

## Geomorphological sedimentary characteristics in the coastal area of Ma river delta, Thanh Hoa province

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### Abstract

The coastal area of the Ma river delta is formed by the interaction of continental and marine processes, between neo-tectonic activities and exogenous processes, between natural factors and human activities during the Late Holocene. Using remote sensing and geoscience research methods (granulometry, paleontology, geochemistry, clay mineralogy) and geomorphological studies (geneses, morphology, dynamics) combined with field survey, this coastal area, except the denuded mountainous remnants, could be distinguished into 12 morpho-sedimentary units formed and developed by the dynamic interactions of the river, waves and tides. The units formed by fluvial dynamics include: 1) Point bar is composed of clayey silt and sandy silt, 2) Channel bar composed of silty sand, 3) Levee with the composition of silty sand and 4) The flood plain of silty clay. The Late Holocene evolution of the Ma river delta was dominated by wave dynamics, reflected by a wave-formed association of dunes, interdune swamps and current sand beaches. The wave-formed units include 5) Dune's sand and silty sand, 6) Back-dune depressions composed of sand silt clay, 7) Beach composed of sand, 8) Lagoon plain of silty clay and 9) Strand plain composed of silty sand. The tide-influenced units include 10) Supratidal flat with the composition of silty clay, 11) Intertidal flat characterized by clay or silty clay interbedded with thin fine sand or silty sand layers, 12) Subtidal flat of sand and silty sand.

**Keywords:** Geomorphology, upper Holocene sediments, Ma river delta, Thanh Hoa province.

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**INTRODUCTION**

The Ma River delta, the third largest delta in Vietnam (after the Mekong River and Red River deltas), was formed by continental and marine processes, between neotectonic activities and exogenous processes, and interaction of continental and marine processes, natural factors, and human activities. It has great potentials for aquatic resources, seaports,

navigation, marine tourism with many beautiful beaches, rice and crops fields, ponds,... Based on geomorphological and sedimentological analyses, the research on morpho-sedimentary features contributes to the scientific basis for spatial orientation to develop the advantages mentioned above in the coastal area of the Ma River delta, Thanh Hoa province.

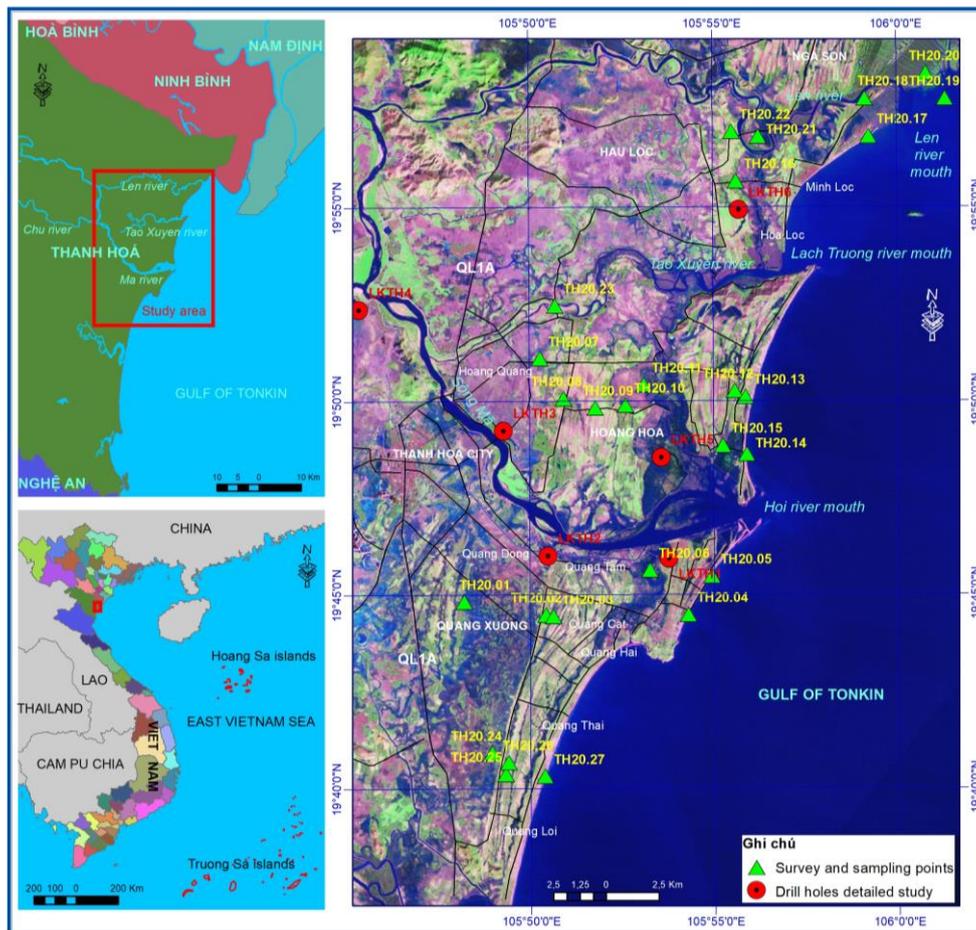


Figure 1. Study area, sampling and borehole sites

The Ma river system originates from Dien Bien province in the northwest of Vietnam, flows through the territory of Laos, and then back into Vietnam in the region of Thanh Hoa province. The Ma river receives water from two major tributaries, the Buoï river and the Chu river, then dividing the water into three major distributaries, namely the Ma river, the Tao Xuyen river and the Len river, which

empties into the sea with three river mouths, respectively, Hoi, Lach Truong and Len (or Lach Sung) (figure 1). Annually, the Ma river drains into the East Vietnam Sea 18 billion m<sup>3</sup>, corresponding to a discharge of 570 m<sup>3</sup>/s. The upstream of Ma River has the largest sediment concentration of about 500 g/m<sup>3</sup>, downstream reduces to approximately 400 g/m<sup>3</sup> at Cam Thuy, and range of 82–402 g/m<sup>3</sup> in the lower

part. The Chu river has a smaller concentration, only about 200 g/m<sup>3</sup>. Annually, the Ma river drains into the East Vietnam Sea a sediment load of about 5.17 million tons/year or 18.4 tons/km<sup>2</sup>, mostly transported during the flood season (90%). The sediment load from the Ma river and those from the Red river make the Thanh Hoa delta expand seaward tens of meters each year.

Waves in the sea of Thanh Hoa have two distinct seasons. In winter, from December to March, the offshore area is dominated by northeastern waves with a stable frequency of 51–70%, their average height in the range of 0.5–1.3 m and the highest of 1.5–6.0 m; In the coastal areas, the wave directions are Northeast (11%), East (34%) and Southeast (22%) with average height around 0.4–0.9 m and the highest of 0.75–3.0 m. Southern waves dominate the offshore from June to September with frequency from 37% to 60%, height from 0.8–1.3 m, and the highest of 4.0–9.0 m. The nearshore area is dominated mainly by southeastern and southern waves with 24% and 20% frequency, respectively.

The irregular diurnal tide characterizes the coast of Thanh Hoa. The flood tide time is short, usually 7–8 hours, up to 8–9 hours on spring tide days, the ebb tide time is about 15–16 hours. The high tide level is 2.9 m, and the low tide is -1.81 m at Hoang Tan station (Ma river estuary); the respective values are 2.58 m and -0.97 m at Lach Sung (Len river mouth).

## **MATERIALS AND METHODS**

### **Material bases**

The used data includes:

Satellite images: Google Earth Pro 2020; Landsat 2017;

Thematic maps: urban geomorphological map of Thanh Hoa at 1/25.000 scale [1]; aerial geomorphological map of Thanh Hoa delta at 1/50.000 scale [2].

Field survey results in 2020 at 32 sites;

Analytical results: particle size (35 samples), spore and pollen (2 samples), diatoms (4 samples), clay mineral composition (5 samples), and environmental geochemistry (4 samples).

### **Methods**

Remote sensing is used for interpreting and determining the spatial distribution of landform units. The interpretation is based on three image signs: Tone/Color, Texture, and Pattern. After interpreting the entire research area, these identified objects are arranged in a certain order according to the geological and structural setting of the study area, then compared with existing documents and verified documents.

Each terrain unit has its characteristics in sedimentary composition, structure, and depth of sediment distribution. Sediment surfaces and the outcrops made by civil excavation works are good sites for description and sampling. Field survey: Based on the units identified by interpretation of remote sensing, a field survey is conducted for verification.

Geological analysis methods include: grain size analyzed by sieve and pipette, pollen and spores identified by a microscope, clay mineralogical analysis by X-ray diffraction (XRD) using a PANALytical diffractometer are carried out respectively at the Department of Sedimentology, Department Quaternary Geology and Department of Mineralogy, Institute of Geological Sciences. The diatom was analyzed at the Department of Geology, Hanoi University of Sciences, Vietnam National University, Hanoi. The physicochemical parameters were analyzed at the National Institute of Agricultural Planning and Projection.

## **RESULTS**

The coastal terrain of the Song Ma delta is very diverse and complex. They were formed by dynamic interactions of waves, tides, and rivers but dominantly by waves. Neotectonic and current tectonic movements and anthropogenic activities also impact this terrain by changing and sometimes erasing the older landforms. The study area is mainly plain ranging from 0–5 m high with scattered hills below 200 m altitudes. Geomorphologically, there are 13 typical landform units (figure 2); mountainous remnants formed by the denudation processes and accumulation processes created the 12 rests with their sedimentary characteristics of composition, texture and structure.

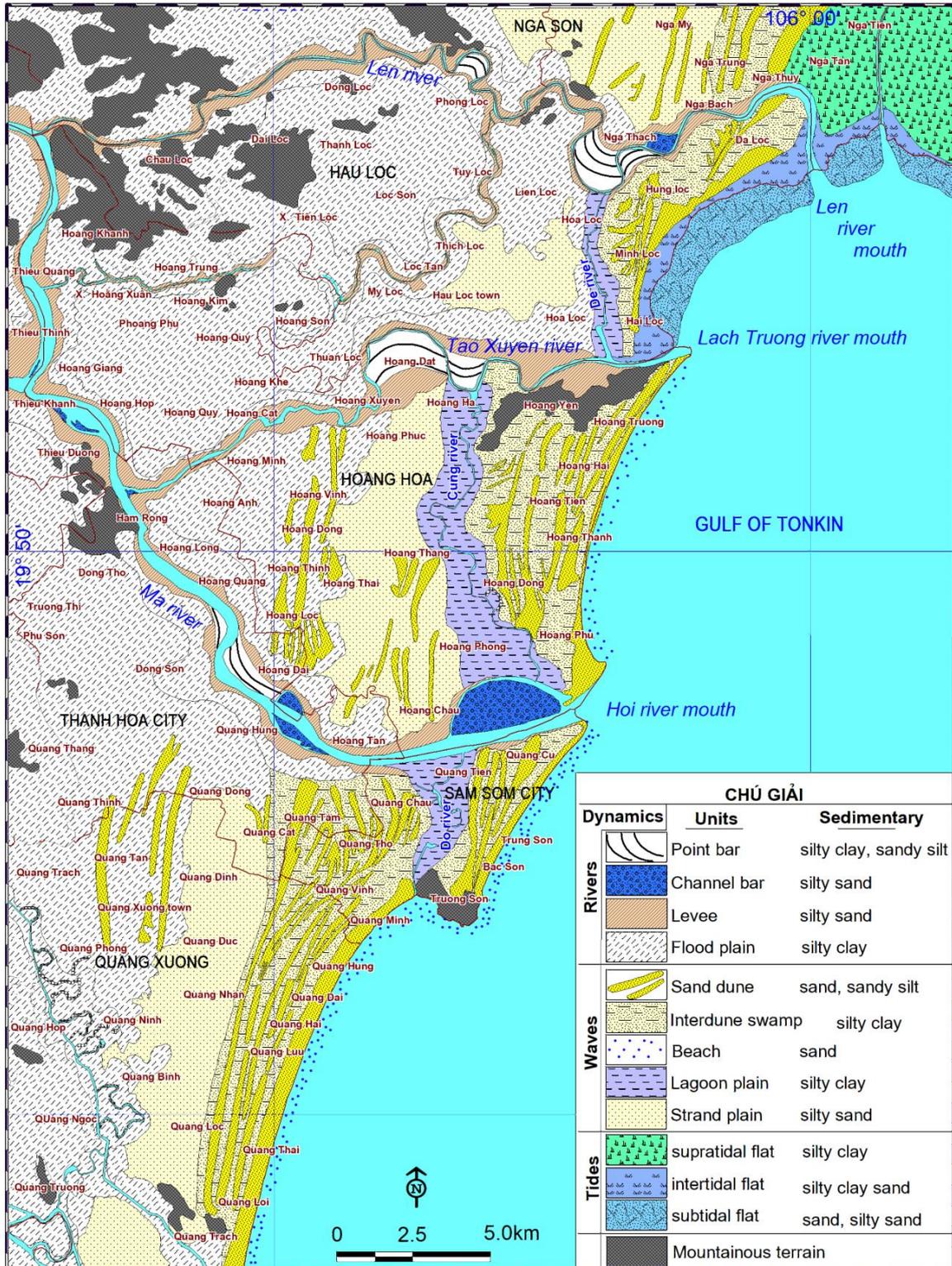


Figure 2. Geomorphology and sediment map of the Song Ma delta coastal area, Thanh Hoa province [Source: Nguyen Minh Quang, Vu Van Ha]

The sediments making up landforms in the coastal zone of Song Ma Delta were formed in Late Holocene, mainly composed of sand, silt and clay. The grain-size analyses showed median dimension (Md) ranging from 0.003–0.274 mm, good to poor sorting (So), and skewness (Sk) from 0.22–3.20, so the

sedimentation was diverse in continental, transitional, and marine environments (table 1). Combining with microbiological, physicochemical - environmental and clay mineral analysis could identify the characteristics of morpho-sedimentary units in the coastal Song Ma delta as follows.

*Table1.* Sedimentological parameters of the Thanh Hoa coastal area

No.	Sample symbol	Percentage			Grain-size parameters			Landform
		Sand	Silt	Clay	Md (mm)	So	Sk	
1	TH20-21/0.4 m	12.0	64.8	23.2	0.010	3.52	3.20	Point bar
2	TH20-22/0.4 m	83.1	14.6	2.3	0.133	1.27	0.92	Levee
3	TH20-16/0.4 m	11.0	37.8	51.2	0.005	4.81	0.38	Flood plain
4	LKTH03/0.6 m	16.5	40.9	42.6	0.006	5.35	1.55	
5	LKTH04/0.3 m	16.5	40.9	42.6	0.006	5.35	1.55	Sand dune
6	TH20-02/0.4 m	86.0	13.6	0.4	0.131	1.27	0.95	
7	TH20-12/0.4 m	80.3	16.6	3.1	0.143	1.39	0.86	
8	TH20-13/0.4 m	99.4	0.6	0.0	0.233	1.16	1.00	
9	TH20-18/0.4 m	98.2	1.8	0.0	0.185	1.26	1.01	
10	TH20-26/0.4 m	93.5	6.5	0.0	0.135	1.28	0.99	
11	LKTH01/0.6 m	84.4	15.6	0.0	0.167	1.29	0.83	Interdune swamp
12	TH20-03/0.4 m	80.3	19.1	0.6	0.147	1.34	0.87	
13	TH20-24/0.4 m	4.0	37.6	58.4	0.004	5.75	0.14	
14	TH20-24(2)1.1 m	21.0	53.1	25.9	0.048	4.44	0.17	
15	TH20-25(1)0.5 m	32.0	30.9	37.1	0.009	6.80	4.20	Beach
16	TH20-25(2)1.2 m	85.1	14.9	0.0	0.140	1.27	0.94	
17	TH20-04/0.4 m	97.5	2.5	0.0	0.274	1.27	1.01	
18	TH20-05/0.4 m	97.4	2.6	0.0	0.185	1.18	1.01	
19	TH20-14/0.4 m	90.0	10.0	0.0	0.196	1.19	0.94	Lagoon plain
20	TH20-27/0.4 m	96.2	3.8	0.0	0.170	1.17	0.97	
21	TH20-06/0.4 m	11.0	61.5	27.5	0.018	3.39	0.65	Strand plain
22	TH20-11/0.4 m	3.0	58.2	38.8	0.008	4.56	0.67	
23	TH20-07/0.4 m	3.0	64.0	33.0	0.011	3.64	0.62	
24	TH20-08/0.4 m	80.2	19.2	0.6	0.142	1.33	0.89	
25	TH20-09/0.4 m	90.8	9.2	0.0	0.142	1.26	0.94	
26	TH20-10(1)/0.4 m	23.0	38.4	38.6	0.010	8.76	0.96	
27	TH20-10(2)1.2 m	60.2	27.2	12.6	0.087	2.46	0.51	Supratidal flat
28	LKTH06/1.0 m	9.6	34.2	56.2	0.003	3.87	1.15	
29	TH20-20/0.4 m	0.0	37.9	62.1	0.003	3.91	0.83	Intertidal flat
30	TH20.17/1.2 m	18.0	53.3	28.7	0.010	3.68	1.47	
31	TH20.17/1.7 m	41.1	46.5	12.4	0.054	2.83	0.22	
32	TH20.17/0.4 m	1.1	47.3	51.6	0.004	2.78	0.72	
33	TH20-19/0.4 m	10.0	29.8	60.2	0.003	4.43	0.44	Subtidal flat
34	TH20.17/2.0 m	48.9	44.4	6.7	0.062	2.23	0.27	
35	TH20.17/2.4 m	71.4	17.7	10.9	0.080	1.28	0.83	

**Cuspate**

Rivers may dominate a delta, waves, or tides, reflected by its morphological characteristics and related association of sedimentary facies (fig. 3A) [3–5]. The wave-dominated deltas are often characterized by cuspate river-mouth, sand bars, and dunes

parallel to the smooth coastlines and few distributary channels [4, 5]. The study area's Lach Truong and Cua Hoi river mouths belong to this cuspate mouth of the wave-dominated delta (fig. 3B). Overall, the Song Ma delta is a wave-dominated delta, where the wave is the dominant factor shaping the fluvial sediment.

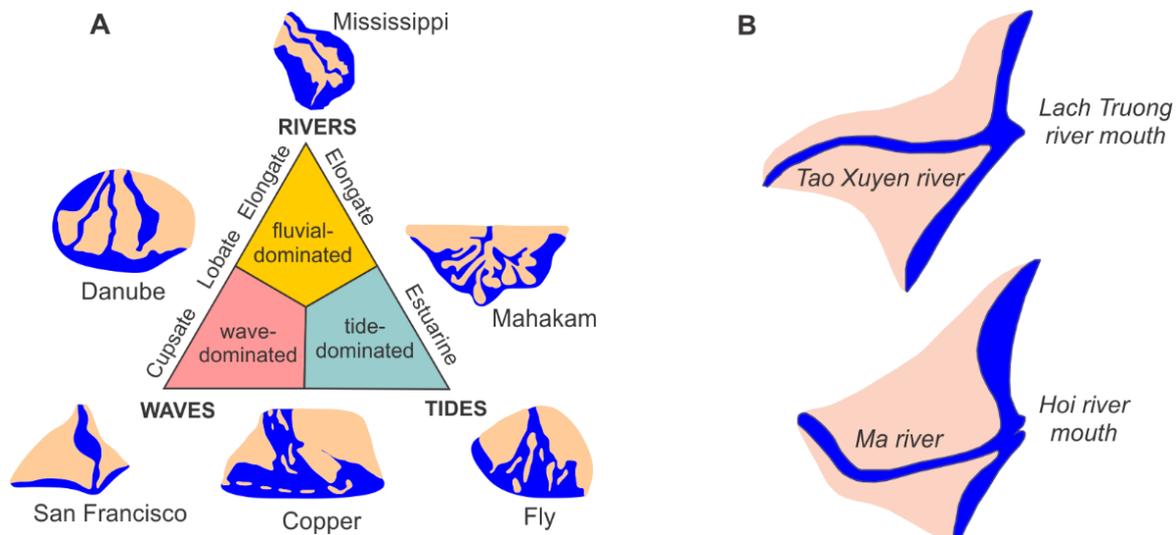


Figure 3. The ternary diagram of delta morphology showing wave dominated deltas in the lower left corner image [5] (A); Hoi and Lach Truong river mouth (B)

**Point bar**

The channel often winds to the two sides within a narrow belt [6]. In a bend of the river, the flow of horizontal circulation brings materials from eroded concave bank to deposited convex bank, forming a point bar [7]. The point bar is often flooded in the rainy season and exposed in the dry season. Their surface is situated at a relative elevation from 0.5–1.0 m to 2.0 m, inclining towards the river (figure 4). Point bars are commonly found on both sides of the Len, Tao Xuyen, and Ma rivers. It is composed of the most Upper Holocene sediments belonging to the Thai Binh Formation - ( $Q_2^3tb_2$ ). In the cross-sections, these sediments are characterized by upwards fining grain-size as shown in the Nga Thach section with the depth from bottom up as follows:

From 3.0 m up to 0.8 m depth: sediments consist of yellow-gray, gray sand and sandy silt directly covering on channel filling formation.

The sediments have a median grain size (Md) of 0.2–0.35 mm, degree of sorting (So): 1.6–2.5 [8], poor fossils containing freshwater Mollusca.

From 0.8 m depth to the surface: sediments include brown-gray, gray clayey silt, sandy silt with percentages as follows: sand - 12.0%; silt - 64.8%, and clay - 23.2%. The sedimentological parameters are median grain-sized (Md): 0.001, degree of sorting (So): 3.52, skewness (Sk): 3.2.

**Channel bar**

Channel bars are typical in zones of rapid deposition (rivers overloaded with coarse bedload), at channel widening, etc. As these become common, they will split the flow into multiple threads. The bars may be deposited in slack water created by flow separation around tightly curved meander bend. These bars are often separated from the bank by a small secondary channel. The channel bar develops at

the Ma, Chu, Tao Xuyen and Hoi rivers with narrow distribution, elongating in the flow direction, widening towards the river mouth (figure 5). Its surface is quite flat with a relative

altitude from 0.5 m to 2 m, sometimes up to 3 m, slightly inclining towards the river. The sediment consists of gray silty sand and clay formed in the Late Holocene.

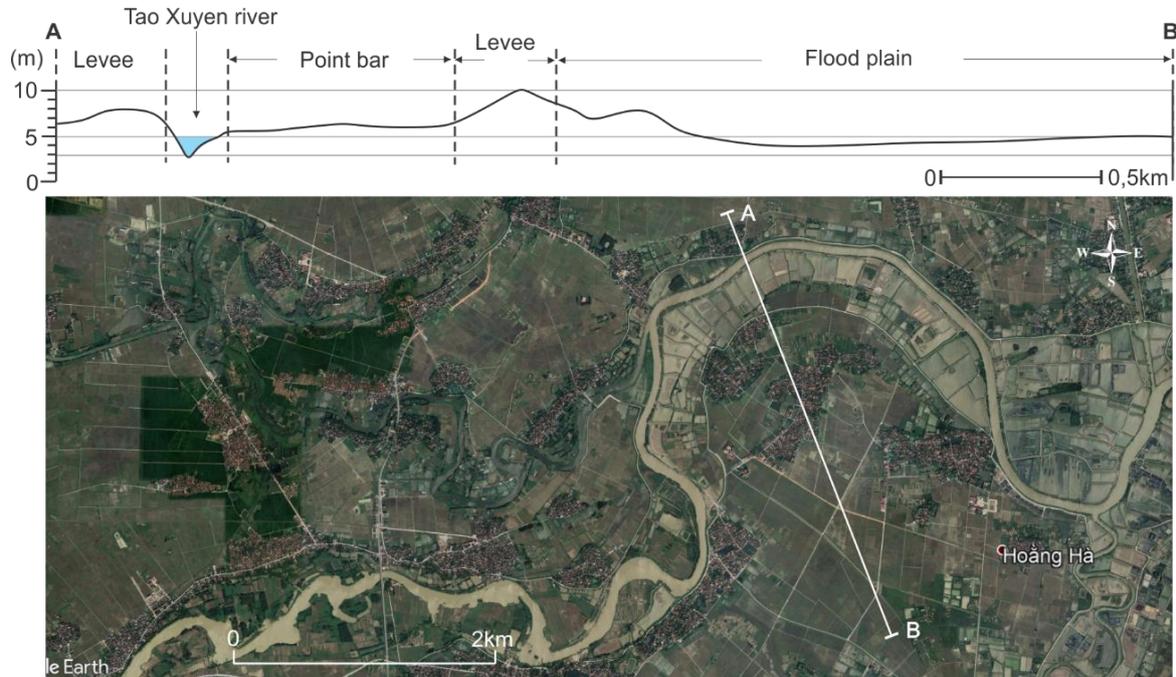


Figure 4. Cross section of meandering terrain in Tao Xuyen river [Source: Google Earth (2020)]



Figure 5. The channel bars in Len river (A), Ma and Chu rivers (B), Ma river mouth (C) [Source: Google Earth (2020)]

**Levee**

Fluvial levees are elevated partitions between channels and floodplains. Because of their character and position, levees may provide critical controls on and insights into geomorphic processes that determine the distribution of water and sediment within river systems. As a

river overflows its banks during the flood, it immediately drops much of its coarser-grained load, forming landforms called natural levees [9]. The levees along the river are interrupted sections, meandering and moving horizontally continuously takes place, over time, they can connect forming continuous natural levees

(figure 6). The natural levee is 0.4–0.8 m higher than the adjacencies. It is composed of sand (81.1%) and silt (14.6%) of the upper part of the Thai Binh formation ( $Q_2^3tb_2$ ). Grain-size analyses showed: median dimension (Md):

0.133 mm, moderate sorting (So): 1.27). The biological remnants are deficient in both the quantity and composition of species. At present, the natural levee is built up and modified by human activities.



Figure 1. Levee and Flood plain along Tao Xuyen river, Thuan Loc commune, Hau Loc district [Source: Nguyen Minh Quang (2021)]

### Flood plain

The flood plain is formed in the flood season when the river overflows its banks, significantly reducing its dynamics, resulting in the deposition of fine-grained (clay and silt) with decreasing size from the riverbank to both sides [10]. The flood plain consists mainly of clay (42.6–51.2%) and silt (37.8–40.9%) and lesser of sand (11.0–16.5%); median dimension (Md) ranges from 0.005 mm to 0.006 mm, bad sorting values (So) from 4.81 to 5.35 and skewness (Sk) of 0.38–1.55 (table 1). Freshwater diatoms include *Aulacosira* sp., *Eunotia clevei*, *E. Pectinalis*, *E. monodon*,... Pollen and spores are found with the presence of *Polypodium* sp., *Quercus* sp., *Polypodiaceae* gen. indet., *Pinus* sp., *Taxodium* sp., *Pteris* sp., *Lygodium* sp.,... The results of physicochemical analysis represent the alluvial environment (pH: 6–7; Eh: 100–150 mV; Kt: 0.5–0.7;  $Fe^{2+}S/Corg$ : 0.02–0.05). The composition of clay minerals is mainly made up of kaolinite and illite. The sediment has an unobvious thin

bedding structure, currently disturbed by human activities; the biological remains are moderately preserved in sediments. The flood plain is distributed along the levee of the Ma river system and from the confluence of Ma and Chu rivers to the center of coastal districts, Thanh Hoa province (figure 6).

### Dune

The dune is often found in the coastal zone dominated by wave dynamics. During the marine regression, the dunes are formed generation by generation, advancing toward the sea. The sand bars are distributed by a narrow strip parallel to the coast (200–1,500 m width and 1–3 m height) (figure 7). They are found in Hoang Hoa, Thanh Hoa city, Sam Son and Quang Xuong. The sediment consists of gray sand (80.3–99.4%) and silt (0.6–16.6%); sedimentological parameters: median grain - size (Md): 0.131–0.233, degree of sorting (So): 1.16–1.39, skewness (Sk): 0.86–1.01) (table 1).



Figure 7. Sand dune in the coast of Hoang Hoa district [Source: Nguyen Minh Quang (2020)]

### Interdune swamp

This swamp is situated between the dunes. Its surface is 1–2 m lower than the surrounding dunes. Protected from the action of waves and tides by the formation of the dune, the swamp is filled with fine-grained materials, mainly dark grey clay (37.1–51.2%), silt (30.9–38.4%) and less sand (11–32%). The grain-size analysis showed: median dimension (Md): 0.001–0.01 mm, degree of sorting (So): 4.81–8.76) (table 1). The physicochemical properties represented a transition from coastal to the alluvial environment (pH: 4.8–6.3; Eh: (-25)–50 mV;

Kt: 1.3–1.5;  $Fe^{2+}S/Corg$ : 0.2–0.3), indicating desalinization in the swamp due to the presence of sand barrier protecting it from the sea. The swamp sediment is one meter thick, containing some fragments of diatoms including *Campylodiscus* sp. and *Cyclotella striata* [12–14], organic matter in thin beds of 1–2 cm thickness, strongly decayed with specific odor (figure 8). The clay minerals consisted of kaolinite (23.9%), illite (65.8%), chlorite (9.8%) and smectite 0.5%. Total mineral analysis showed that quartz (69%), mica (15%), feldspar (5%), chlorite (3%), kaolinite (3%), pyrite (3%) and gypsum (3%).



Figure 8. Interdune swamp in Hoang Thang commune, Hoang Hoa district [Source: Nguyen Minh Quang (2020)]

### Sand beach

Sand beach is very popular, distributed continuously from Hoang Hoa district, Sam Son city, Quang Xuong district to Tinh Gia district, and separated by estuaries. This landform characterizes the coast dominated by waves. The beach is composed mainly of sand (> 90%) with statistic values of grain-size as follows: median grain - size (Md):

0.17–0.274 mm, degree of sorting (So): 1.17–1.27), skewness (Sk): 0.94–1.01) (table 1). On the surface of the sand beach has the structure of ripple marks parallel to the shoreline characterizing a zone of surf wave. The sediment contains an abundance of bioturbation and many shell fragments gathered and zoned by waves (figure 9).

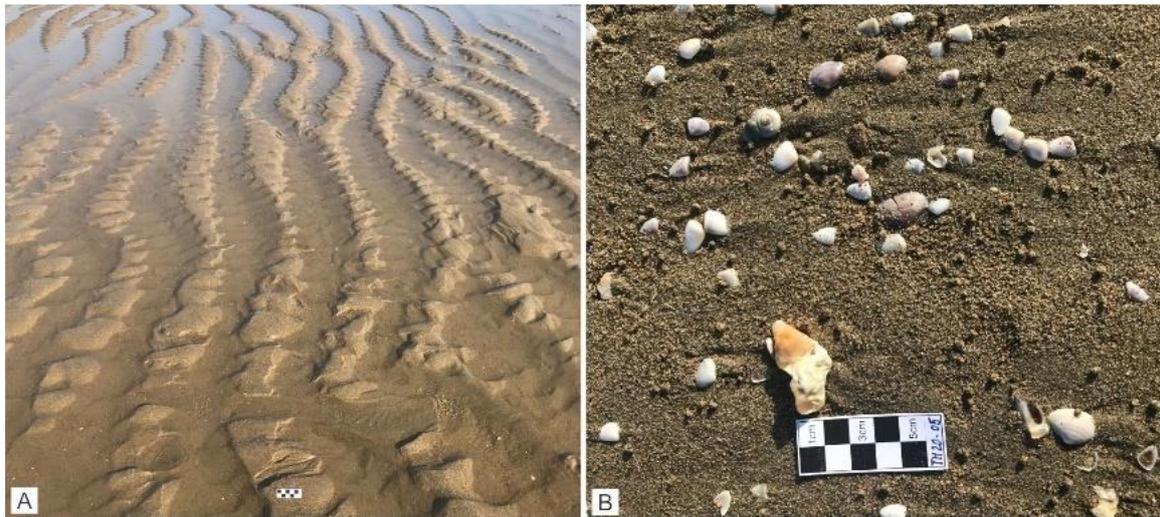


Figure 9. Sam Son beach: A - parallel ripples, B - shell fragments  
[Source: Nguyen Minh Quang (2020)]

### Lagoon plain

When barrier bars and spits form at the mouth of a bay and block it, a lagoon forms. The lagoons would gradually fill up by sediments from the land, giving rise to a coastal plain. The lagoon plain has a height from 2–2.5 m to 4–4.5 m and width from 1 km to 2 km (figure 10), distributed in a narrow strip, along Kanh De river - Hau Loc district, Cung river - Hoang Hoa district, Do river - Sam Son City. This landform is relatively flat, often flooded, and affected by the tide. It is principally composed of dark gray silt, clay, and organic humus in 7 m to 9 m thick (figure 11). The grain-size percentages are: clay 27.5–38.8%, silt 58.2–61.5%, sand 3–11%; statistical parameters: median grain-size (Md): 0.008–0.018 mm, poor sorting (So): 3.39–4.56, skewness (Sk): 0.65–0.67) (table 1). The clay minerals are kaolinite 25%, illite 65.2%, chlorite 9.4% and smectite 0.5%. Total mineral analysis showed that quartz

(50%), mica (25%), feldspar (11%), chlorite (2%), kaolinite (7%), pyrite (5%), amphibole (< 1%), magnetite (< 1%).

### Strand plain

By the end of the Early Holocene, the sea level rise slowed down, approaching to zero, changing to marine regression in Middle Holocene, the accretion rate was greater than the subsidence rate, favoring the formation of the Song Ma delta [10]. In the river mouth and coastal area, the sediments supplied by rivers are redistributed by marine dynamics such as tide, wave, and longshore drift. Under the strong wave dynamics, removing the fine materials, so the coarser sand and silty sand were left in form of strand plains. A strand plain is a broad belt of sand along a shoreline with a surface exhibiting well-defined parallel or semi-parallel sand ridges separate by shallow swales.

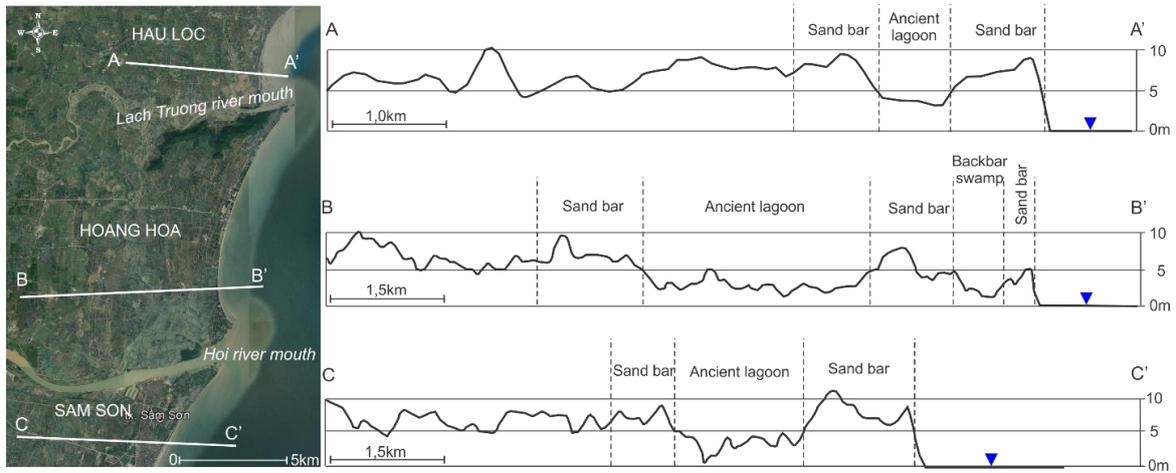


Figure 10. Cross-section - perpendicular to the coast [Source: Google Earth (2020)]



Figure 11. Lagoon plain: surface (A) and sediment (B) [Source: Nguyen Minh Quang (2020)]



Figure 12. Field of crops on the strand plain [Source: Nguyen Minh Quang (2020)]

The strand plain is made up principally of sand (60.2–90.8%) with grain-size parameters: Median size (Md): 0.087–0.142 mm, sorting coefficient (So): 1.26–2.46) (table 1). The surface of the strand plain is covered by arable soil of 0.4 m thickness with finer sediment composed of clay (33.0–56.2%) and silt (34.2–64.0%). The clay minerals composition consists of kaolinite (24.2%), illite (51.8%), chlorite (13.4%) and smectite (10.5%). Total mineralogical analysis showed quartz (70%), mica (13%), feldspar (6%), chlorite (< 1%), kaolinite (6%), smectite (3%), magnetite (< 1%). The strand plain distributed in Hoang Phuc, Hoang Thang and Hoang Chau commune - Hoang Hoa district and Quang Dinh, Quang Duc, Quang Nhan, Quang Loc commune - Quang Xuong district (figure 12).

#### Supratidal flat

The supratidal flat is flooded during the tidal maxima or storms. This area is vegetated by halophilous species such as *Imperata cylindrica*, *Pragmites australis*, *Cynodon dactylon*, *Ipomoea pes-caprae*,... Currently, in Nga Son, the supratidal flat is reclaimed for

sedge cultivation (figure 13). The sediment is characterized by clay (62.1%), silt (37.9%) and plant residues in brown, gray color. Sedimentological parameters: Median grain-size (Md): 0.003mm, poor sorting (So): 3.91), skewness (Sk): 0.83 (table 1). The results of physicochemical analysis represent a swamp environment with pH: 5–6; Eh: (-20)–60 mV; Kt: 0.9–1.3; Fe<sup>2+</sup>S/Corg: 0.1–0.25. In the composition of clay minerals, kaolinite and illite are in the majority, monmorinollite is absent or present with insignificant quantity. Microfossils are found abundantly in the sediment, especially diatoms, spores, and pollen. Diatom species include *Achnanthes brevipes*, *Achnanthes* sp., *Diploneis smithii*, *Coscinodiscus lacustris*, *C. asteromphalus*, *C. lineatus*, *Cyclotella stylorum*, *Cyclotella striata*, *Cymbella affinis*, *Cymbella cymbiformis*, *Cymbella ventricosa*, *Epithemia zebra*, *Eunotia monodon*, *Gomphonema longiceps*, *Synedra* sp.,... For spore and pollen, the common species include *Sonneratia* sp., *Hibiscus* sp., *Rhizophora* sp., *Acrostichum* sp., *Taxodium* sp. [8].



Figure 13. Sedge field on supratidal flat in Nga Son district [Source: Nguyen Minh Quang (2020)]

#### Intertidal flat

The intertidal flat is distributed along the coast of Nga Son and Hau Loc districts. It consists of dark gray sandy silt clay, favoring mangrove development (figure 14). The flood/ebb tides making an alternation of finer (clay, silty clay) and coarser (sand, silty sand) grained deposition in 1–2 mm thick beds

resulting in the structure of tidal bedding, even flasher or lenticular bedding, depending on clay and sand contents. Spore and pollen are found abundantly in sediments with the presence in a large number of mangrove species such as *Acanthus* sp., *Acroctichum* sp., *Rhizophora* sp., *Bruguiera* sp., *Kandela* sp., *Avicenia* sp., *Aegicera* sp., *Sonneratia* sp. The mangrove

species were abundant and diverse, taking a high percentage in the palynological spectrum of tidal sediments and resulting in specific peats with branches and leaves of mangroves. Diatoms found in the intertidal flat are mainly the saline and brackish water species such as *Actinocyclus ehrenbegii*, *Caloneis bannajensis*, *Campylodiscus cf. daemelianus*, *Coscinodiscus lacustris*,... The freshwater took insignificantly account. Statistically the intertidal sediments had a median size (Md) of 0.003–0.0054 mm and very bad to moderate sorting (So): 2.78–

4.43 (table 1). An environment of deltaic tidal flat is indicated by physicochemical parameters as follows: pH: 5.5–7.5; Eh: (-20)–60 mV; Kt: 1.3–1.5;  $Fe^{2+}S/Corg$ : 0.15–0.2. The clay minerals composition consists of kaolinite 18.8%, illite 65.3%, chlorite 15.0% and smectite 1.0%. Total mineralogical analysis showed that quartz (45%), mica (28%), feldspar (4%), chlorite (6%), kaolinite (7%), pyrite (1%), amphibole (2%), pyroxene (2%), hematite (1%), gibbsite (2%), sepiolite (< 1%), gypsum (1%).



Figure 14. Intertidal flat: with mangrove forest (A); with creature corpse (B)  
[Source: Nguyen Minh Quang (2020)]

### Subtidal flat

The dynamics of tidal current attains its maximum at the depth equivalent to the tidal amplitude, dissipating when going landward shallower depth because of bed friction. As a result, the sediment in the subtidal zone influenced by the tidal current is deposited with the grain size finning landward, i.e., coarser grain is far shore and vice versa finer is near

shore. The subtidal flat is virtually always underwater except during the lowest of spring tides. It is distributed in the coastal of Nga Son and Hau Loc districts (figure 15). The subtidal flat consists of sand (48.9–71.4%) and silt (44.4–17.7%). The sediment has a median size (Md): 0.062–0.08 mm, moderate to good sorting (So): 1.28–2.23).



Figure 15. Subtidal flat in the coastal of Hau Loc district [Source: Nguyen Minh Quang (2020)]

### Mountainous terrain

The mountainous terrain is scattered along the Thanh Hoa coastal area. Its northern and southern sides are the original rock ranges. The terrain develops on the bedrock of limestone (distributed in the North and Southwest of Thanh Hoa city, the Northwest Ham Rong) with a slope of 45°; basalt of Cam Thuy formation (P<sub>2ct</sub>) in Do and Quyet Thang mountains with slope of 20–30° and elevation over 150 m [1, 4]; granite of Muong Lat Complex (γaC<sub>1</sub> mL) in Sam Son with slope over 25°; mica quartz schist of the Nam Co Formation (PR<sub>3</sub> -ε<sub>1nc</sub>), in Hoang Hoa mountain with an elevation of 190.5 m [1, 13].

### DISCUSSION

The coastal zone of Song Ma delta, from Hoang Hoa district, Sam Son city to Quang Xuong district, is geomorphologically characterized by strand plain, dunes, and interdune swamps, dominated by wave dynamics [3–5, 11, 14–21].

The seaward accretion strongly occurs in the river mouths of Hoi, Lach Truong and Len [22–24]. Wave dynamics dominate the Hoi and Lach Truong in cusped shapes, and the Len is an estuary influenced by tidal dynamics.

Bank erosion in the Ma river system results in landforms such as point bars, channel bars, levees, and flood plains, distributed in narrow areas along the rivers. They were formed after the formation of Song Ma plain being relatively stable and unaffected by sea. At that time, the horizontal erosion of the rivers led to the development of the point bars and channel bars. The natural levee and flood plain formed sediment deposition in flood water flowing over the river bank. This sedimentation is differentiated in grain size, with coarser material near the bank forming natural levee and the finer far further, creating a floodplain.

For the coast of Nga Son and Hau Loc, due to the protection of Hon Ne islet and the accretion flats of Binh Minh (Kim Son), and Rang Dong (Nghia Hung), the dominant role of wave dynamics is reduced and replaced by tidal dynamics, expressed by the presence of tidal landforms such as supratidal, intertidal and subtidal flats.

The deltaic plain is formed when the subsidence rate is lower than the sedimentation rate. This formation began by the end of the Early Holocene when the sea level rise slowed down, approaching zero, changing to marine regression in Middle Holocene [10]. From the end of the Early Holocene to 3,000 years Bp, the delta expanded enormously toward the sea, forming a large strand plain covering most of the coastal zone of the Song Ma delta, including dunes and interdune swamps after 3,000 years Bp.

### CONCLUSION

The coastal area of the Song Ma delta, except the small parts of denuded mountainous remnants, is characterized by 12 morpho-sedimentary units. They are the depositional relief formed by the river, wave and tide.

1. The river-formed morpho-sedimentary units are 1) Point bar characterized by grain size fining upward in sediments; 2) Channel bar mainly composed of gray sand, silt; 3) Levee formed on two sides of the channel with the composition of yellow gray sand, silty sand; 4) Flood plain with silty clay or clayey silt distributed in a narrow area along the rivers.

2. The wave-formed morpho-sedimentary units are 5) Dunes extending in narrow strip quasi-parallel to the coast; 6) Interdune swamps lower than surroundings, consisting of clay, silt, and sand in small thickness; 7) Sand beach with good sorted and very high content of sand, distributed continuously in the south of the study area; 8) Lagoon plain in form of narrow strip, made up of dark gray silty clay with organic humus; 9) Strand plain covering widely in the study area.

3. The tide-formed morpho-sedimentary units, mainly distributed in the northern part of the study area, include: 10) Supratidal flat consisting of clay and silt; 11) Intertidal flat with alternation of finer (clay, silty clay) and coarser (sand, silty sand) grained deposition in 1–2 mm thick beds; 12) Subtidal flat with the main component of sand and silty sand.

4. The cusped mouths, the landforms along and parallel the shoreline such as generations of dunes, interdune swamps, sand beaches,... all this shows that wave dynamics dominate the Song Ma delta.

5. The coastal area of the Song Ma delta is characterized by the association of strand plain, dunes, swamps, sand beach, and cusped shape of the river mouth, indicating wave dynamics dominating the Late Holocene evolution of the Song Ma delta.

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