Land-ocean interaction in modern delta formation and development: A case study of the Pearl River delta, China

LI Chunchu (李春初), LEI Yaping (雷亚平), HE Wei (何 为) & DAI Zhijun (戴志军)

Institute of estuarine and coastal studies, Zhongshan University, Guangzhou 510275, China
Correspondence should be addressed to Li Chunchu (e-mail: eeslyp@zsu.edu.cn)

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Abstract The distinctive characteristics of the modern Pearl River delta formation and development are divided phases, diversity and imbalance in spatial and temporal. The delta was moving seaward gradually in a long period after the last Holocene glacial stage and the ancient drowned Pearl River estuary was predominated by tide. The delta was expanding quickly since fluvial force was turned to be leading status about 2500 years ago. The sediment grain size was changing longitudinally from coarser to finer. As well as the finer sediment may be reworked and redistributed shoreward by tidal current nearby the river mouth. And the fluvial-dominated delta is developed by the mutual deposition reflected in the vertical direction. According to the spatial difference of land-ocean interaction, the main body of the Pearl River delta which is the fluvial-dominated and protruding seaward is coupled with or concomitant with the estuaries and tide-dominated deltas which are adjoined to both sides of the main part like two wings.

Keywords: fluvial-dominated delta, tide-dominated delta, wave-dominated delta, Land-Ocean Interaction in the Coastal Zone (LOICZ).

The Land-Ocean Interaction in the Coastal Zone (LOICZ) is an important field of the present global change research[1,2]. Deltas are the gifts of river to the sea[3]. Delta sedimentary facies are formed by the mutual deposition of fluvial and oceanic forces. And it is the right place for the LOICZ studies. However, up to now, it does not acquire definite and integrated knowledge on the coupling and interaction of fluvial and oceanic forces and the sedimentary processes during the formation and development of modern delta. In this paper, by the formation and evolution of the Pearl River delta, these problems are discussed.

1 Types and characteristics of modern delta

Modern delta is deposited by input river sediment discharge in the receiving basin after the finish of Holocene transgression about 5000—6000 aBP. The factors impact on the formation and development of modern delta can be classified into fluvial force (derived from land environment) tide and wave (stand for oceanic forces). According to the importance of these three types of hydrodynamic effect, modern deltas can be divided into three primary types, i.e. fluvial-dominated, tide-dominated and wave-dominated delta[4]. The abundant sediment discharge develops the architecture of fluvial-dominated delta, in which the most marked characteristic is that digitate or

lobate sand bodies extend along the straight distributary channels. It is distinct of the three layers of vertical sedimentary facies structure, i.e. silt and mud prodelta at the bottom, the center layer of delta front with coarser-grained sandy bodies and the clay deltaic plain at the top layer with coaly mud marsh facies deposition. Because low fluvial energy and little solid discharge, especially the bedload run out into the sea, the tide-dominated delta is generally formed by the suspended sediment derived from the large river nearby, which are reworked and transported shoreward by flood tidal current. Therefore, delta of this type is mainly constructed by fine silt and clay without clearly three layers of vertical sedimentary structure like that of the classical delta. There are a lot of sinuous and winding tidal channels and creeks on the deltaic plain. For example, the Yangtze River delta has radiated tidal-formed sand bodies[5]. It is caused by removing seaward of Holocene sand bodies that preexisted in the drowned estuarine bed during transgression, therefore, it is not certain that the sediment is directly and completely from bedload transport of the upper reaches[6]. Wave dominated delta is characterized by wave-shaped sand bodies, i.e. beach-ridge and barriers islands, which are parallel to the coastline.

2 Characteristics of formation and development of modern Pearl River delta

Studies have shown that the head of the ancient drowned Pearl River estuary was not a simply shoreline but a complicated geomorphology zone by the end of Holocene transgression. There was not only an ancient coastline marked by wave-formed erosion and accumulation topography but also a seawater intrusion limit which was a landward concave line without a wave-formed mark. The latter is the boundary between marine and alluvial deposition[7] or seawater intrusion northernmost limit[8]. The formation of the modern Pearl River delta is caused by sediment propelled from three larger rivers (i.e. West, North and East rivers) as well as two smaller rivers (i.e. Liuxihe and Tanjiang rivers). The input sediment is deposited in ancient bay, the mean tidal range is only 1.1 m (see fig. 1). The Pearl River is the largest one in South China. The drainage area is $45.26\times10^4 km^2$. Mean annual discharge and mean annual sediment transportation are $3.086\times10^{11}m^3$ and 8.694×10^7t, respectively. Among these input rivers, the largest one is the West River that is 2214 km long. Due to the difference of water and solid discharges of input rivers and the spatial imbalance of regional hydrodynamic environments in different developmental phases, the characteristics of the modern Pearl River delta are as follows.

2.1 Developmental phases

Many studies[7—12] had obtained the same conclusion that the modern Pearl River delta developed quite slowly in a long period after the end of Holocene transgression in the head of ancient bay. From 6000 to 2500 aBP, the aggradation was limited in the region between the ancient coastline and Holocene seawater upstream intrusion limit. With the gradual development of civilization and exploitation in South China, the sediment discharge was increasing since the Qin and Han dynasties. The Modern Pearl River delta began to extend seaward markedly over the

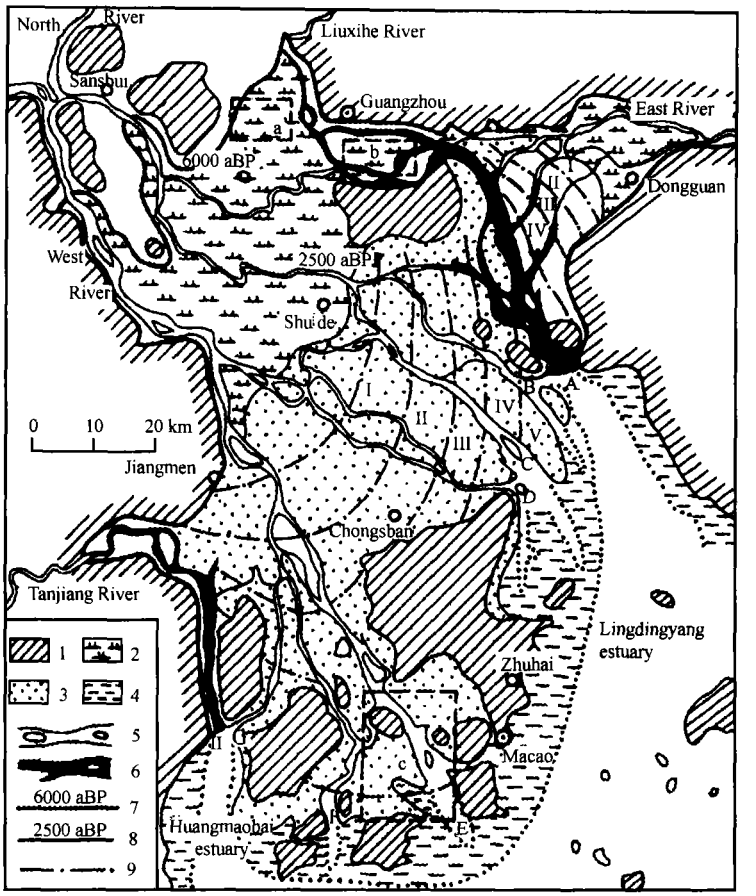

Fig. 1. The sketch map of modern Pearl River delta development. 1, Hills; 2, earlier delta area from 6000 to 2500 aBP; 3, delta area since 2500 aBP; 4, subaqueous delta; 5, river channel; 6, tidal channel; 7, northernmost ancient coastal line; 8, deltaic coastline in 2500 aBP; 9, delta developmental isochrone. A, Humen inlet; B, Jiaomen mouth; C, Hongqili mouth; D, Hengmen mouth; E, Modaomen mouth; F, Jitimen mouth; G, Hutiaomen mouth; H, Yamen inlet.

ancient coastline. After the Tang and Song dynasties, the delta developmental rate was speeding up quickly. During the Ming and Qing dynasties, mean annual extending rate is about tens meters. And nowadays, it is over 100 m. Therefore, there are two distinct phases in the developmental process of modern Pearl River delta. One is the long-term earlier slowly developmental phase. The other is quickly developmental phase since 2500 aBP.

2.2 Varied formational types

During the developmental process of modern Pearl River delta, because of different hydrodynamic and sedimentary environments in different phases and regions, it can be classified into four formational delta types, i.e. tide-dominated, fluvial-dominated, fluvial-wave compounded deltas and tidal inlet deposition[7]. Now, the distributing and features for each are:

(1) The tide-dominated delta is located in the north of modern Pearl River delta, including the

deltaic plain formed at bay head during the earlier slowly developmental phase and the regions of extended reaches of the Tanjiang and Liuxihe rivers, which are from Shuikou down to Yamen and from Guangzhou down to Humen, respectively. The primary feature is that most sediment is clay or fine silt with saltwater or semi-saltwater aquatic organism fossils. Another marked feature is that there are many sinuous and winding tide-formed channels (called Jiao in local dialect) on the deltaic plain. The latter feature can be seen distinctly in the aerial photograph (fig. 2), but it can hardly be found in other area of the whole Pearl River delta.

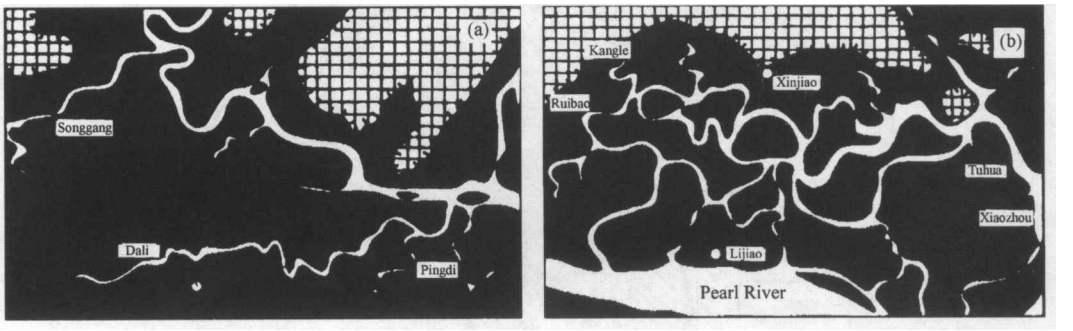

Fig. 2. The sinuous and winding tidal channel and creek in tidal-dominated deltaic plain. For the location see enframed areas a and b in fig. 1. The grid area is hills or terrace and the black area is tide-dominated deltaic plain.

(2) The center and south part of the Pearl River delta belongs to fluvial-dominated delta. It is the regions that are quickly expanding seaward since 2500 aBP, which are characterized by network distributary channels and run out to the sea through six distributary river mouths finally, such as Jiaomen, Hongqili, Hengmen, Modaomen, Jitimen and Hutiaomen from east to west along the deltaic coast. Lobate or digitate sand bodies are developed well paralleling with riverbanks in the alluvial plain. And the vertical three layers stratigraphic structure is very distinct[13] (see fig. 3).

(3) The fluvial-wave compound dominated delta refers to the region nearby the Modaomen distributary mouth. It is the most protrudent point of the Pearl River delta and runs out to the inner shelf sea and is impacted by relatively strong wave action, where there is not islands barrier any longer. The new-formed deltaic plain is characterized by beach-ridge topography in some degree.

(4) The deltaic plain formed by tidal inlet deposition needs certain landform and hydrodynamic conditions like Humen tidal inlet with tidal-dominated inside the Shiziyang channel and outside the Lidingyang estuary. Due to the geomorphydynamic structure of Humen tidal inlet, it develops tidal inlet sedimentary geomorphyological system consequently[9]. In other words, there is a deep channel scoured by strong tidal current, and the eroded sediment is transported by flood and ebb tidal current inside and outside of the inlet to form radiate tidal sand ridges. It can also be regarded as one kind of tide-dominated delta.

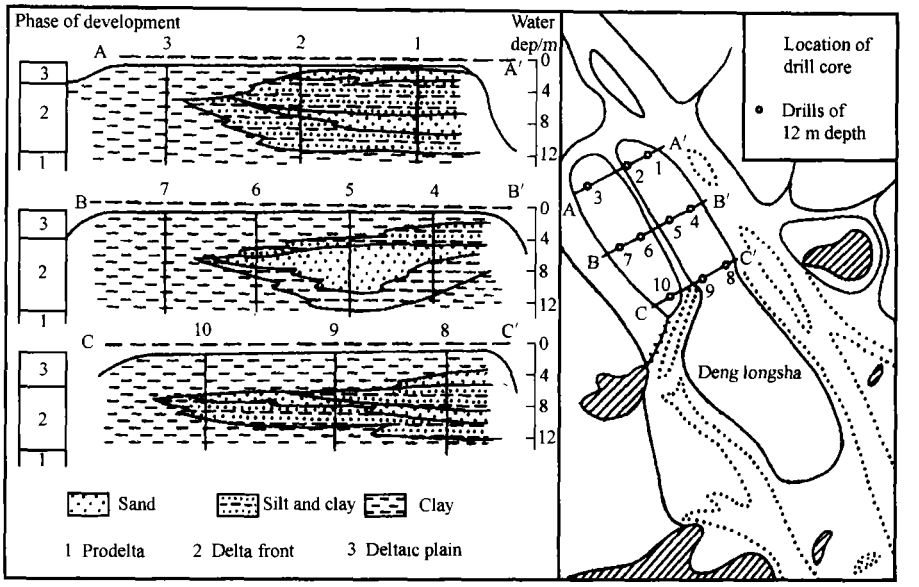

Fig. 3. Delta sedimentary architecture of Denlongsha shoal in the Modaomen mouth (for the location see enframed area c in fig. 1).

2.3 Spatial developmental imbalance

The East River delta, part of the whole modern Pearl River delta, develops southwestward separated by the Shiziyang tidal channel. However, the West and North River complexed delta, the main body of Pearl River delta, extends from northeast to southeast. With the quickly extending of the complex main body southeastward, the two smaller river mouths, Liuxihe and Tanjiang rivers, are driven to extending seaward accordingly. The sum of discharge and sediment transportation of West and North is 89.9 and 95.8% of the whole Pearl River network system, respectively. It is much larger than that of the Liuxihe and Tanjiang rivers. Therefore, It causes the spatial developmental imbalance in the whole complex Pearl River delta. The West and North rivers delta expands seaward quickly whereas the sedimentary systems of Luixihe and Tangjiang rivers develop seaward slowly. The West and North rivers delta is a protrudent fan-shaped delta whereas the extending reaches of Liuxihe and Tanjiang rivers are concave landward tidal channels and estuaries. Distributary mouths of West and North rivers extending seaward are propelled by fluvial energy and sediment transport of their own, which belongs to fluvial-formed distributary with fluvial-dominated river mouths. Whereas Shiziyang and Yinzhouhu tidal channels extending toward Humen and Yamen tidal inlets are driven by the sideways deposition caused by flood tidal current carrying sediment derived from other rivers (such as West, North and East rivers). And it is not caused by the fluvial dynamic and sediment transport of the Liuxihe and Tanjiang rivers. The elongations of these tidal channnels are driven by other rivers' sedimentary system nearby one or both sides and the channels are occupied by flood tidal prism from outer sea rather than discharge of its own input river[14]. Tidal current dominates these channels all the time, and the flood current

can flow upstream very far away from the inlet. Therefore, they are essentially tide-formed channels and tide-dominated estuaries[15] (Humen and Yamen).

3 Discussions and results

The characteristics of formation and development of modern Pearl River delta reveal a lot of information on the LOICZ. Combined with studies in other deltas, it can be concluded some important conception and knowledge on the LOICZ during the developmental processes of modern delta.

3.1 Coastal environment and the LOICZ situation by the end of last transgression

During the period of Holocene transgression, the fluvial force was retreating while the oceanic tidal and wave forces were expanding landward. As the delta was eroded and destroyed, the deltaic coastline was moving backward. By the end of the transgression in 5000—6000 aBP, the delta coastal environment was either tide-dominated estuary where the tidal range was higher or barrier-lagoon system formed by wave reworking the remnant sediment where the tidal range was lower. By the end of the last transgression, it was a noteworthy feature that there were ancient shoreline and the behind seawater intrusion limit in the bay head of the drowned Pearl River estuary. It probably had been barrier-lagoon system environment. At that time, the ancient Pearl River estuary drowned onshore a long distance. Furthermore, there were many sporadic rocky islands in the bay. The wave energy was not so strong to develop large-scale wave-shaped barrier islands.

3.2 Bay head gradual aggradation and the LOICZ situation in the transition period

Modern Pearl River delta was slowly developing for a long period after the end of Holocene transgression. The reason explicated by Li Chunchu et al. in 1981 is as follows. It was an essential transition period in the ancient Pearl River estuary evolution from the retrogradation process during the transgression to the progradation process after the transgression. After the transgression disaster, under the relatively steady sea level condition, the Pearl River delta could not begin to expand seaward until it underwent a period to adapt and adjust to the new environment. During this transition period, influenced by the transgression aftereffects, river sediment, especially the bedload is retarded by the backwater and accumulated along the riverbed upstream the tidal current limit line. As a result, at that time, there was not considerable extending of river mouth, and the deltaic coastline was stable. The fluvial energy could not move seaward markedly and turns into the leading force in the estuary. Sedimentary processes were controlled by tide action or compound of tidal and fluvial forces which formed the delta and deltaic plain with tide-dominated features in some degree. This viewpoint is also applied to explaining the same transition stage of gradual infilling in the Hanjiang River delta[9] and the Yangtze River delta[6] in China. Deposition in the Hanjiang River delta was infilling the lagoons behind the arc of barrier islands. The deposition in the Yangtze River delta was infilling the ancient drowned estuary. However, it displayed lagoon deposition at both sides of the ancient Yangtze River estuary. It is universal that delta de-

velopment undergoes the gradual aggradation transition stage. And nowadays, because of lack of solid discharge, many estuaries or backbarrier lagoons are not filled up yet since the end of the Holocene transgression.

3.3 The occurrence and LOICZ of fluvial-dominated delta

The occurrence of fluvial-dominated delta is the result of the sequential progradation when the drowned estuary or backbarrier lagoon is filled up by input sediment and the fluvial force turns into the dominator. The LOICZ in fluvial-dominated delta development is incarnated in two aspects as follows. One is the well-known gravitational different settling of sediment-laden river flow downward to the sea. In other words, the river mouth is controlled by effluent jet. With the advancing and expanding of effluent jet and suspension-laden plume vertically and laterally, the solid substance propelled from the river mouth is settling out and deposited on the slope where the sediment grain size is changing smaller seaward. Consequently, fine silt and clay prodelta and delta front with lobate or digitate sand bodies are formed[16]. The other is reworking and redistributing shoreward of the fine grain sediment, which is easy to be ignored. At both sides of the effluent jet, the onshore compensating current area, flood tidal current transport and redistribute the sediment resuspended by wave and tidal action, which had been deposited on the delta slope. This onshore transportation and accumulation is one cause of interdistributary bays infilling and deltaic plain development. It had shown that this sedimentation is more remarkable in low water seasons, neap tide and flood tidal phase[13]. If the hydrodynamic environment is not suitable for the resuspended sediment redistributing and deposition, for example, drifted away by strong longshore current, the fluvial-dominated delta has fully developed sandy subaqueous and subaerial levees while the muddy plain is not adjoined to the protruding digitate sand bodies. This may be one development mechanism of bird-foot delta.

3.4 LOICZ reflected by coupling and coexistence of different types

With modern delta expanding seaward, the head part of fan-shaped delta belongs to fluvial-dominated type. However, one or both sides of head part with small branch (including single small stream's runoff to the sea) tend to develop tide-dominated or wave-dominated delta. This natural phenomenon gives an appropriate expression to the coupling and interaction between ocean and land forces in the whole modern delta developmental process. It is a lively exhibition in the Pearl River delta that there is the coexistence and complex of river channel and tide-formed channel as well as protruding fluvial-dominated fan-shaped delta and concave landward tide-dominated estuary (fig. 1). The author[17] found the same positive-negative coupling phenomena when he studied the abandoned Yellow River delta in the north of Jiangsu Province in 1997. The region from Yuntiguan down to river mouth running through by the abandoned Yellow River channel is fluvial-dominated deltaic plain. However, the region of sinuous lower reaches of the Guanghe and Sheyanghe rivers neighboring both sides of the abandoned Yellow River delta is a tide-dominated delta, in which the flood tidal current excursion is very far upstream along the

two typical tide-formed channels (arriving at Xiangshui and Hali port respectively). As another example, it develops a wave-dominated delta at the western side of trunk distributary mouth of the Nandu River in Hainan Island, South China[17]. Tide-dominated or wave-dominated delta adjoined to the main distributary mouth can also be seen in many deltas in the world, such as Gangs-Brahmaputra[18], Nile[19], Ebro[20], Nigeria[21]and Red River[22] deltas. The formation of tide-dominated or wave-dominated delta at one or both sides of the main distributary mouth not only depends on tide or wave action but also relates with the magnitude and grain-size of sediment transporting out of the river mouth. If the sediment consists mainly of fine-grain suspension substance, it tends to develop a clay and silt tide-dominated delta at one or both sides of the river mouth. If large amounts of coarser bedload (such as fine, medium and coarse sand) run out of the river mouth, it tends to develop a wave-dominated delta with reworking and redistributing the sediment by wave action.

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