PERGAMON

Quaternary Science Reviews 22 (2003) 2345–2361

QSR

Song Hong (Red River) delta evolution related to millennium-scale Holocene sea-level changes

Susumu Tanabe[a,*], Kazuaki Hori[b], Yoshiki Saito[c], Shigeko Haruyama[d], Van Phai Vu[e], Akihisa Kitamura[f]

[a] Graduate School of Science and Technology, Niigata University, Ikarashi-2 8050, Niigata 950-2181, Japan
[b] Japan Society for the Promotion of Science, c/o MRE, Geological Survey of Japan, AIST, Central 7, Higashi 1-1-1, Tsukuba 305-8567, Japan
[c] MRE, Geological Survey of Japan, AIST, Central 7, Higashi 1-1-1, Tsukuba 305-8567, Japan
[d] Graduate School of Frontier Sciences, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan
[e] Department of Geography, Hanoi National University, Nguyen Trai 334, Thanh Xuan, Hanoi, Viet Nam
[f] Institute of Geosciences, Shizuoka University, Ohya 836, Shizuoka 422-8529, Japan

Received 28 September 2002; accepted 19 April 2003

Abstract

The Song Hong (Red River) delta occurs on the northwest coast of the South China Sea. Its evolution in response to Holocene sea-level changes was clarified on the basis of sedimentary facies and 14 radiocarbon dates from the 40 m long Duy Tien core from the delta plain, and using previously reported geological, geomorphological, and archaeological data. The delta prograded into the drowned valley as a result of early Holocene inundation from 9 to 6 cal. kyr BP, as sea-level rise decelerated. The sea-level highstand at +2–3 m from 6 to 4 cal. kyr BP allowed widespread mangrove development on the delta plain and the formation of marine notches in the Ha Long Bay and Ninh Binh areas. During sea-level lowering after 4 cal. kyr BP, the former delta plain emerged as a marine terrace, and the delta changed into the present tide- and wave-influenced delta with accompanying beach ridges. Delta morphology, depositional pattern, and sedimentary facies are closely related to Holocene sea-level changes. In particular, falling sea level at 4 cal. kyr BP had a major impact on the evolution of the Song Hong delta, and is considered to be linked to climate changes.

1. Introduction

Deltas, a major landform of coastal lowlands, are extremely sensitive to sea-level changes. To predict their future response to a sea-level rise, which may result from global warming (Milliman and Haq, 1996), it is important to understand how their evolution was affected by past sea-level changes.

Large deltas in Southeast and East Asia began to form as a result of the early Holocene deceleration of sea-level rise (Stanley and Warne, 1994). During the middle Holocene, progradation was enhanced by huge riverine sediment discharges and the relatively stable or slowly falling sea level (Saito, 2001). Recent studies of Chinese and Southeast Asian deltas have shown that, on a millennial time scale, coastal hydrodynamics and past sediment discharges are the key factors controlling delta morphology and progradation rates during the middle to late Holocene, e.g. the Huanghe (Yellow River) (Saito et al., 2000, 2001), the Changjiang (Yangtze River) (Hori et al., 2001, 2002), the Mekong River (Ta et al., 2002a, b; Tanabe et al., 2003a), and the Chao Phraya River (Tanabe et al., 2003b) deltas. However, it is not well understood how delta formation was initiated or how deltas developed physiographically in relation to the millennium-scale sea-level changes during the early to middle Holocene.

The Song Hong (Red River) delta, located on the west coast of the Gulf of Bac Bo (Tonkin) in the South China Sea, is one of the largest deltas in Southeast Asia. It was formed by the Song Hong, which originates in the mountains of Yunnan Province in China (Fig. 1). The delta includes Vietnam's capital Hanoi (Figs. 2 and 3). Geological, geomorphological, and archaeological studies suggest that its evolution was closely related to the sea-level changes during the Holocene (Nguyen,

*Corresponding author. Present address: Sedimentary Geology Research Group, Geological Survey of Japan, AIST, Central 7, Higashi 1-1-1, Tsukuba 305-8567, Japan. Tel.: +81-29-861-3663; fax: 81-29-861-3579.

E-mail address: s.tanabe@aist.go.jp (S. Tanabe).

0277-3791/03/$ - see front matter
doi:10.1016/S0277-3791(03)00138-0

1991a, b; Nishimura, 1993; Tran, 1993, 1999; Mathers et al., 1996; Mathers and Zalasiewicz, 1999; Dinh and Nguyen, 2000; Lam and Boyd, 2000; Tran and Ngo, 2000; Vu, 2000; Tanabe et al., 2003c). On the other hand, marine notches on the northeast and southwest margins of the delta plain give us detailed information about the Holocene sea-level highstand at 2–3 m above the present sea level (PSL), known as the Dong Da transgression (Nguyen, 1991a, b; Mathers et al., 1996; Mathers and Zalasiewicz, 1999), which lasted from 6 to 4 cal. kyr BP (Lam and Boyd, 2001). The Song Hong delta, therefore, affords us a good opportunity to study delta evolution as it relates to the early Holocene sea-level rise and the middle to late Holocene sea-level fall.

The purpose of this study was to reconstruct the Song Hong delta evolution in relation to millennium-scale Holocene sea-level changes. To promote this aim, we first describe the sedimentary facies and radiocarbon dating of the recently obtained Duy Tien (DT) sediment core from the delta plain, and then we briefly review Holocene sea-level changes in the region surrounding the delta. Finally, we discuss the delta's evolution in the context of those changes and additional findings from previously reported studies.

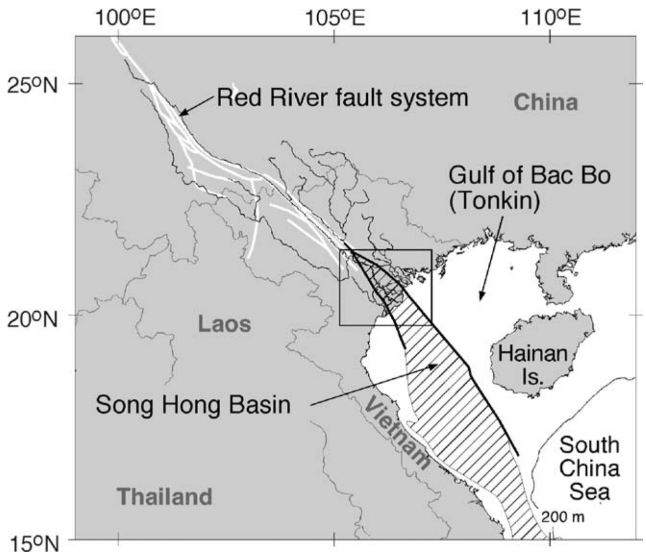

Fig. 1. Location map showing the Song Hong drainage area. Distribution of the Red River fault system is based on Rangin et al. (1995) and Harrison et al. (1996). The Song Hong Basin is after Nielsen et al. (1999). The area within the rectangle is enlarged in Fig. 3.

2. Regional setting

2.1. Geology

The Song Hong delta is surrounded by a mountainous region composed of Precambrian crystalline rocks and Paleozoic to Mesozoic sedimentary rocks (Mathers et al., 1996; Mathers and Zalasiewicz, 1999). The NW–SE-aligned Red River fault system (Rangin et al., 1995)

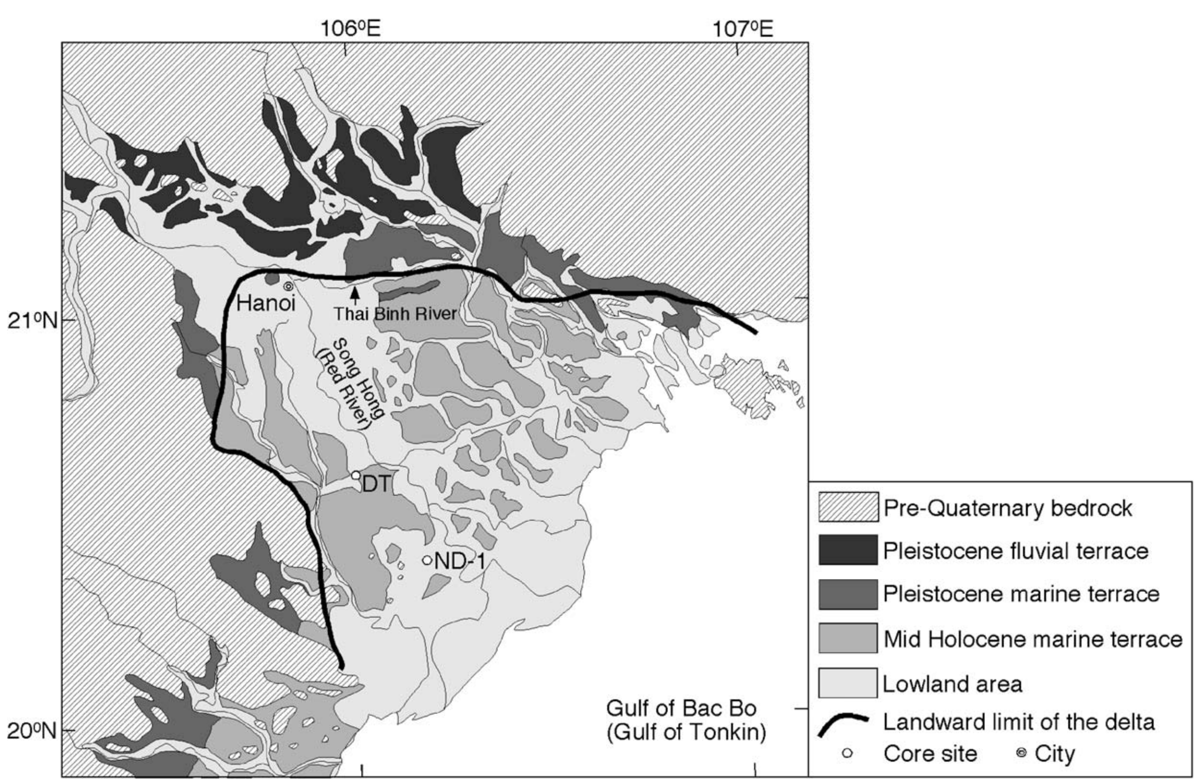

Fig. 2. Quaternary geological map of the Song Hong delta and adjacent area (modified after Nguyen T.V., et al., 2000).

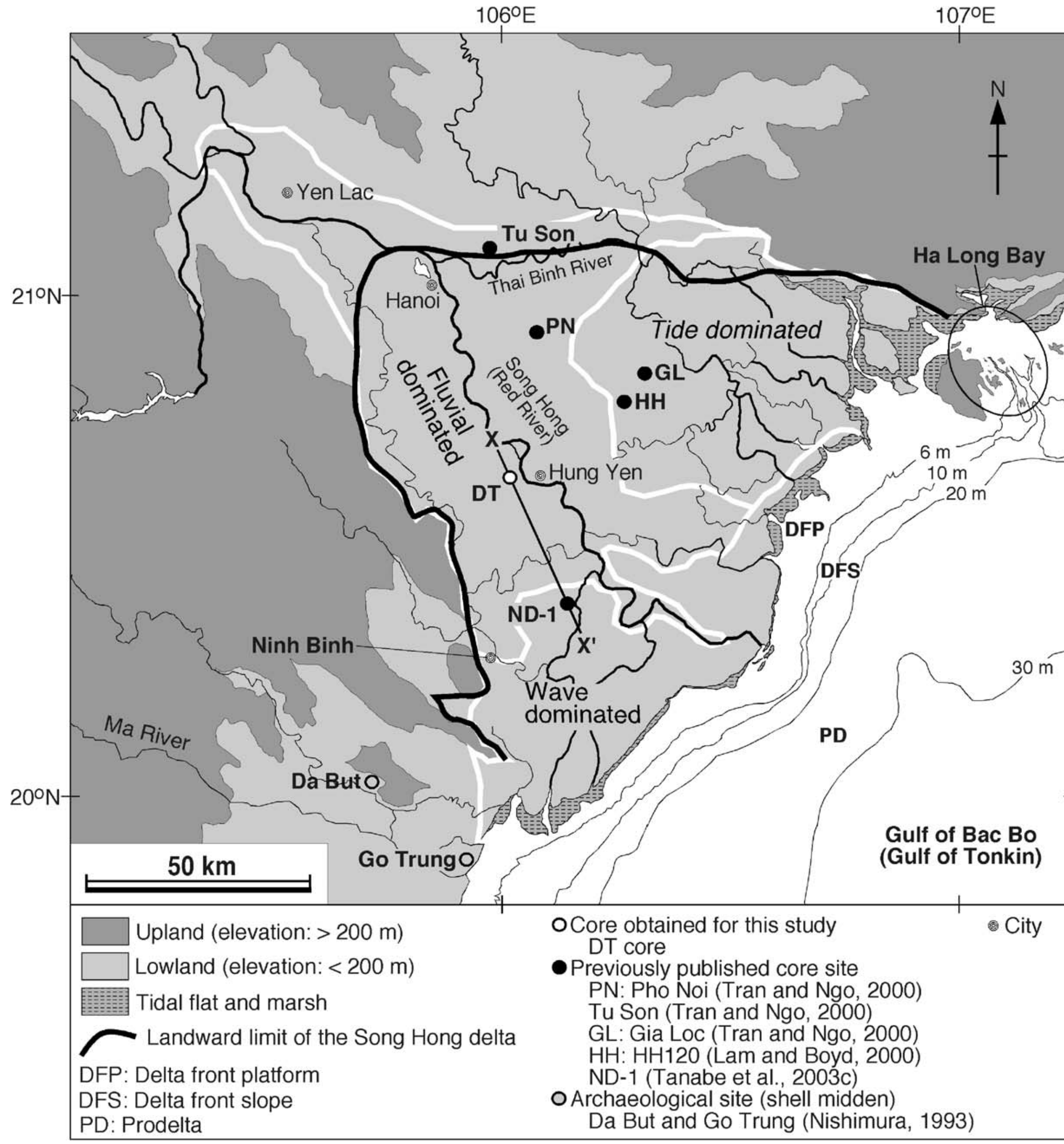

Fig. 3. Song Hong delta and adjacent areas. Landward limit of the delta is based on Dinh and Nguyen (2000) and Tran and Ngo (2000). The three geomorphological divisions on the delta plain of fluvial-, tide-, and wave-dominated systems are based on Mathers et al. (1996) and Mathers and Zalasiewicz (1999). The geomorphological division of the subaqueous delta is based on Tanabe et al. (2003c). Elevation, bathymetric data, and the distribution of tidal flat and marsh are based on 1/250,000 map sheets published by the Department of Geography of Vietnam.

regulates the distribution of the mountainous areas, the drainage area, and the straight course of the Song Hong (Fig. 1). The fault movements have been minor since the late Miocene (Lee and Lawver, 1994). However, several earthquakes are reported to have occurred along the fault system during the last millennia (General Department of Land Administration, 1996).

The delta is situated in a Neogene NW–SE-trending sedimentary basin (Song Hong Basin) (Nielsen et al., 1999) approximately 500 km long and 50–60 km wide (Fig. 1). The basin is bounded and regulated by the fault system, and it is filled with Neogene and Quaternary sediments to a thickness of more than 3 km (Mathers et al., 1996; Mathers and Zalasiewicz, 1999). The subsidence rate of the basin is 0.04–0.12 mm/yr (Mathers et al., 1996; Mathers and Zalasiewicz, 1999; Tran and Dinh, 2000).

2.2. Quaternary geology

The Quaternary sediments, which unconformably overlie the Neogene deposits, are composed mainly of sands and gravels with subordinate lenses of silt and clay. The sediments thicken seaward to a maximum thickness of 200 m beneath the coastal area of the delta. The uppermost Quaternary sediments deposited after the Last Glacial Maximum (LGM) consist of three formations, the Vinphuc, Haihung, and Thai Binh formations, in ascending order. Each formation has a maximum thickness of approximately 30 m. The Vinphuc Formation is composed of an upward-fining succession of gravels and clay, and the Haihung formation is composed of sand. The Thai Binh formation is composed of an upward-fining unit of gravel, sand, and clay (Mathers et al., 1996; Mathers and Zalasiewicz, 1999).

In this study, we consider the Song Hong delta to be a prograding coastal system (Boyd et al., 1992; Reading and Collinson, 1996) formed mainly as a result of river sediment supply. The landward limits of the Holocene mangrove clay and mid-Holocene marine terrace are regarded as the landward limit of the delta plain (Dinh and Nguyen, 2000; Tran and Ngo, 2000) (Figs. 2 and 3). The delta area is approximately 10,300 km^2. To the north, the delta area is bounded by Pleistocene marine/alluvial terraces, which are 5 m or more above the PSL (Tran and Ngo, 2000) (Fig. 2). The mid-Holocene marine terraces are between 3 and 5 m above PSL, and the lowland area located seaward from the mid-Holocene marine terrace, is lower than 3 m above PSL (Haruyama and Vu, 2002).

2.3. Geography

The Song Hong delta plain can be divided into wave-, tide-, and fluvial-dominated systems on the basis of surface topography and hydraulic processes (Fig. 3) (Mathers et al., 1996; Mathers and Zalasiewicz, 1999). The wave-dominated system is located in the southwestern part of the delta, where wave energy generated by summer monsoon winds is relatively strong. The system is characterized by alternating beach ridges and back marshes. The tide-dominated system has developed in the northeastern part of the delta, where Hainan Island (Fig. 1) shelters the coast from strong waves. The system comprises tidal flats, marshes, and tidal creeks/channels. The fluvial-dominated system is composed of meandering rivers, meandering levee belts, flood plain, and fluvial terraces. It is located in the western portion of the delta, where the fluvial flux is relatively strong compared with that of the other two systems. Most abandoned tidal flats are located inland of the tide-dominated system on the mid-Holocene marine terrace.

The subaqueous part of the delta can be divided into delta front and prodelta on the basis of the subaqueous topography (Tanabe et al., 2003c) (Fig. 3). The delta front is from 0 to 20–30 m below PSL, and the prodelta is further offshore. The delta front can be further divided into two parts: platform and slope (Tanabe et al., 2003c). The delta front platform is above the slope break where the water is about 6 m deep, and it has a gradient of $<0.9/1000$. The delta front slope has a relatively steep face with a gradient of $>3.0/1000$.

2.4. Hydrology

The Song Hong, which has a drainage area of $160 \times 10^3\,km^2$ (Milliman et al., 1995), flows 1200 km to the Gulf of Bac Bo (Gulf of Tonkin) in the South China Sea. The total sediment discharge and water discharge of the Song Hong river system is 100–130 million t/yr and 120 km^3/yr (Milliman et al., 1995; Pruszak et al., 2002), respectively, and the average sediment concentration of the river is 0.83–1.08 kg/m^3. The water discharge varies seasonally because most of the drainage area is under a subtropical monsoon climate regime. The discharge at Hanoi station reaches a maximum in July–August (about 23,000 m^3/s) and a minimum during the dry season (January–May) (typically 700 m^3/s). Approximately 90% of the annual sediment discharge occurs during the summer monsoon season, at which time the sediment concentration may reach 12 kg/m^3 (Mathers et al., 1996; Mathers and Zalasiewicz, 1999).

In the delta plain, the river diverges into two major distributaries in the vicinity of Hanoi: the Song Hong to the southwest and the Thai Binh River to the northeast (Fig. 3). The Thai Binh River carries only 20% of the total water discharge (General Department of Land Administration, 1996).

2.5. Oceanography

The mean tidal range is 2.0–2.6 m (Coleman and Wright, 1975; Tran Duc Thanh, personal communication, 2000), and the maximum tidal range is 3.2–4.0 m, along the Song Hong delta coast (Mathers et al., 1996; Mathers and Zalasiewicz, 1999; Tran and Dinh, 2000). In the summer monsoon season, tidal influences within the delta are restricted because of the overwhelming effect of the high freshwater discharge, but in the dry season, tidal effects are evident in all of the major distributaries almost as far inland as Hanoi (Mathers et al., 1996; Mathers and Zalasiewicz, 1999).

Along the delta coast, the mean and the maximum wave heights are 0.88 and 5.0 m, respectively (Tran and Dinh, 2000). Strong southwest winds during the summer monsoon tend to produce NNW-directed wave action in the Gulf of Bac Bo. Throughout most of the rest of the year, winds are from the ENE, and then the delta coastline is well protected by the Chinese mainland and Hainan Island (Mathers et al., 1996; Mathers and Zalasiewicz, 1999).

In accordance with the classification scheme of Davis and Hayes (1984), the deltaic coast is considered a mixed energy (tide-dominated) coast.

3. Materials and methods

The DT core was obtained from the western margin of the fluvial-dominated system in the Song Hong delta plain (altitude +3–4 m, lat 20°37′59″N, long 105°59′20″E). The site is located 8 km east of Hung Yen (Fig. 3) on a channel levee of the Song Hong distributary. The core was drilled in December 2000 by using the rotary drilling method with drilling mud. The total core length was 41.3 m, and core recovery was 65%.

The sediment core was split, described, and photographed. X-ray radiographs were taken of slab samples (6 cm wide × 20 or 25 cm long × 1 cm thick) from the split core. Sand and mud contents were measured in 5 cm thick samples collected every 20 cm by using a 63 μm sieve. Fourteen accelerator mass spectrometry (AMS) radiocarbon dates were obtained on molluscan shells and plant materials from the core by Beta Analytic Inc. Calibrated ^{14}C ages were calculated according to Method A of Stuiver et al. (1998). For the calculation of ages from molluscan shells and shell fragments, ΔR (the difference between the regional and global marine ^{14}C age) (Stuiver and Braziunas, 1993) was regarded as -25 ± 20 yr (Southon et al., 2002), and the marine carbon component as 100%. All ages in this manuscript are reported as calibrated ^{14}C ages (cal. yr BP) unless otherwise noted as yr BP (radiometric and conventional ^{14}C ages).

4. Results

4.1. Sedimentary units and sedimentary facies

The DT core sediments can be divided into two sedimentary units, 1 and 2, in ascending order, consisting of three and four sedimentary facies, respectively. Each sedimentary unit and each facies is characterized according to lithology, color, sedimentary structures, textures, contact character, succession character, fossil components, and mud content (Fig. 4). Unit 1 is interpreted as estuarine sediments, and Unit 2, which conformably overlies Unit 1, is interpreted as deltaic sediments. Unit 1 did not reach to the base of the latest Pleistocene post-LGM sediments. Detailed characteristics of these units and their facies are described below.

4.1.1. Unit 1 (estuarine sediments)

Depth in core: 41.3–22.6 m.

Unit 1 consists of interbedded sand and mud (Facies 1.1), red-colored clay (Facies 1.2), and bioturbated clay (Facies 1.3), in ascending order. The sediments display an overall fining-upward succession and are rich in plant/wood fragments and contain no shells or shell fragments.

Facies 1.1 (depth in core: 41.3–30.0 m) shows an overall fining-upward succession from medium sand to laminated clay. Medium to fine sand (Fig. 5A), which overlies the laminated silt and clay with an erosional contact, contains mud clasts (<25 mm in diameter) and ripple cross-laminations. The ripple cross-laminations contain bidirectional or multidirectional foresets (Fig. 5B). Peaty layers and very fine sand layers less than 10 mm thick interlaminate the silt and clay (Fig. 5C and D). Rootlets occur at the top of this facies.

Facies 1.2 (depth in core: 30.0–26.5 m) is characterized by dark reddish brown silty clay rich in calcareous concretions (35–55 mm in diameter). Plant/wood fragments are rare compared with Facies 1.1 (Fig. 5D).

Facies 1.3 (depth in core: 26.5–22.6 m) consists of brownish black massive clay containing minor plant/wood pieces, smaller than 3 mm, and very coarse silt laminations, thinner than 1 mm. The occurrence of burrows (<30 mm in diameter) shows that this lithology was strongly bioturbated (Fig. 5E). Wood fragments and rootlets occur at the top of this facies (Fig. 5F). Calcareous concretions (<30 mm in diameter) scatter in the clay.

Interpretation: These facies are interpreted as estuarine sediments because of the presence of bidirectional ripple cross-laminations and abundant plant/wood fragments, and the lack of shells/shell fragments indicates that the sediments were strongly influenced by flood- and ebb-tidal currents and freshwater processes. The facies succession suggests that the sedimentary environments deepen upward, as described in detail below.

Facies 1.1 is interpreted as tide-influenced channel fill to coastal marsh sediments. An overall fining-upward lithological succession and the occurrence of bidirectional ripple cross-laminations indicate that the sediments were deposited as a result of lateral accretion in a tide-influenced meander belt (Miall, 1992). Peaty laminated clay or clay with roots, as in the top of this facies, is a common feature of flood plain and coastal marsh environments (Frey and Basan, 1985; Miall, 1992; Collinson, 1996); however, when we consider the stratigraphic relationships with the overlying sedimentary facies (Facies 1.2), it is more suitable to interpret the facies as coastal marsh sediments.

Facies 1.2 resembles Facies 2.1 in the ND-1 core sediments (Tanabe et al., 2003c), which has been interpreted as lagoon sediments (Reinson, 1992).

Facies 1.3 is interpreted as tidal flat and salt marsh sediments. A similar lithology has been reported from estuarine mud and carbonaceous marsh mud from the Holocene Gironde estuary in France (Allen and Posamentier, 1993).

4.1.2. Unit 2 (deltaic sediments)

Depth in core: 22.6–0.0 m.

Unit 2 can be divided into lower massive (Facies 2.1 and 2.2) and upper fining-upward (Facies 2.3 and 2.4)

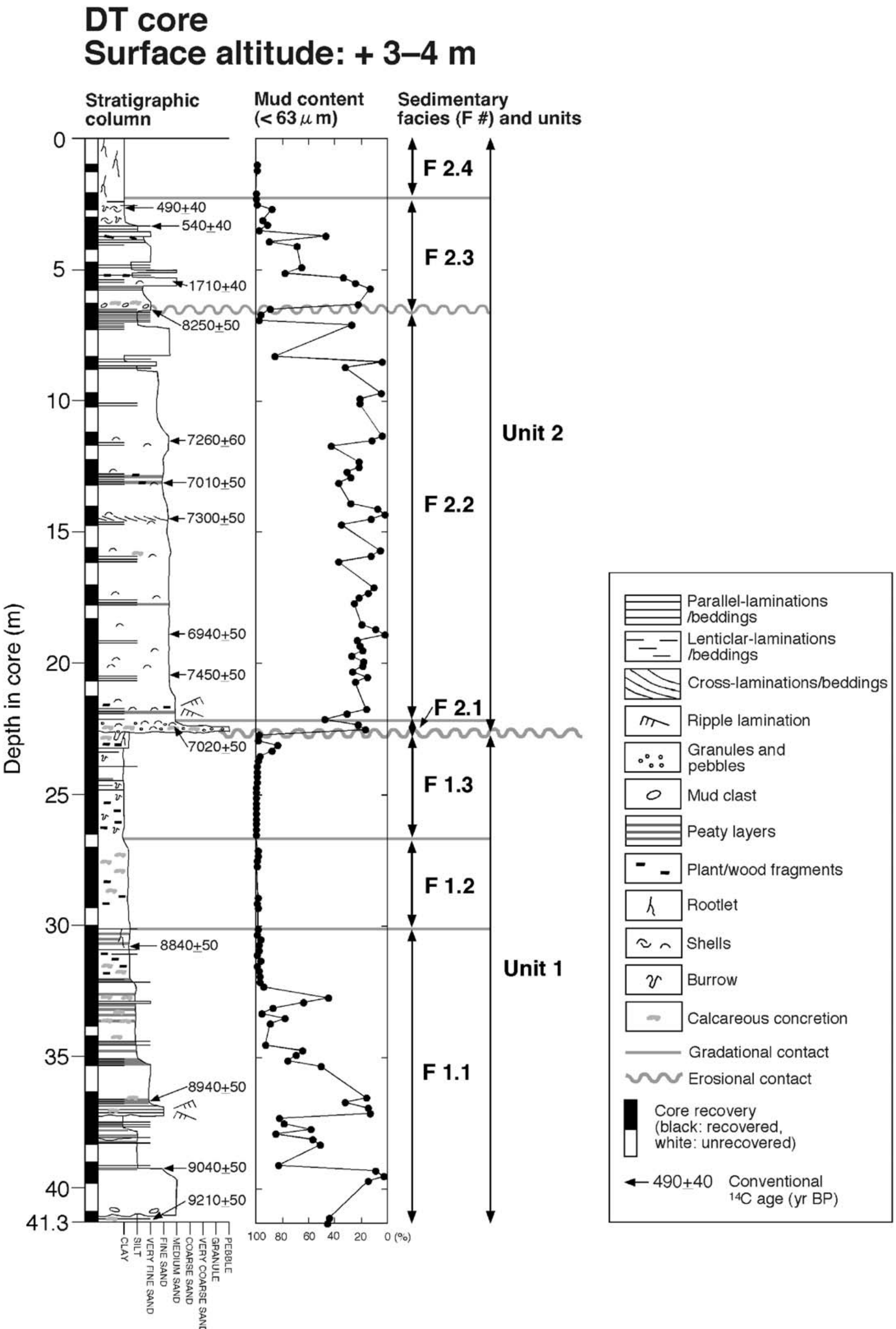

Fig. 4. Sedimentary column of DT core.

portions separated by the erosional surface between Facies 2.2 and 2.3. The lower portion contains abundant shell fragments, and consists of poorly sorted pebbles (Facies 2.1) and massive shelly sand (Facies 2.2) in ascending order. The upper portion contains abundant plant/wood fragments and is composed of interbedded

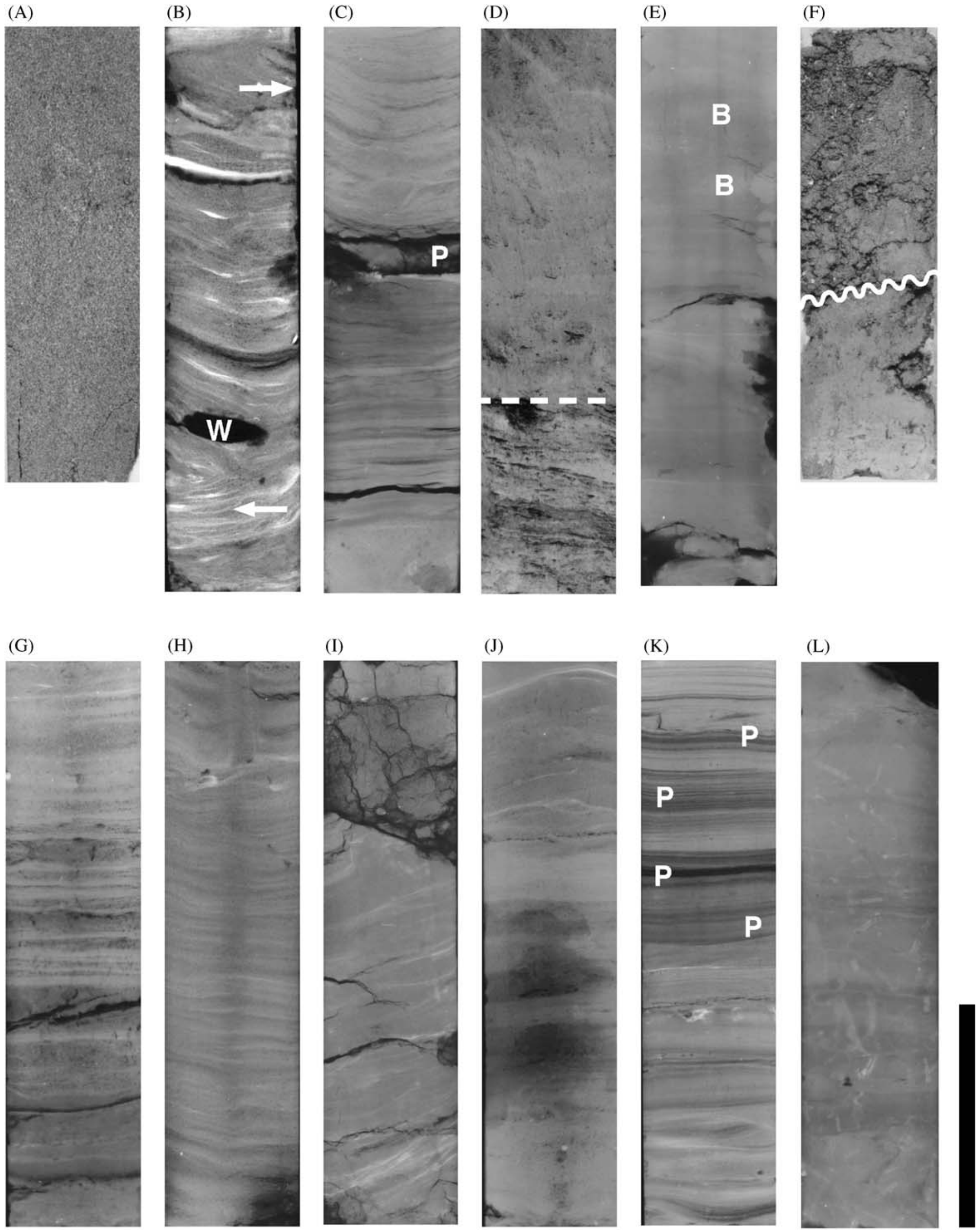

Fig. 5. Selected photographs (A, D, F) and radiographs (negatives) (B, C, E, G, H, I, J, K, L) from the DT core. Scale bar, 10 cm. (A) (39.60–39.80 m depth): Well-sorted medium sand (Facies 1.1). (B) (36.55–36.80 m): Low-angle cross-laminated sand (Facies 1.1). Arrows indicate directions of the ripple foresets. W, wood piece. (C) (35.05–35.30 m): Silt is intercalated with very fine sand laminations and peaty layers (dark-colored layers) (Facies 1.1). P, peaty layer. (D) (30.30–30.55 m): Peaty laminated clay (Facies 1.1) is gradually overlain by silty clay (Facies 1.2). The gradual contact is shown as a white dotted line. (E) (24.50–24.75 m): Massive clay (Facies 1.3). B, burrow. (F) (22.47–22.67 m): Mottled clay (Facies 1.3) is overlain by poorly sorted pebbly sand (Facies 2.1) with an erosional contact (white wavy line). Oyster shell fragments (white dots) can be observed in Facies 2.1. (G) (21.70–21.95 m): Interlaminated sand and mud (Facies 2.2). Silt/clay laminations (light-colored layers) create bundles 2–3 cm thick. (H) (20.45–20.70 m): Interlaminated sand and mud (Facies 2.2). Silt/clay laminations (light-colored layers) thickness <5 mm.(I) (14.25–14.50 m): Cross-laminated sand (Facies 2.2). (J) (9.95–10.20 m): Interbedded sand and mud (Facies 2.2). Silt/clay beds (light-colored layers) thickness >2 cm. (K) (6.45–6.70 m): Interlaminated sand, mud, and peaty layers (Facies 2.2). P, peaty layer. (L) (2.05–2.30 m): Clay with iron-encrusted rootlets (Facies 2.4).

sand and clay (Facies 2.3) and clay with roots (Facies 2.4) in ascending order.

Facies 2.1 (depth in core: 22.6–22.4 m) contains quartz and feldspar grains and calcareous concretions of various sizes, ranging from very coarse sand to pebbles. The calcareous concretions are well rounded compared with those obtained from the underlying Facies 1.3. Oyster shell fragments are abundant in this facies (Fig. 5F).

Facies 2.2 (depth in core: 22.4–6.4 m) consists of well-sorted medium sand partly interlaminated/bedded with mud (clay and silt). The medium sand contains abundant shell fragments of *Mactridae* gen. et sp. indet. which are mostly broken into thin pieces smaller than 5 mm long. Ripple laminations with bidirectional foresets and cross-laminations dipping approximately 10° (Fig. 5I) occur in the sand. The clay and silt laminations/beds range in thickness from <1 mm to 12 cm (Fig. 5G, H, and J). They occasionally create "bundle sequences" 3–30 cm thick in the medium sand (Fig. 5G and H). The top portion (depth in core: 7.2–6.4 m) of this facies consists of rhythmically interlaminated sand, mud, and peaty layers, between 1 and 5 mm thick (Fig. 5K).

Facies 2.3 (depth in core: 6.4–2.3 m) shows an overall fining-upward succession. Mud clasts (<15 mm in diameter) and parallel laminations occur in the sand. Burrows and in situ jointed *Corbicula* sp. are common in the grayish red-colored clay at the top of this facies.

Facies 2.4 (depth in core: 2.3–0.0 m) consists of mottled reddish brown clay. Abundant rootlets with iron encrustation are common in this facies (Fig. 5L).

Interpretation: This unit is interpreted as deltaic sediments because the lower portion resembles the tide-influenced channel-fill sediments reported from other tide-dominated deltas (Galloway, 1975; Galloway and Hobday, 1996), and the upper portion can be regarded as channel-fill sediments deposited in the modern Song Hong distributary. These interpretations are discussed in detail below.

The lithologies of Facies 2.1 and 2.2 resemble those reported from the modern tide-influenced channel-fill deposits of the Fly River delta in the Gulf of Papua (Dalrymple et al., 2003) and the Colorado River delta in the Gulf of California (Meckel, 1975; Galloway and Hobday, 1996). The well-rounded calcareous concretions and the oyster shell fragments in Facies 2.1 indicate that the sediments were deposited in a tide-influenced channel cut into the underlying Facies 1.3. The lithological succession of Facies 2.2 is relatively thick compared with those of channel-fill deposits in the Fly and Colorado rivers, but the heterolithic nature of the interbedded/laminated sand and mud is just the same. The rhythmically interlaminated sand, mud, and peaty layers are regarded as tidal bar or tidal flat sediments, which cap the channel-fill sequence (Dalrymple et al., 2003).

Facies 2.3 is interpreted as channel-fill sediments of the modern Song Hong distributary. A series of channel levees beside the DT site and along the modern distributary indicate that the site is located on a filled cut-off meander channel of the Song Hong distributary. Furthermore, occurrences of burrows and *Corbicula* sp. found in life position suggest that the sediments were influenced by brackish water. Brackish water prevails in the modern distributary channel because tidal effects penetrate all of the major distributaries almost as far inland as Hanoi during the dry season (Mathers et al., 1996; Mathers and Zalasiewicz, 1999). Facies 2.4, a lateritic weathering profile developed in flood plain and channel-levee sediments, corresponds to the land surface at the core site.

4.2. Radiocarbon dates and accumulation curve

The radiocarbon dates obtained are summarized in Table 1. They all fall within the Holocene.

All radiocarbon dates, except those obtained from Facies 2.2, are in stratigraphic order. Most dates obtained from Facies 2.2 are relatively old in comparison with that from the oyster shell fragment, dated 7020 ± 50 yr BP, obtained from Facies 2.1. Only two shell fragments, dated 6940 ± 50 and 7010 ± 50 yr BP, yielded reasonable dates. We regard all shells and shell fragments that dated between 7260 ± 50 and 7450 ± 50 yr BP as reworked material, eroded and redeposited by the channel-fill processes. The peaty material, which shows an anomalous old age of 8250 ± 50 yr BP, is also regarded as reworked material, but it may have been reworked from the older fluvial or deltaic deposits found further upstream from the core site (Stanley, 2001).

An age–depth plot (accumulation curve) of the DT core is shown in Fig. 6. The two breaks shown in the accumulation curve are considered to correspond to the erosional surfaces identified in the core sediments. Comparison of the plot for the DT core with those for other cores in the delta suggest that Units 1 and 2 date to 10–9 cal. kyr BP and 8–0 cal. kyr BP, respectively. The lower (Facies 2.1 and 2.2) and upper (Facies 2.3 and 2.4) portions of Unit 2 date to 8–7 and 2–0 cal. kyr BP, respectively.

5. Discussion

5.1. Stratigraphy

On the basis of their lithology, depths, and radiocarbon dates, sedimentary units identified in the DT core were correlated with those of the ND-1 core (Fig. 7). ND-1 core, obtained from the wave-dominated part (beach-ridge strandplain) of the Song Hong delta plain in December 1999 (Fig. 3), consists of

Table 1
Summary of radiocarbon dates obtained from the DT core

Sedimentary facies	Depth in core (m)	Material	Species	$\delta^{13}C$ (‰)	Conventional ^{14}C age (yr BP)	Calibrated ^{14}C age: Intercept (cal. yr BP)	Calibrated ^{14}C age: 1σ range (cal. yr BP)	Sample code (BETA-#)
2.3	2.7	Shell	*Corbicula* sp.	−7.9	490±40	134	234–0	157762
2.3	3.3	Shell	*Corbicula* sp.	−6.6	540±40	245	268–137	157763
2.3	5.1	Plant fragment	—	−28.7	1710±40	1685/1683/1609/1575	1692–1549	159435
2.2	6.4	Peaty organic	—	−28.7	8250±50	9263/9167/9152	9398–9093	157764
2.2	11.4	Shell fragment	—	−9.8	7260±60	7730	7792–7668	157765
2.2	13.1	Shell fragment	—	−9.6	7010±50	7529/7517	7566–7467	157766
2.2	14.5	Shell	*Mactridae* gen. et sp. indet	−7.5	7300±50	7773	7831–7713	157767
2.2	18.9	Shell	*Mactridae* gen. et sp. indet	−10.4	6940±50	7455	7504–7417	157768
2.2	20.4	Shell	*Mactridae* gen. et sp. indet	−10.4	7450±50	7929	7969–7865	157769
2.1	22.5–22.6	Shell	Oyster	−3.9	7020±50	7545	7571–7476	159436
1.1	30.7	Plant fragment	—	−28.0	8840±50	10,105/10,098/9912	10,147–9779	159438
1.1	36.6	Plant fragment	—	−29.7	8940±60	10,154	10,191–9919	159439
1.1	39.2	Plant fragment	—	−29.4	9040±50	10,213	10,234–10,186	157773
1.1	41.2	Plant fragment	—	−29.3	9210±50	10,396/10,388/10,382/10,367/10,363/10,338/10,331/10,318/10,310/10,299/10,288	10,479–10,242	159440

$\delta^{13}C$ and conventional ^{14}C ages were measured by AMS by Beta Analytic Inc. (BETA). Intercept, intercept between the conventional ^{14}C age and the calibration curve of Stuiver et al. (1998). 1σ range, calibration result of the conventional ^{14}C age $\pm 1\sigma$.

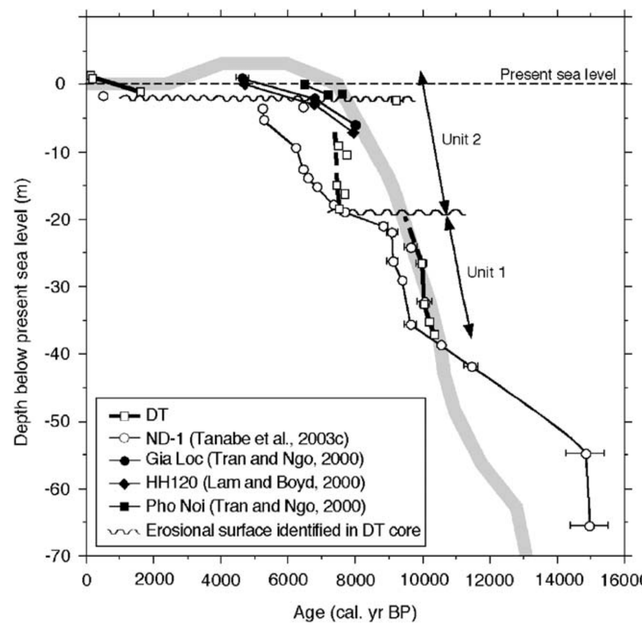

Fig. 6. Accumulation curves for the DT, ND-1, HH120, Gia Loc, and Pho Noi sites. The accumulation curves do not take into account sediment compaction. Data sets for the HH120 (Lam and Boyd, 2000), Gia Loc, and Pho Noi (Tran and Ngo, 2000) sites are listed in Table 2. Sea-level curve (broad gray line) is illustrated based on Figs. 8 and 9. Age uncertainties in this and subsequent figures correspond to 1σ estimates.

three sedimentary units 1, 2, and 3 in ascending order which are, respectively, interpreted as fluvial, estuarine, and deltaic sediments (Tanabe et al., 2003c). The boundary between the estuarine and deltaic sediments can be interpreted as a maximum flooding surface (Van Wagoner et al., 1988) because the estuarine and deltaic sediments show upward-deepening and upward-shallowing sedimentary facies successions, respectively.

The estuarine and deltaic sediments are furthermore comparable to the upper part of Vinphuc Formation/Q^1_{IV} and the Haihung–Thai Binh formations/$Q^2_{IV}-Q^3_{IV}$, respectively (Mathers et al., 1996; Mathers and Zalasiewicz, 1999; Tran and Ngo, 2000).

The location of the incised valley formed during the LGM has been estimated on the basis of the distribution of the groundwater table in the Quaternary sediments (Vietnam National Committee for International Hydrological Programme, 1994). The northwest–southeast-oriented narrow elongated valley, approximately 20 km wide, is located south of the present Song Hong (Figs. 10A–E). The distribution of the groundwater table fits well with the upper limits of the sand beds in the estuarine sediments of the DT core and the fluvial sediments (Unit 1) of the ND-1 core, dated approximately 10–15 cal. kyr BP (Fig. 7). The groundwater table might reflect the depth distribution of the latest Pleistocene–Holocene sediments.

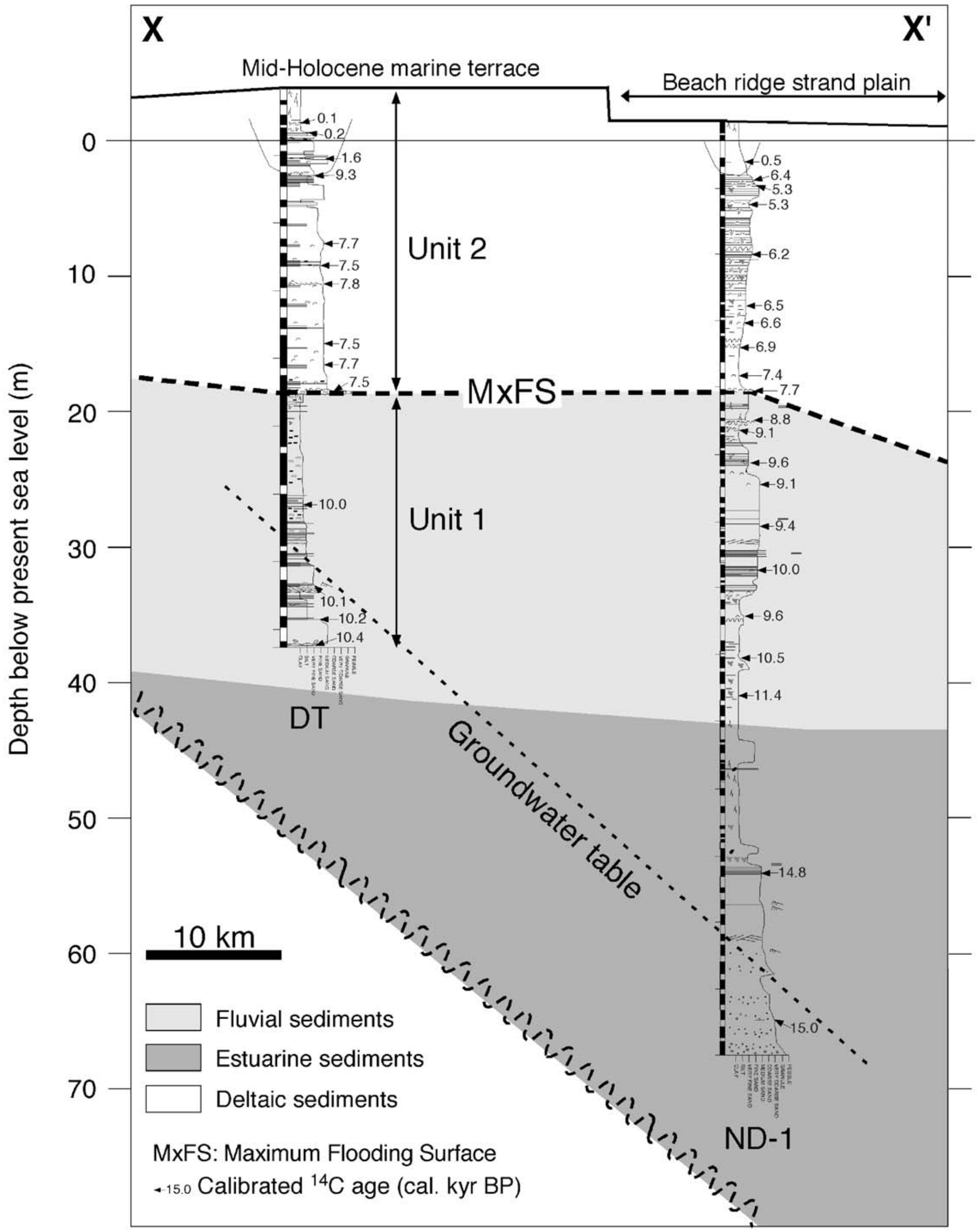

Fig. 7. Stratigraphic correlation between the DT and ND-1 cores. The stratigraphic column and the radiocarbon dates of the ND-1 core are based on Tanabe et al. (2003c). Groundwater table is after Vietnam National Committee for International Hydrological Programme (1994).

5.2. Sea-level change

5.2.1. Sea-level curves for the Song Hong delta region

A sea-level curve for the Song Hong delta region during the past 20 kyr was compiled from those previously reported for the west coast of the South China Sea and for the Sunda Shelf (Fig. 8). During the LGM, the sea level was about 120 m below the present level. It reached approximately 30, 15, and 5 m below the present level at about 10, 9, and 8 cal. kyr BP, respectively. The Holocene sea-level rise began to decelerate (Nakada and Lambeck, 1988; Stanley and Warne, 1994) between 10 and 9 cal. kyr BP.

The sea-level curve for the Song Hong delta region during the past 8 kyr (Fig. 9) is derived from age–height plots based on the marine notches in the Ha Long Bay and Ninh Binh areas (Lam and Boyd, 2001), the mangrove clay at Tu Son (Tran and Ngo, 2000), and

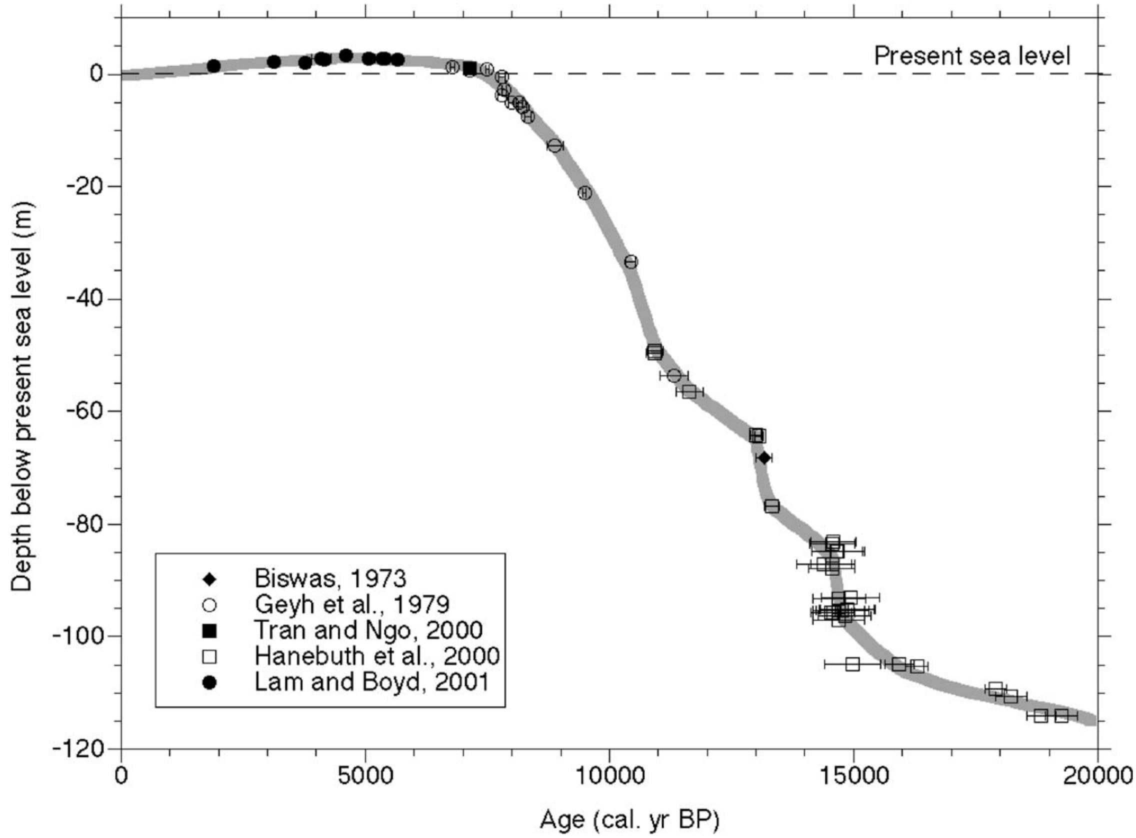

Fig. 8. Sea-level curve on the western margin of the South China Sea during the past 20 kyr. The data used for this curve are a combination of those for the Sunda Shelf between 20 and 11 cal. kyr BP (Biswas, 1973; Hanebuth et al., 2000), the Strait of Malacca between 11 and 7 cal. kyr BP (Geyh et al., 1979), and the Song Hong delta region between 7 and 0 cal. kyr BP (Tran and Ngo, 2000; Lam and Boyd, 2001). All dates used for this curve were calibrated using the Calib 4.3 program (Stuiver et al., 1998) except those from Hanebuth et al. (2000). Radiometric ^{14}C ages ($^{14}C/^{12}C$ ratio), cited from Biswas (1973) and Geyh et al. (1979) were calibrated using the procedure described for Table 2. The radiocarbon data sets of Tran and Ngo (2000) and Lam and Boyd (2001) are listed in Table 2.

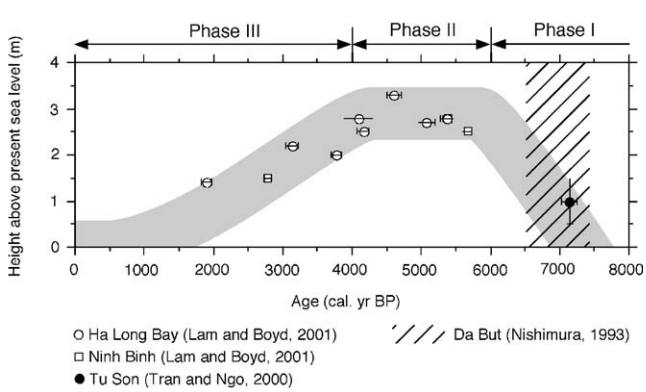

Fig. 9. Sea-level curve in the Song Hong delta region during the past 8 kyr. Heights of marine notches described in Lam and Boyd (2001) were corrected into heights above mean sea-level by adopting a height between the tidal datum and the mean sea-level in Ha Long Bay (2.06 m) (Tran Duc Thanh, personal communication, 2002). Data sets from Tran and Ngo (2000) and Lam and Boyd (2001) are listed in Table 2.

the archaeological sites (shell midden) at Da But (Nishimura, 1993) (Fig. 3). The sea reached its present level at 8–7 cal. kyr BP, after reaching a high of 2–3 m above the present level at 6–4 cal. kyr BP, and then, at first rapidly and later gradually, falling to the present level from 4 to 0 cal. kyr BP. It can be divided into three phases: Phase I (9–6 cal. kyr BP), Phase II (6–4 cal. kyr BP), and Phase III (4–0 cal. kyr BP). During Phase I, sea level rose from 15 m below the present level to 3 m above the present level at a rate of 6 mm/yr. During Phase II, sea level was stable. During Phase III, it dropped from 3 m above the present level to the present level at an average rate of 0.6 ± 0.1 mm/yr.

5.2.2. *Comparison with other sea-level curves for the western coast of the South China Sea*

The relatively rapid sea-level fall of Phase III can be widely observed along the western coast of the South China Sea. The mid-Holocene marine terraces in the Song Hong delta plain (Mathers et al., 1996; Mathers and Zalasiewicz, 1999; Tran, 1999; Vu, 2000; Tran and Ngo, 2000) and those on Hainan Island (Qiu, 1986 in Pirazzoli, 1991), along the Vietnamese coast (Fontaine and Delibrias, 1974 in Pirazzoli, 1991; Nguyen, 1991b), and on the small islands off the Vietnamese coast (Korotky et al., 1995) suggest that rapid sea-level lowering, ranging in magnitude from 0.5 to 4 m, occurred after about 4 kyr BP (4.5–4.0 cal. kyr BP). An emerged marine notch in the Mekong delta plain, which indicates a sea level 2.5 m above the present level at 4150 ± 140 yr BP (4.2 cal. kyr BP) (Nguyen V.L., et al., 2000), also supports this suggestion. Along the coast of Gyangdong, China, indicators of higher sea levels, including cheniers (Huang et al., 1986, 1987 in Pirazzoli, 1991), suggest that the sea level started to fall gradually from a height of 2 m above the present level to the present level at about 3 kyr BP (2.8 cal. kyr BP). Furthermore, recently reported sea-level curves, reconstructed on the basis of numerous age–height plots, including those from marine notches along the Gulf of Thailand and the Malay Peninsula (Sinsakul, 1992; Tjia, 1996; Fujimoto et al., 1999; Choowong, 2002), indicate that sea level started to fall at 4–3 kyr BP (4.5–2.8 cal. kyr BP) from a height of 2–4 m above the present level. In summary, a relatively rapid sea level fall with a magnitude of 0.5–4 m occurred widely along the western coast of the South China Sea during the past 4.5 kyr, particularly at 4–3 cal. kyr BP.

The late Holocene sea-level lowering may have been triggered by global changes such as an increase in Antarctic ice volume, which primarily controls changes in ocean water volume (Goodwin, 1998), or by late Holocene climatic cooling events, such as have been reported from the western Pacific (Jian et al., 1996, 2000). Slight differences in the timing and the magnitude of the sea-level fall are expected to result from local tectonic or hydro-isostatic land-level changes (Lambeck and Nakada, 1990).

5.3. Delta evolution and sea-level changes

The evolution of the Song Hong delta within the context of Holocene sea-level changes is discussed here on the basis of data from the DT and ND-1 cores (Tanabe et al., 2003c) and previously reported data. Additional stratigraphic information on the lithology and 11 ^{14}C ages were collected from the HH120 (HH) (Lam and Boyd, 2000), Gia Loc (GL), Pho Noi (PN), and Tu Son (TS) sites (Tran and Ngo, 2000). The locations are shown in Figs. 3 and 10, and the cited and calibrated radiocarbon dates are listed in Table 2. Depositional ages for the sites were calculated from the accumulation curves shown in Fig. 6.

Fig. 10 shows the paleogeography of the Song Hong delta since 9 cal. kyr BP. The delta evolution can be divided into three stages: Stage I (9–6 cal. kyr BP), Stage II (6–4 cal. kyr BP), and Stage III (4–0 cal. kyr BP). Stages I, II, and III correspond respectively to Phases I, II, and III, described in the above section. The paleogeography and the sedimentary processes characterizing these stages are described in detail below.

5.3.1. Stage I (9–6 cal. kyr BP)

During this stage, the drowned incised valley of the Song Hong (the Song Hong Drowned Valley: SHDV) (Fig. 10A and B) was in-filled, mainly by Song Hong riverine sediments, and then the large area of the present delta plain was covered by mangrove flats (Dinh and Nguyen, 2000) as a result of the overall sea-level rise after the LGM (Fig. 10A–D).

The SHDV was filled by the following depositional processes. From 10 to 9 cal. kyr BP, riverine sediment accumulation in the vicinity of Hanoi was enhanced by the deceleration of the sea-level rise. The DT and ND-1 sites were under subtidal–intertidal flat environments during this period. Between 9 and 7 cal. kyr BP, a sediment body, perhaps a river mouth bar, rapidly migrated and filled the incised valley from the vicinity of Hanoi toward the Gulf of Bac Bo (Fig. 10A–C). As a result, the channel floor at the DT site was rapidly overlain by tide-influenced channel-fill sediments. Between 7 and 6 cal. kyr BP, the paleo-shoreline migrated from the DT site toward the ND-1 site (Fig. 10C and D). As a result, the ND-1 site changed from a prodelta environment to a delta front environment (Tanabe et al., 2003c). The drowned valley may have been completely filled by 6 cal. kyr BP (Fig. 10D). The relatively thick nature of the channel-fill sediments (Facies 2.2) in the DT core may have been caused by aggradation as a result of the overall rise in sea level during this stage.

Between 8 and 6 cal. kyr BP, mangrove flats migrated landward because of the overall sea-level rise, but the facies successions of the Holocene mangrove clay and the distribution of the mid-Holocene marine terrace (Fig. 10F) indicates that the paleo-shoreline was stable in the vicinity of the HH and GL sites and Ninh Binh (Fig. 10B–D). Holocene mangrove clay, which consists of massive clay, was aggradationally deposited at the HH, GL, and PN sites and at Ninh Binh between 8 and 5 cal. kyr BP (Lam and Boyd, 2000; Nguyen and Le, 2000; Tran and Ngo, 2000).

Along the Ma River, the paleo-shoreline might be located near the archaeological site (shell midden) at Da But at around 7–6 cal. kyr BP because the brackish shells obtained from the midden are dated from 5710 ± 60 yr BP to 6430 ± 50 yr BP (Nishimura, 1993).

5.3.2. Stage II (6–4 cal. kyr BP)

During this stage, the large area of the present delta plain was covered by a mangrove flat as a result of the sea-level stillstand of Phase II. The landward limits of the mangrove flat and the paleo-shoreline migrated several km seaward because of the sediment discharges from the Song Hong distributaries (Fig. 10 D and E).

As a result of the shoreline migration, the ND-1 site changed from a delta front environment to a beach-ridge strandplain. A series of beach ridges, extending from Go Trung to the ND-1 site, is dated at 4700 ± 50 yr

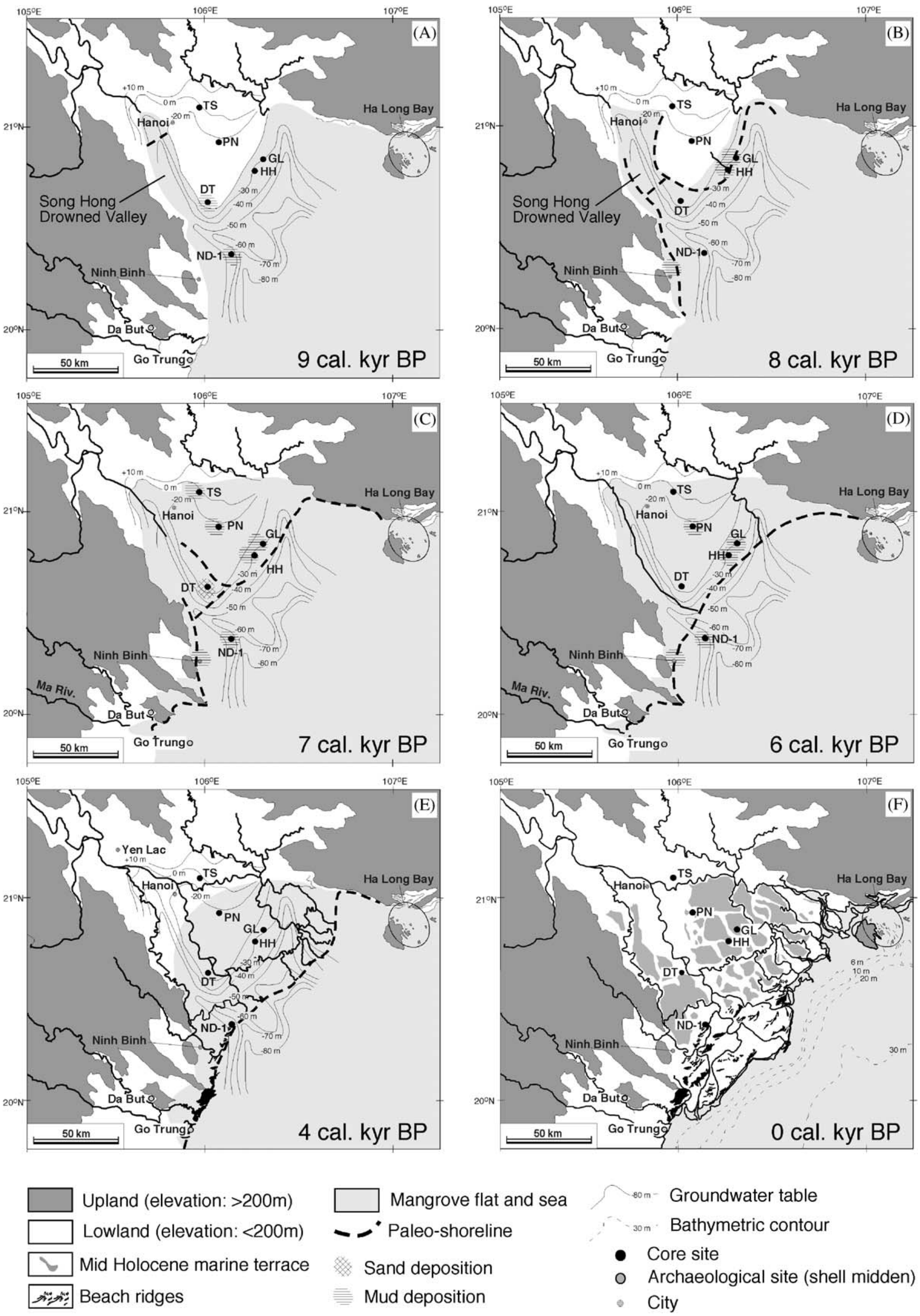

Fig. 10. Paleogeographic map illustrating the evolution of the Song Hong delta during the past 9 kyr. Paleo-shorelines are estimated on the basis of core data, surface geological data, archaeological data, and the depth distribution of the latest Pleistocene–Holocene sediments (groundwater table) (Vietnam National Committee for International Hydrological Programme, 1994). The mangrove flat is modified from the distribution of the Holocene mangrove clay (Dinh and Nguyen, 2000). Mid-Holocene marine terrace and beach-ridge locations in (F) are based on Nguyen T.V., et al. (2000) and Tran (1993), respectively.

Table 2
Summary of radiocarbon dates compiled from other studies

Site	Altitude of the site (m)	Sample depth in core (m)	Altitude of the sample (m)	Material	Radiometric ^{14}C age (yr BP)	$\delta^{13}C$ (‰)	Conventional ^{14}C age (yr BP)	Calibrated ^{14}C age		References
								Intercept (cal. yr BP)	1σ range	
HH120	2.0	2.0	0.0	Shell	4145±50	0.0	4545±50	4805	4829–4724	Lam and Boyd (2000)
HH120	2.0	5.0	−3.0	Peat	6000±50	−27.5	5960±50	6784/6771/6755	6853–6689	Lam and Boyd (2000)
HH120	2.0	9.0	−7.0	Shell	7129±80	0.0	7529±80	7992	8103–7928	Lam and Boyd (2000)
HH120	2.0	22.0	−20.0	Wood	>40000	—	—	—	—	Lam and Boyd (2000)
Gia Loc	3.0	2.0	1.0	Peat	4145±50	−27.5	4105±50	4776/4773/4607/4601/4571/4555/4553	4809–4454	Tran and Ngo (2000)
Gia Loc	3.0	5.0	−2.0	Peat	6000±50	−27.5	5960±50	6784/6771/6755	6853–6689	Tran and Ngo (2000)
Gia Loc	3.0	9.0	−6.0	Peat	7190±90	−27.5	7150±90	7960	8106–7868	Tran and Ngo (2000)
Pho Noi	2.0	2.0	0.0	Peat	5730±60	−27.5	5690±60	6468/6460/6450	6534–6407	Tran and Ngo (2000)
Pho Noi	2.0	3.5	−1.5	Peat	6360±75	−27.5	6320±75	7252	7315–7105	Tran and Ngo (2000)
Pho Noi	2.0	3.5	−1.5	Peat	6800±40	−27.5	6760±40	7609/7598/7591	7663–7577	Tran and Ngo (2000)
Tu Son	3.0–4.0	2.5	0.5−1.5	Peat	6290±60	−27.5	6250±60	7208/7186/7183/7166/7163	7251–7029	Tran and Ngo (2000)
Ha Long Bay	0.0	—	2.8	Oyster	—	—	4990±90	5323	5466–5276	Lam and Boyd (2001)
Ha Long Bay	0.0	—	2.5	Oyster	—	—	4100±50	4161	4248–4089	Lam and Boyd (2001)
Ha Long Bay	0.0	—	2.0	Oyster	—	—	3820±50	3811	3862–3708	Lam and Boyd (2001)
Ha Long Bay	0.0	—	2.8	Oyster	—	—	4050±140	4095	4308–3902	Lam and Boyd (2001)
Ha Long Bay	0.0	—	2.2	Oyster	—	—	3280±60	3154	3238–3059	Lam and Boyd (2001)
Ha Long Bay	0.0	—	1.4	Oyster	—	—	2280±60	1912	1984–1843	Lam and Boyd (2001)
Ha Long Bay	0.0	—	2.7	Oyster	—	—	4770±60	5039	5214–4958	Lam and Boyd (2001)
Ha Long Bay	0.0	—	3.3	Oyster	—	—	4420±70	4600	4773–4507	Lam and Boyd (2001)
Ninh Binh	0.0–1.0	—	2.8	Oyster	—	—	5040±60	5440	5483–5316	Lam and Boyd (2001)
Ninh Binh	0.0–1.0	—	2.5	Oyster	—	—	5300±60	5666	5739–5603	Lam and Boyd (2001)
Ninh Binh	0.0–1.0	—	1.5	Oyster	—	—	3000±60	2770	2847–2736	Lam and Boyd (2001)

The radiometric ^{14}C ages ($^{14}C/^{12}C$ ratio), cited from Lam and Boyd (2000) and Tran and Ngo (2000), are reported as conventional and calibrated ^{14}C ages. The conventional ^{14}C ages of Lam and Boyd (2001) were converted into calibrated ^{14}C ages. $\delta^{13}C$ was regarded as 0 and −27.5‰ for shells and peat and wood fragments, respectively (Stuiver and Reimer, 1993). Conventional ^{14}C ages were calculated by normalization with a $\delta^{13}C$ value of −25‰: conventional ^{14}C age of shells = radiometric ^{14}C age + 400 yr; conventional ^{14}C age of peat and wood fragments = radiometric ^{14}C age−40 yr. Calibrated ^{14}C ages were calculated from the conventional ^{14}C ages according to Method A of Stuiver et al. (1998). For the calculation of ages from shell fragments, ΔR was regarded as -16 ± 17 yr (Southon et al., 2002) and marine carbon content as 100%. BPSL, below PSL.

BP (4.9 cal. kyr BP) (Nishimura, 1993). Therefore, the ND-1 site emerged prior to 5 cal. kyr BP.

5.3.3. Stage III (4–0 cal. kyr BP)

During this stage, the large area occupied by the mangrove flat in the earlier stages emerged as mid-Holocene marine terraces as a result of the rapid sea-level lowering in Phase III (Fig. 10F). The mangrove flat emerged during the past 4 kyr because the mid-Holocene marine terraces are dated to 7–4 cal. kyr BP (Nguyen, 1991b; Vu, 2000; Tran and Ngo, 2000). The terraces located northeast and southwest of the present delta plain were previously covered by abandoned tidal flats/tidal creeks (tide-dominated system) or channel levee/flood plain (fluvial-dominated system), respectively (Mathers et al., 1996; Mathers and Zalasiewicz, 1999) (Figs. 3 and 10F). Archaeological sites of the Bronze Age Dong Son culture (3–2 cal. kyr BP) widespread on the delta plain during this stage (Ogura, 1997).

During this stage, the beach-ridge strandplain (wave-dominated system) developed in the Song Hong river mouths (Fig. 10F). The shoreline prograded from the ND-1 site to its present position at a rate of >10 m/yr. However in the Thai Binh river mouths (Fig. 3), there was no remarkable shoreline progradation. This difference may be due to the differences in the sediment discharges between the rivers. The Song Hong distributaries carry more than 80% of the total water discharge (General Department of Land Administration, 1996), and the sediment discharges are presumably large compared with those of the Thai Binh distributaries.

5.4. Spatial evolution

Active sediment deposition and shoreline progradation occurred mainly along the Song Hong distributaries or within the SHDV during the past 9 kyr.

If we regard the seaward limits of the river mouth bars, observed in the drowned valley during 9–6 cal. kyr BP, as the approximate positions of paleo-shorelines, then the shoreline prograded more than 100 km, from the vicinity of Hanoi to its present position, during the past 9 kyr. On the other hand, the area adjacent to the Thai Binh distributaries was continuously covered by aggradational mangrove flats, and no remarkable shoreline progradation occurred there during the past 9 kyr. The shoreline prograded less than 50 km, from the vicinity of the HH and GL sites to its present position, during the past 9 kyr.

A delta can be regarded as a prograding, coastal system (Boyd et al., 1992; Reading and Collinson, 1996) formed mainly as a result of river sediment supply. Therefore, the areas along the Song Hong and Thai Binh distributaries can be regarded as the active part and the marginal part, respectively, of the delta. The different amounts of sediment discharge between the Song Hong and Thai Binh distributaries have resulted in different types of coastal evolution within a single delta during the last 9 kyr.

6. Conclusion

To clarify the relationship between millennium-scale sea-level changes and the evolution of the Song Hong delta during the Holocene, we first described the sedimentary facies and radiocarbon dates of the recently obtained DT core; second, we briefly reviewed Holocene sea-level changes in the region surrounding the Song Hong delta; and third, we reconstructed the paleogeography of the delta within the context of those sea-level changes. The results can be summarized as follows.

(1) The 40-m-long DT core was subdivided into Unit 1 (estuarine sediments) and Unit 2 (deltaic sediments), which unconformably overlies Unit 1. Units 1 and 2 were dated at 10–9 and 8–0 cal. kyr BP, respectively. The boundary between the units was interpreted as a maximum flooding surface.
(2) The sea-level changes in the Song Hong delta region during the Holocene were divided into three phases: Phase I (9–6 cal. kyr BP), Phase II (6–4 cal. kyr BP), and Phase III (4–0 cal. kyr BP). During Phase I, sea level rose from 15 m below the PSL at about 9 cal. kyr BP to 2–3 m above the PSL at about 6 cal. kyr BP. During Phase II, sea-level remained stable at 2–3 m above the PSL. During Phase III, sea level rapidly lowered, reaching the present level at about 1 cal. kyr BP (the late Holocene sea-level lowering). The late Holocene sea-level lowering can be widely identified on the western coast of the South China Sea.
(3) The Holocene evolution of the Song Hong delta was divided into three stages within the context of the sea-level changes: Stage I (9–6 cal. kyr BP), Stage II (6–4 cal. kyr BP), and Stage III (4–0 cal. kyr BP). During Stage I, a sand body such as a river mouth bar formed in the bay-head portion of the Song Hong drowned valley as a result of the deceleration of sea-level rise (Phase I), and then it prograded toward the Gulf of Bac Bo, filling the valley. During Stage II, sea level was stable (Phase II), and mangrove flats widely occupied the present delta plain. During Stage III, the mangrove flats emerged to form the mid-Holocene marine terraces in response to the rapid sea-level lowering (Phase III), and a beach-ridge strandplain developed in the Song Hong river mouths. Archaeological sites of the Do Song culture widespread on the delta plain during this stage. During the last 9 kyr, active sediment deposition and shoreline progradation occurred along the Song Hong distributaries as a result of their relatively large sediment discharge.

Acknowledgements

This research was funded by a grant-in-aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan and by the Global Environmental Research Fund of the Ministry of the Environment of Japan. We would like to thank Prof. J. Rose, Prof. C.D. Woodroffe, and Dr. S. Mathers for their careful reviews that improved the manuscript.

References

Allen, G.P., Posamentier, H.W., 1993. Sequence stratigraphy and facies model of an incised valley fill: the Gironde Estuary, France. Journal of Sedimentary Petrology 63, 378–391.

Biswas, B., 1973. Quaternary changes in sea-level in the South China Sea. Geological Society of Malaysia Bulletin 6, 229–256.

Boyd, R., Dalrymple, R.W., Zaitlin, B.A., 1992. Classification of clastic coastal depositional environments. Sedimentary Geology 80, 139–150.

Choowong, M., 2002. The geomorphology and assessment of indicators of sea-level changes to study coastal evolution from the Gulf of Thailand. In: Mantajit, N. (Ed.), Proceedings of the Symposium on Geology of Thailand. Department of Mineral Resources, Bangkok, pp. 207–220.

Coleman, J.M., Wright, L.D., 1975. Modern river deltas: variability of processes and sand bodies. In: Broussard, M.L. (Ed.), Deltas: Models for Exploration. Houston Geological Society, Houston, pp. 99–149.

Collinson, J.D., 1996. Alluvial sediments. In: Reading, H.G. (Ed.), Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Science, Oxford, pp. 37–82.

Dalrymple, R.W., Baker, E.K., Harris, P.T., Hughes, M.G., 2003. Sedimentology and stratigraphy of a tide-dominated, foreland-basin delta (Fly river, Papua New Guinea). In: Sidi, F.H., Nummendal, D., Imbert, P., Darman, H., Posamentier, H.W. (Eds.), Tropical Deltas of Southeast Asia—Sedimentology, Stratigraphy, and Petroleum Geology, SEPM Special Publication 76 (in press).

Davis, R.A., Hayes, M.O., 1984. What is a wave-dominated coast? Marine Geology 60, 313–329.

Dinh, V.T., Nguyen, D.D., 2000. The stages of development of mangrove in the Red River's delta during Holocene. Journal of the Sciences of the Earth 22, 120–126 (in Vietnamese with English abstract).

Frey, R.W., Basan, P.B., 1985. Coastal salt marshes. In: Davis, R.A. (Ed.), Coastal Sedimentary Environments. Springer-Verlag, New York, pp. 225–301.

Fujimoto, K., Miyagi, T., Murofushi, T., Mochida, Y., Umitsu, M., Adachi, H., Pramojanee, P., 1999. Mangrove habitat dynamics and Holocene sea-level changes in the Southwestern coast of Thailand. Tropics 8, 239–255.

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

Galloway, W.E., Hobday, D.K., 1996. Terrigenous Clastic Depositional Systems: Applications to Fossil Fuel and Groundwater Resources. Springer-Verlag, Berlin, 489pp.

General Department of Land Administration, 1996. Vietnam National Atlas. General Department of Land Administration, Hanoi, 163pp.

Geyh, M.A., Kudrass, H.-R., Streif, H., 1979. Sea-level changes during the late Pleistocene and Holocene in the Strait of Malacca. Nature 278, 441–443.

Goodwin, I.D., 1998. Did changes in Antarctic ice volume influence late Holocene sea-level lowering ? Quaternary Science Reviews 17, 319–332.

Hanebuth, T., Stattegger, K., Grootes, P.M., 2000. Rapid flooding of the Sunda Shelf: a late-glacial sea-level record. Science 288, 1033–1035.

Harrison, T.M., Leloup, P.H., Ryerson, F.J., Tapponnier, P., Lacassin, R., Chen, W., 1996. Diachronous initiation of transtension along the Ailao Shan–Red River Shear Zone, Yunnan and Vietnam. In: Yin, A., Harrison, T.M. (Eds.), The Tectonic Evolution of Asia. Cambridge University Press, New York, pp. 208–226.

Haruyama, S., Vu, V.P., 2002. Coastal change in the Southern Song Hong delta. Journal of Geography 111, 126–132 (in Japanese with English abstract).

Hori, K., Saito, Y., Zhao, Q., Cheng, X., Wang, P., Sato, Y., Li, C., 2001. Sedimentary facies and Holocene progradation rates of the Changjiang (Yangtze) delta, China. Geomorphology 41, 233–248.

Hori, K., Saito, Y., Zhao, Q., Wang, P., 2002. Architecture and evolution of the tide-dominated Changjiang (Yangtze) River delta, China. Sedimentary Geology 146, 249–264.

Jian, Z., Li, B., Uwe, P., Wang, P., 1996. Late Holocene cooling in the western Pacific. Science in China (Series D) 39, 543–550.

Jian, Z., Wang, P., Saito, Y., Wang, J., Pflaumann, U., Oba, T., Cheng, X., 2000. Holocene variability of the Kuroshio Current in the Okinawa Trough, northwestern Pacific Ocean. Earth and Planetary Science Letters 184, 305–319.

Korotky, A.M., Razjigaeva, N.G., Ganzey, L.A., Volkov, V.G., Grebennikova, T.V., Bazarova, V.B., Kovalukh, N.N., 1995. Late Pleistocene–Holocene coastal development of islands off Vietnam. Journal of Southeast Asia Earth Sciences 11, 301–308.

Lam, D.D., Boyd, W.E., 2000. Holocene coastal stratigraphy and model for the sedimentary development of the Hai Phong area in the Red River delta, north Viet Nam. Journal of Geology (Series B) 15–16, 18–28.

Lam, D.D., Boyd, W.E., 2001. Some facts of sea-level fluctuation during the late Pleistocene–Holocene in Ha Long Bay and Ninh Binh area. Journal of Sciences of the Earth 23, 86–91 (in Vietnamese with English abstract).

Lambeck, K., Nakada, M., 1990. Late Pleistocene and Holocene sea-level change along the Australian coast. Palaeogeography, Palaeoclimatology, Palaeoecology 89, 143–176.

Lee, T-Y., Lawver, L.A., 1994. Cenozoic plate reconstruction of the East Vietnam Sea region. Tectonophysics 235, 149–180.

Mathers, S.J., Zalasiewicz, J.A., 1999. Holocene sedimentary architecture of the red river delta vietnam. Journal of Coastal Research 15, 314–325.

Mathers, S.J., Davies, J., McDonald, A., Zalasiewicz, J.A., Marsh, S., 1996. The Red River Delta of Vietnam. British Geological Survey Technical Report WC/96/02, 41pp.

Meckel, L.D., 1975. Holocene sand bodies in the Colorado Delta area, northern Gulf of California. In: Broussard, M.L. (Ed.), Deltas, Models for Exploration. Houston Geological Society, Houston, pp. 237–265.

Miall, A.D., 1992. Alluvial deposits. In: Walker, R.G., James, N.P. (Eds.), Facies Models: Response to Sea Level Change. Geological Association of Canada, Waterloo, Ontario, pp. 119–139.

Milliman, J.D., Haq, B.U. (Eds.), 1996. Sea-level Rise and Coastal Subsidence: Causes, Consequences, and Strategies. Kluwer Academic Publishers, Dordrecht, 369pp.

Milliman, J.D., Rutkowski, C., Meybeck, M., 1995. River Discharge to the Sea: A Global River Index. LOICZ Core Project Office, Texel, Netherlands, 125pp.

Nakada, M., Lambeck, K., 1988. The melting history of the Late Pleistocene Antarctic ice sheet. Nature 333, 36–40.

Nguyen, D.T., 1991a. Coastal Evolution: Changes of Environment in Coastal Regions of Viet Nam and Problems of Management and Exploration, Mineral Resources Development Series, Vol. 60. United Nations, New York, pp. 109–114.

Nguyen, D.T., 1991b. Marine Terraces of Indochina. Mineral Resources Development Series 60. United Nations, New York, pp. 47–50.

Nguyen, Q.M., Le, K.P., 2000. Some results of ^{14}C dating in investigation on Quaternary geology and geomorphology in Nam Dinh–Ninh Binh area, Viet Nam. Journal of Geology (Series B) 15–16, 106–109.

Nguyen, T.V., Nguyen, D.D., Pham, V.H., Pham, V.M., Dao, V.T., Ngo, Q.T. (Eds.), 2000. Weathering Crust and Quaternary Sediments Map of Vietnam. Department of Geology and Minerals of Vietnam, Hanoi.

Nguyen, V.L., Ta, T.K.O., Tateishi, M., 2000. Late Holocene depositional environments and coastal evolution of the Mekong River Delta, Southern Vietnam. Journal of Asian Earth Sciences 18, 427–439.

Nielsen, L.H., Mathiesen, A., Bidstrup, T., Vejbaek, O.V., Dien, P.T., Tiem, P.V., 1999. Modelling of hydrocarbon generation in the Cenozoic Song Hong Basin, Vietnam: a highly prospective basin. Journal of Asian Earth Sciences 17, 269–294.

Nishimura, M., 1993. Shell midden sites in Vietnam and Thailand. Journal of Southeast Asian Archaeology 13, 25–50 (in Japanese).

Ogura, S., 1997. History of Vietnam: Dynamics of One Billion Peoples. Chuko-shinsho 1372, Chuokoronshinsya, Tokyo, 388pp (in Japanese).

Pirazzoli, P.A., 1991. World Atlas of Holocene Sea-level Changes. Elsevier, Amsterdam, 300pp.

Pruszak, Z., Szmytkiewicz, M., Nguyen, M.H., Pham, V.N., 2002. Coastal processes in the Red River Delta area, Vietnam. Coastal Engineering Journal 44, 97–126.

Rangin, C., Klein, M., Roques, D., LePichon, X., Trong, L.V., 1995. The Red River fault system in the Tonkin Gulf, Vietnam. Tectonophysics 243, 209–222.

Reading, H.G., Collinson, J.D., 1996. Clastic coast. In: Reading, H.G. (Ed.), Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Science, Oxford, pp. 154–231.

Reinson, G.E., 1992. Transgressive barrier island and estuarine systems. In: Walker, R.G., James, N.P. (Eds.), Facies Models: Response to Sea Level Change. Geological Association of Canada, Waterloo, Ontario, pp. 179–194.

Saito, Y., 2001. Deltas in Southeast and East Asia: their evolution and current problems. In: Mimura, N., Yokoi, H. (Eds.), Global Change and Asia Pacific Coasts. Proceedings of APN/LOICZ Joint Conference on Coastal Impacts of Climate Change and Adaptation in the Asia-Pacific Region. APN and Ibaraki University, Ibaraki, Japan, pp. 185–191.

Saito, Y., Wei, H., Zhou, Y., Nishimura, A., Sato, Y., Yokota, S., 2000. Delta progradation and chenier formation in the Huanghe (Yellow River) delta, China. Journal of Asian Earth Sciences 18, 489–497.

Saito, Y., Yang, Z., Hori, K., 2001. The Huanghe (Yellow River) and Changjiang (Yangtze River) deltas: a review on their characteristics, evolution and sediment discharge during the Holocene. Geomorphology 41, 219–231.

Sinsakul, S., 1992. Evidence of Quaternary sea level changes in the coastal areas of Thailand: a review. Journal of Southeast Asian Earth Sciences 7, 23–37.

Southon, J., Kashgarian, M., Fontugne, M., Metivier, B., Yim, W.W.-S., 2002. Marine reservoir corrections for the Indian Ocean and Southeast Asia. Radiocarbon 44, 167–180.

Stanley, J.D., 2001. Dating modern deltas: progress, problems, and prognostics. Annual Review on Earth and Planetary Sciences 29, 257–294.

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

Stuiver, M., Braziunas, T.F., 1993. Modeling atmospheric ^{14}C influences and ^{14}C ages of marine samples back to 10,000 BC. Radiocarbon 35, 137–189.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon 35, 215–230.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J., Spurk, M., 1998. INCAL98 radiocarbon age calibration, 24,000–0 cal BP. Radiocarbon 40, 1041–1083.

Ta, T.K.O., Nguyen, V.L., Tateishi, M., Kobayashi, I., Saito, Y., Nakamura, T., 2002a. Sediment facies and late Holocene progradation of the Mekong River delta in Bentre Province, southern Vietnam: an example of evolution from a tide-dominated to a wave-dominated delta. Sedimentary Geology 152, 313–325.

Ta, T.K.O., Nguyen, V.L., Tateishi, M., Kobayashi, I., Tanabe, S., Saito, Y., 2002b. Late Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam. Quaternary Science Reviews 21, 1807–1819.

Tanabe, S., Ta, T.K.O., Nguyen, V.L., Tateishi, M., Kobayashi, I., Saito, Y., 2003a. Delta evolution model inferred from the Mekong delta, southern Vietnam. In: Sidi, F.H., Nummendal, D., Imbert, P., Darman, H., Posamentier, H.W. (Eds.), Tropical Deltas of Southeast Asia—Sedimentology, Stratigraphy, and Petroleum Geology, SEPM Special Publication 76 (in press).

Tanabe, S., Saito, Y., Sato, Y., Suzuki, Y., Sinsakul, S., Tiyapairach, S., Chaimanee, N., 2003b. Stratigraphy and Holocene evolution of the mud-dominated Chao Phraya delta, Thailand. Quaternary Science Reviews 22, 789–907.

Tanabe, S., Hori, K., Saito, Y., Haruyama, S., Doanh, L.Q., Sato, Y., Hiraide, S., 2003c. Sedimentary facies and radiocarbon dates of the Nam Dinh-1 core from the Song Hong (Red River) delta, Vietnam. Journal of Asian Earth Sciences 21, 503–513.

Tjia, H.D., 1996. Sea-level changes in the tectonically stable Malay-Thai Peninsula. Quaternary International 31, 95–101.

Tran, D.T., 1993. Geological evolution of the Bach Dang Estuary during the Holocene. Ph.D. Thesis, Hanoi University, Hanoi, 135pp., unpublished.

Tran, D.T., 1999. Holocene stratigraphy and structure of the intertidal flats in Haiphong Coastal Area. Journal of Sciences of the Earth 21, 197–206 (in Vietnamese with English abstract).

Tran, D.T., Dinh, V.H., 2000. Coastal development of the modern Red River delta. Bulletin of the Geological Survey of Japan 51, 276.

Tran, N., Ngo, Q.T., 2000. Development history of deposits in the Quaternary of Vietnam. In: Nguyen, T.V. (Ed.), The Weathering Crust and Quaternary Sediments in Vietnam. Department of Geology and Minerals of Vietnam, Hanoi, pp. 177–192 (in Vietnamese).

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Louit, T.S., Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea-level Changes: An Integrated Approach, No. 42. Society of Economic Paleontologists and Mineralogists, Special Publication, pp. 39–45.

Vietnam National Committee for International Hydrological Programme, 1994. Vietnam Hydrometeorological Atlas. General Department of Land Administration, Hanoi, 68pp.

Vu, Q.L., 2000. Changes of coastal line in the Red river delta during Holocene. CCOP Technical Publication 27, 67–73.