SEDIMENT FACIES AND LATE HOLOCENE EVOLUTION OF THE MEKONG RIVER DELTA IN BENTRE PROVINCE

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ABSTRACT: *Three cores (BT1, BT2, and BT3) were taken from Bentre Province in the lower delta plain, Mekong River Delta, with the objective to investigate the sediment facies and evolution of the Mekong River Delta during late Holocene. These cores were examined by analyses of grain size, molluscan shells, foraminifers, diatoms, sedimentary structure by X-radiographs and ^{14}C ages by accelerator mass spectrometry (AMS). The incised valley that formed during last glacial maximum was located around the BT2 site. Transgressive incised-valley fill sediments are composed of estuarine channel/tidal river sandy silt, muddy tidal flat/salt marsh, estuarine marine sand, transitional sandy silt, and finally open bay mud facies in ascending order and dated from 13 to 5.3 ky BP. The coarsening-upward succession of regressive deltaic facies after 5.3 ky BP., with the thickness ranging from 10 to 20 m, are prodelta mud, delta front sandy silt, subtidal to intertidal flat sandy silt, and subaerial delta plain facies. Progradation rate was decreased from 17–18 m y^{-1} during 5.3 to 3.5 cal ky BP to 13–14 m y^{-1} during the last 3.5 cal ky. The reduced progradation rates are reflected by southward sediment dispersal by longshore currents caused by monsoon-generated waves.*

1. Introduction

The Mekong River Delta is the largest delta in Southeast Asia in terms of drainage basin size, water discharge, and sediment discharge. It is characterized by a wide, low-lying delta plain. The river has two main channels in the delta plain area, the Bassac River and the Mekong River. The Mekong River channel, furthermore, is divided into four distributaries in Bentre Province. Morphological and surficial sediment analyses of the delta have been previously published [1,2,3,6]. The characteristics of the Mekong River Delta and outlined its Holocene morphological evolution were reviewed, providing a detailed geomorphological map of the Mekong [3]. However, due to the paucity of detailed descriptions and ^{14}C ages from subsurface sediments, the sedimentological and stratigraphical evolution of the Mekong River Delta system has not yet been clarified.

Stable to slightly falling sea levels for the last 6 ky, in combination with high sediment discharge from the Mekong River, the delta has prograded more than 250 km from Cambodia to the East Sea with area to be about 62,520 km^2 [3]. This paper presents the sediment facies and Holocene evolution of the Mekong River Delta based on analyses of samples from three borehole cores with high-resolution ^{14}C chronology taken in Bentre Province, Vietnam.

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2. Study area

Bentre Province consists of a broad coastal plain corresponding to the lower northeastern part of the delta plain, located among the active distributaries of the Mekong River system (Fig. 1). The Bentre coastal plain contains numerous beach ridges marking former positions of the shoreline during the last 4 ky, and indicating the efficacy of wave processes at reworking the prograding delta front sediments [3,7]. It has been identified as an active delta lobe and a site of interaction between river and marine processes. The river's influence extends 60 km out to sea, and the marine influence reaches 80 to 100 km inland via the river channels [1]. Under the influence of the semidiurnal tide of the East Sea, salty water intrudes into the river systems of almost the entire Bentre area. The climate of this area is subtropical and dominated by the monsoon, which is characterized by a wet season lasting from June to October and a dry season during the remaining months. Fine silt is deposited in the nearshore zone during the wet season, and some of this silt is reworked up the channels during the dry season. The mean tidal range is 2.5 ± 0.1 m and the maximum tidal range is 3 to 4 m [3]. Dominant southwestward longshore currents are generated by the winter monsoon.

3. Materials and Methods

In 1997, three borehole cores were taken from the lower delta plain: BT1 (altitude +3 m above the present mean sea level, depth 40 m); BT2 (altitude +2 m, depth 71 m); BT3 (altitude +2 m, depth 29 m) (Fig.1). The core samples were split, described and photographed. X-radiographs of slab samples were taken throughout all split cores. Sand and mud contents were measured every 20 cm throughout the core. Sand samples were 5 cm thick and mud samples were 2 cm thick. After organic materials were removed with 10% H_2O_2, sands were separated on a 63-µm sieve under pored water. After measuring the dry weight of sand portion, sand contents were calculated. Fossils and microfossils such as diatoms, foraminifers, and mollusca species were identified and counted under optical microscope. Fifteen ^{14}C ages were measured on plant fragments and molluscan shells by accelerator mass spectrometry (AMS) at the Center for Chronological Research, Nagoya University, Japan, and at Beta Analytic Inc. Calendar ages were calculated by the INCAL98 calibration curve.

4. Results

11 sedimentary facies have been divided on the basis of the combined characteristics of grain size, color, and sedimentary structure of the sediments and the contained mollusca, foraminifers, and diatoms from the BT1, BT2 and BT3 cores. The identified facies are Late Pleistocene undivided sandy silt, estuarine channel/tidal river sandy silt, muddy tidal flat/salt marsh, estuarine marine sand and sandy silt, transitional sandy silt, open bay mud, sandy lag, prodelta mud, delta front sandy silt, subtidal to intertidal flat sandy silt, and subaerial delta plain facies (Fig. 2).

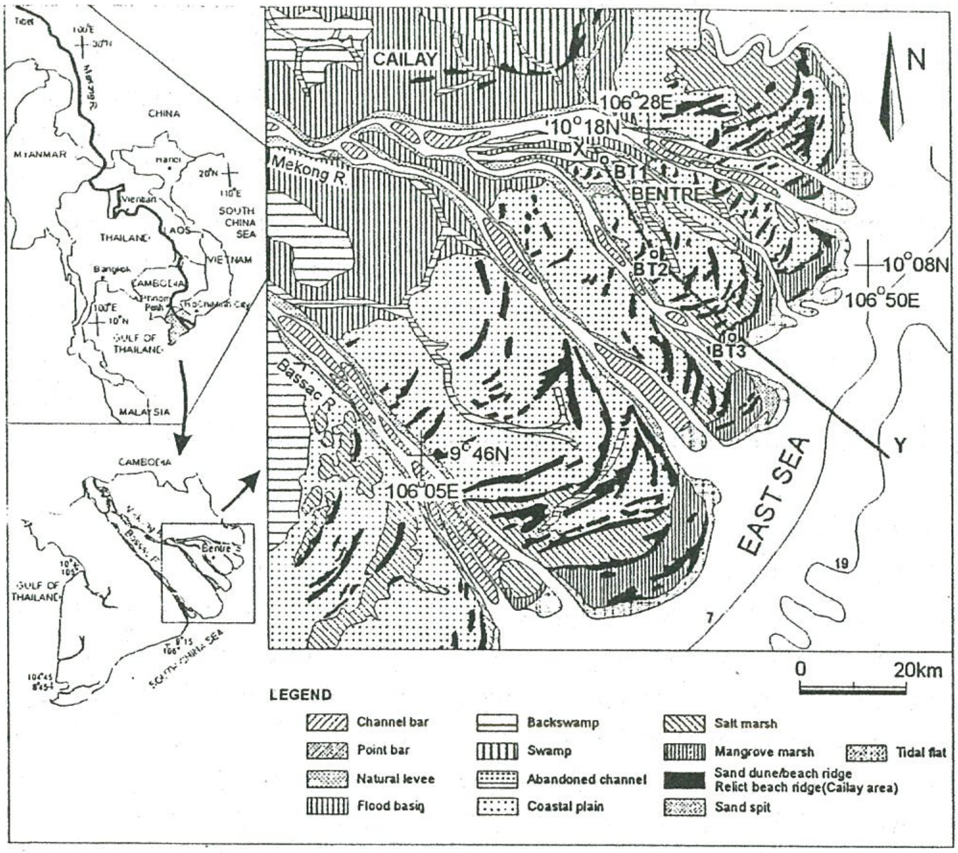

Fig. 1. Location of the borehole sites and index map of the Mekong River Delta. The cross-section XY is shown in Figure 2. Geographical information is simplified after Nguyen et al (2000). Open circles indicate the borehole sites.

4.1. Late Pleistocene Undivided sandy silt facies

This facies is the lowest part of the section, below approximately –10 m (below present sea level) at BT1 and –19.5 m at BT3; the facies was not recovered at the BT2 site. It is composed mainly of mottled, slightly oxidized, yellowish gray stiff silt, silty clay, sandy silt with subangular quartz pebbles 0.5–1 cm in diameter, and laterite, suggesting a period of subaerial exposure. Diatoms and foraminifers are not found in this facies. This facies is unconformably overlain by the prodelta or delta front facies with a sharp contact in lithology and color. The overlying sediments may have been deposited in a terrestrial to coastal marine environment. Radiocarbon dates of oyster shells from similar facies in borehole samples taken between the Bassac River and the Mekong River suggest an age of 43,420 y BP.

4.2. Estuarine channel/tidal river sandy silt facies

This facies only presented in the lowest part of the BT2 core from –69.0 m to –62.30 m. It consists of slightly oxidized grey silty sand and fine to medium sand bearing scattered quartz pebbles in the lower part. Sedimentary structures such as parallel lamination and lenticular bedding are found. There is an intermixture of marine plankton and marine-brackish and freshwater diatom species. *Stephanodiscus astrea, Synedra* spp. and *Aulacoseira granulata,* indicating a freshwater habitat, are common. Foraminifer species are few, but suggest a marine, in particular a tidal, influence. This facies is interpreted as an estuary channel/tidal river.

4.3. Muddy tidal flat/salt marsh facies

This facies presented only at the BT2 site from –62.30 to –54.50 m. It is composed of interbedded, stiff brownish gray silty clay. Faint lamination is found in the lower portion, and discontinuous parallel lamination is found in the upper part. Plant fragments and calcareous concretions are common. Several diatom species, such as *Coscinodiscus* spp., *Thalassiosira excentrica, Nitzschia sigma, Cyclotella styrolum,* and *C. caspia,* indicating a marine–brackish-water habitat are found in low abundance. This facies is interpreted as a muddy tidal flat/salt marsh sediment.

4.4. Estuarine marine sand and sandy silt facies

This facies is found from –54.50 to –35.95 m only at the BT2 site. The base of this facies is characterized by intercalated yellowish gray coarse sand, silty sand, round to angular quartz pebbles, and lenticular bedding, current-ripple lamination, and small-scale cross-bedding. The lower part shows a fining-upward succession consisting of brownish gray sandy silt with parallel lamination and wavy bedding. The upper part displays a coarsening-upward succession and consists of intercalated dark gray sandy silt and fine sand with parallel lamination, cross-lamination (current ripples), wavy bedding, and small-scale cross-bedding. These characteristics indicate that this facies is strongly influenced by tides. There is an intermixture of marine plankton and marine-brackish and freshwater diatom species. *Synedra* spp., freshwater species *Aulacoseira granulata* and *Stephanodiscus astrea,* and marine planktonic species *Coscinodiscus radiatus,* C. *nodulifer*, and *Thalassiosira excentrica* are common. This facies is characterized by a high content of small-sized foraminifers. Shallow-marine genera such as *Ammonia* spp., *Asterorotalia* spp., and *Quinqueloculina* spp. are abundant. The presence of marine bivalves and the abundance of shallow-marine microfossils indicate that the sediments were deposited in an estuarine environment and were strongly influenced by tides. The coarsening-upward succession might indicate an estuary-mouth sandy sediment.

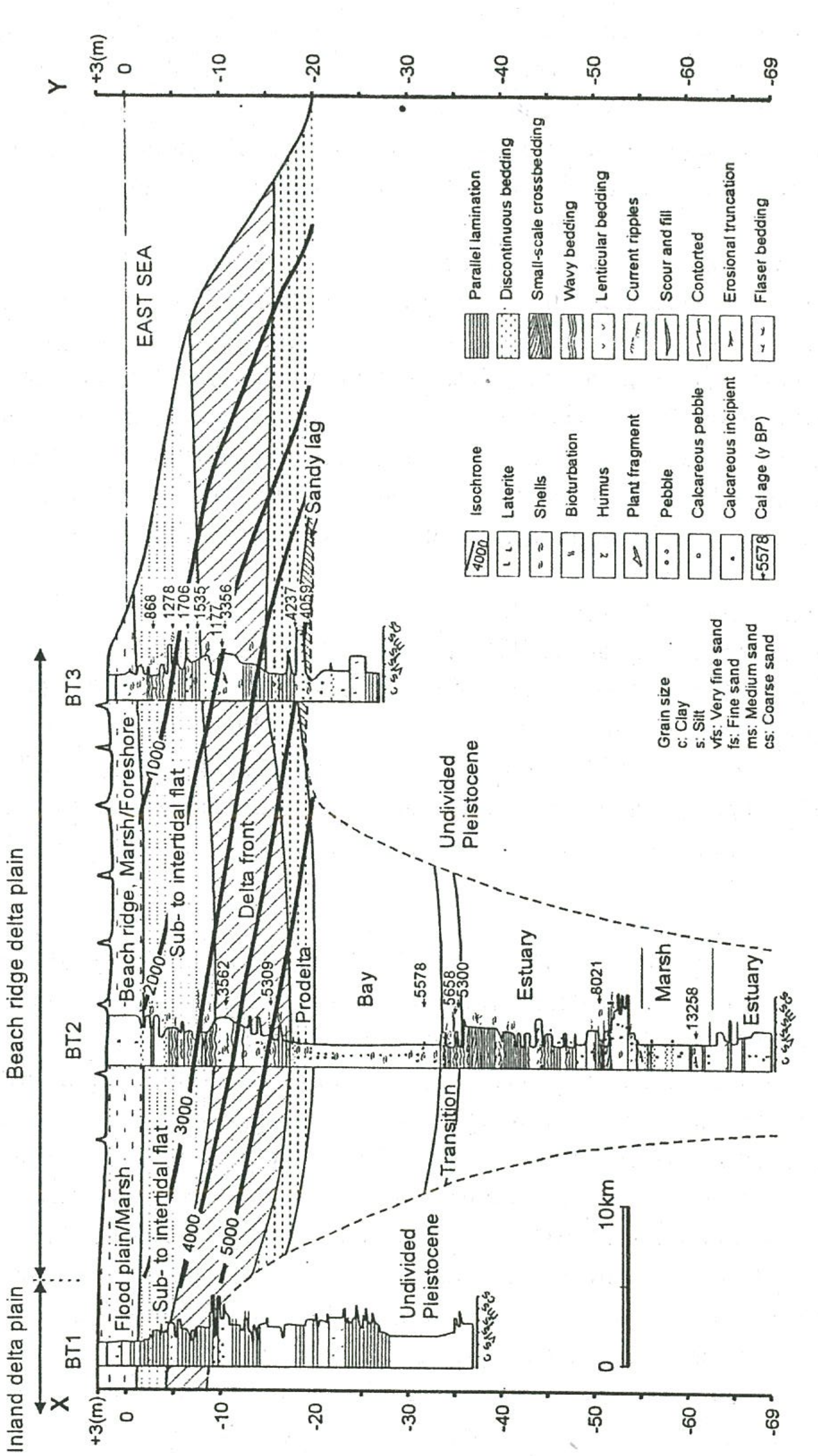

Fig. 2. Core logs and inferred depositional facies with facies distribution and isochrones in cross-section XY. Location is shown in Figure 1

4.5. Transitional sandy silt facies

This facies is found from –35.95 to –33.5 m at the BT2 site and consists of intercalated dark gray clayey silt and sandy silt. Wavy bedding is common in the lower part, which changes into parallel lamination in the upper part of the interval. Shell fragments and bioturbation are common. Marine planktonic diatom and foraminifer species significantly increase. This facies is interpreted as the transition from the estuary environments of the underlying facies to the open bay environments of the overlying facies.

4.6. Open bay mud facies

This facies is from –35.95 to –20 m at the BT2 site, and mainly consists of homogenous greenish gray mud with some faintly parallel laminae. Mud content is over 95%. Shell fragments and incipient nodules are scattered throughout the facies. Marine planktonic diatom species increase upward and reach over 70%, with high abundance of *Coscinodiscus radiatus*, *C. nodulifer*, *Thalassiosira excentrica,* and *Thalassionema nitzschioides,* indicating an open bay or outer bay environment [4,5]. Foraminifer species characteristic of a deep-water environment increase upward significantly. Marine and shallow marine mollusca are also found.

4.7. Sandy lag facies

This facies is found only in the basal part of the Holocene succession at the BT3 site from –19.9 to –18.0 m with its thickness of 1.9 m. It consists of pebbly sand and marine shell fragments overlying Pleistocene sediments with erosional contact and overlain by prodelta facies.

4.8. Prodelta mud facies

This facies occurred at the BT2 and BT3 sites and is about 3 to 4 m thick. It consists of dark gray silty clay to very fine sand in a coarsening-upward succession. The grain size of this facies in BT3 is coarser than that in BT2. This facies characterized by interbedded sand and mud with discontinuous and parallel lamination suggests tidal influence. Shell fragments and incipient nodules are common. Marine plankton species of diatom are abundant but decrease in comparison to the underlying embayment mud facies, *Thalassionema nitzschioides* obviously decreases in individual. Brackish-water species such as *Paralia sulcata* and *Cyclotella caspia* increase upward measurably. This indicates a shallow marine habitat that has been supplemented by fresh and brackish-water sources. Total number of foraminifer species decrease upward markedly. This facies is interpreted as a prodelta deposit.

4.9. Delta front sandy silt facies

Prodelta mud facies is overlain by delta front sandy silt facies with the gradational contact. This facies has a thickness of 7 to 10 m at all three sites and represents a common upward succession consisting of intercalated greenish gray silt, sandy silt, and fine sand. Cross-lamination (current ripples), lenticular bedding, wavy bedding, discontinuous parallel lamination, and contorted structures are common. These structures suggest the deposit was formed under tidal influence. The facies may reflect strong hydrodynamic conditions caused mainly by tidal currents and high depositional rates. Small shell fragments and mica flakes are scattered throughout the facies. Diatoms, foraminifer species, and mollusca reflect an increasing influence of a freshwater habitat. This facies is interpreted as a delta front facies.

4.10. Subtidal to intertidal flat sandy silt facies

This facies is 6 to 8 m thick and consists of laminated dark gray sandy silt and fine sand, which is characterized by wavy bedding, parallel lamination, and lenticular bedding. Shell fragments and mica flakes are common. Marine planktonic diatom species are obviously less abundant in comparison with the underlying delta front deposits, but brackish-water diatom species are very abundant. This facies is characterized by scarcely and poorly preserved benthic foraminifers. Shallow-marine foraminifer species decrease upward [5]. This sedimentary facies differs somewhat between core BT1 and cores BT2 and BT3 with respect to grain size and sedimentary structures. The grain size of sediments of BT2 and BT3 is coarser than that of BT1 sediments. BT1 sediments display a fining-upward succession with parallel lamination and lenticular bedding, followed by an overlying subaerial delta plain facies. BT2 and BT3 sediments also show a fining-upward succession; however, they display a wide variation in sedimentary structures, including wavy bedding, flaser bedding, and cross-lamination (current ripples) in addition to parallel lamination and lenticular bedding, and they are covered by coarse sediments of the subaerial delta plain facies.

The features of this facies are tide-influenced, and it is interpreted as a subtidal to intertidal flat facies. However, the facies in BT2 and BT3 was influenced not only by tides but also partly by waves as evidenced by the increasing in sand content, and the presence of current ripples in the sedimentary structures.

4.11. Subaerial delta plain facies (marsh and beach ridge)

The thickness of this facies is 4 to 5 m. The sediments of BT1 consist of peaty dark silty clay and sandy silt with rich organic matter and mica flakes. The facies is characterized by discontinuous parallel lamination and lenticular bedding. Brackish- and freshwater diatom species obviously increase, while marine plankton species decrease. *Cyclotella caspia, C. styrolum, Synedra affinis,* and *Stephanodiscus astrea* increase appreciably, while *Coscinodiscus radiatus, C. nodulifer, Thalassiosira excentrica,* and *Actinocyclus ehrenbergii* decrease. This indicates a brackish-water habitat. Foraminifers are not found in the sediments. The sediment facies in the BT2 and BT3 cores consists of well-sorted fine yellowish brown and gray sand, with some rootlets and scattered shell fragments at the BT3 site. Fresh/brackish water diatom species are common. This facies probably represents an intertidal to supratidal flat/salt marshy deposit at BT1. The sediment facies at the BT2 and BT3 site is interpreted as sand dune/foreshore sand forming beach ridges.

5. Discussion

5.1 Sea-level changes and sediment facies

The BT2 core shows a thick succession for the last 13 ky after the LGM, while the sediments from the other two sites are only 10 to 20 m thick and represent the Holocene succession overlying weathered Pleistocene sediments. Therefore, the incised valley formed by the paleo-Mekong River during the LGM passes under the BT2 site, and the other two sites sit above terrace-like interfluves. The incised valley was filled by estuarine sediments during the rise of sea level after the LGM. Because the onset of Holocene sea-level highstand is reported to be about 5 to 6 ky BP in southern Vietnam [3,7], the boundary between the estuarine facies and the bay facies almost coincides with the highest sea level of the Holocene. The occurrence of the maximum flooding surface (MFS) also dates to around this time in this area. The deltaic sediments in the three cores formed after the MFS.

The lowest part of the Holocene succession at the BT3 site consists of a sandy and shelly lag facies. Although the sediments appear to be transgressive lag sediments on the basis of facies characteristics and succession, ^{14}C ages date the facies to 4.0–4.2 ky BP, or after the MFS. This means that these sandy lag sediments were deposited on the downlap surface after the maximum flooding and that such sandy lags can be formed not only by transgressive erosion, but also by regressive marine erosion on the shelf, or by tidal currents or by delta lobe switching, when waves rework the abandoned delta lobe. This indicates that it is not easy to identify whether an erosional surface is transgressive or regressive only from the presence of a lag sediment facies without dating.

5.2. Delta progradation

The coastal progradation rate of the Mekong River Delta has not been continuous during the sea-level highstand of the last 6 ky. A decrease in the progradation rate, from 17–18 m y^{-1} during 5.3 to 3.5 cal ky BP to 13–14 m y^{-1} during the last 3.5 cal ky, and a change in coastal plain topography from fluvial/tide-dominated features to wave-dominated (beach ridge) features. Reduced progradation rates are reflected by southward sediment dispersal by longshore currents caused by monsoon-generated waves [5].

The detailed isochrones in the cross-section (Fig. 2) indicate the changes in delta progradation for the last 5 ky. By using ^{14}C dates and the present topography of the subaqueous delta, we can calculate the progradation rates between sites BT2 and BT3, and between site BT3 and the present subaqueous topography. Estimated progradation rates are 8.5 m y^{-1} at –20 m altitude between BT3 and the present subaqueous topography, 10.5 m y^{-1} and 10.1 m y^{-1} at –15 m altitude between sites BT2 and BT3 and between the BT3 site and the present subaqueous topography, respectively, and 12.4 m y^{-1} and 14.4 m y^{-1} at –10 m altitude between sites BT2 and BT3 and between the BT3 site and the present subaqueous topography, respectively. These data indicate that the shallower part of the delta has a high rate of migration, resulting in the change to a steeper delta front topography with delta progradation during the last 5 ky. This topographic change can be linked to changes in sediment facies, progradation rate, and increased wave influence.

The reason for the abrupt change of delta system is estimated to the result of outbuilding of the delta system beyond the critical lines to be sheltered by the headland, east of Ho Chi Minh City. Climate change in the Holocene does not coincide with this delta system change in timing. Because after the Holocene optimum and highstand at 2-4 m above the present sea level [3,7], cooling events occurred about 4 ky BP until about 2 ky BP in the South China Sea and East China Sea.

6. Conclusion

Detailed analyses of borehole samples taken from three sites on the coastal plain of the Bentre Provine of the Mekong River Delta show the sedimentation in the incised valley during the last transgression and the late Holocene delta evolution.

The Pleistocene interfluvial zones are covered unconformably by Holocene regressive deltaic sediments in BT1 and BT3 sites. The incised valley that formed during last glacial maximum was located around the BT2 site. The fining-upward succession of the transgressive incised valley overlain by the coarsening-upward succession of regressive deltaic facies. Transgressive incised-valley fill sediments are composed of estuarine channel/tidal river sandy silt, muddy tidal flat/salt marsh, estuarine marine sand, transitional sandy silt, and finally open bay mud facies in ascending order and dated from 13 to 5.3 ky

BP. The coarsening-upward succession of regressive deltaic facies after 5.3 ky BP., are prodelta mud, delta front sandy silt, subtidal to intertidal flat sandy silt, and subaerial delta plain facies. There are a decrease in the progradation rate, from 17–18 m y^{-1} during 5.3 to 3.5 cal ky BP to 13–14 m y^{-1} during the last 3.5 cal ky, and a change in coastal plain topography from fluvial/tide-dominated features to wave-dominated (beach ridge) features. Reduced progradation rates are reflected by southward sediment dispersal by longshore currents caused by monsoon-generated waves.

TƯỚNG TRẦM TÍCH VÀ SỰ PHÁT TRIỂN CỦA TAM GIÁC CHÂU SÔNG CỬU LONG Ở BẾN TRE

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TÓM TẮT: *Tướng trầm tích và sự phát triển của Đồng bằng sông Cửu Long trong thời Holoxen được khảo sát trên cơ sở phân tích thành phần cấp hạt, cấu trúc trầm tích, vi cổ sinh và tuổi tuyệt đối ^{14}C của ba lỗ khoan BT1, BT2 và BT3 ở tỉnh Bến Tre. Một thung lũng bào mòn được thành lập vào giai đoạn mực nước biển thấp nhất cuối Kỷ Thứ Tư được phát hiện tại lỗ khoan BT2. Thung lũng này được lấp đầy bởi trầm tích cửa sông và vịnh biển trong giai đoạn biển tiến liên tục từ 13000 năm đến 5300 năm cách nay. Các tướng trầm tích hạt thô của giai đoạn biển lùi tam giác châu tiếp theo có chiều dầy 10-20 m được thành tạo sau 5300 năm. Tốc độ bồi lấn của tam giác châu giảm từ 17–18 m/năm trong thời gian 5300-3500 năm đến 13-14m/năm sau 3500 năm. Tốc độ bồi lấn giảm do sự phân tán trầm tích về phía nam bởi các dòng ven biển do tác động của sóng từ gió mùa.*

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