lying with one end on the tide-affected floodplain and the other on the coastal complex. The upper tidal flat depositional layer is an intertidal depositional layer that runs parallel to the tidal flat layer. On the inter-tidal layer were formed sand ridges, inter-ridges, and the coastal plain. The uppermost layer is a recent and sub-recent riverine depositional layer, which covers the lagoonal depositional layer and increase in thickness toward the river bank. It is only found in the high floodplain and tide-affected flood plain.

The characteristics of the sedimentary environments in the delta are summarized in table 1.

IV Summary and Conclusion

Depending on topography, water regime and agro-ecology, the delta was divided into five landform units, namely, floodplain, coastal complex, broad depression, ancient alluvial terrace and hills-mountains. Their chemical characteristics and pollen analysis showed that the major landforms of the Mekong delta were shaped by transgression and regression in the Holocene period. The thick old soil layer located between the bedrock and the Holocene sediment layer was formed during the Tertiary to late Pleistocene. The fan wash-out deposited into a littoral environment, which covers the old alluvial sediments, was formed during the Holocene transgression. These two layers form the foundation of the delta.

Several layers overlie the foundation layers, namely, mangrove, marine, transitional, tidal flat and intertidal sediments, and these were formed during the marine regression. The uppermost layer, that is the topsoil, is recent freshwater sediments. Recent freshwater sediments deposited by the river formed natural levees and backswamps after the sea had regressed. Many sand ridges, inter-ridges and coastal flats have been formed parallel to the coastline, mainly due to the interactions between river discharge and sea tides during the regression.

Generally, in this study, the origin of sediments in the Holocene period has been made relatively clear, but that of older sediments was not determined exactly. To reach a definite conclusion, it is necessary to bore deeper to know the structure of soil profile and to take samples for detailed analysis.

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