CHARACTERISTICS AND FORMATION OF LATE QUATERNARY INCISED-VALLEY-FILL SEQUENCES IN SEDIMENT-RICH DELTAS AND ESTUARIES: CASE STUDIES FROM CHINA

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ABSTRACT: Four sediment-rich incised-valley systems in China, which underlie the Luanhe fan delta, the Changjiang delta, the Qiantangjiang estuary, and the Zhujiang delta, are examined based on over 800 drill cores. These four systems are of different shapes and sizes, and are located in different tectonic zones with different tide regimes ranging from microtidal to macrotidal. Because of the abundant fluvial sediment supply and relative dominance of river forcing, sediments in the modern Qiantangjiang and paleo-Changjiang estuaries display a fining-seaward trend. This is different from the classical estuarine facies model of coarse bay-head delta, fine central basin, and coarse bay-mouth deposits. The abundant sediment supply also results in the presence of relatively thick transgressive successions in the overall incised-valley fill. The transgressive succession constitutes more than 50% of the total strata thickness and approximately 60–70% of the total sediment volume within the valley. The river-channel facies in the transgressive succession was formed by retrogressive aggradation during postglacial sea-level rise. Retrogressive aggradation extends far inland beyond the reach of flood-tidal currents, and, therefore, no marine signatures were found at the lower portion of the incised-valley fill. The regressive succession in the incised-valley systems consists of fluvial facies or tidal facies and deltaic facies, and was developed as the estuary filled and evolved into a progradational delta. The tide-dominated facies tends to be developed in the apical areas of funnel-shaped estuaries, such as the modern Qiantangjiang and paleo-Changjiang estuaries.

Four generalized facies successions (FS-I, FS-II, FS-III, and FS-IV) are recognized within the valley fill. An idealized schematic incised-valley fill contains FS-I at the coastline region, FS-II and FS-III in the middle, and FS-IV at the apex area of the delta/estuary, reflecting a decreasing marine influence and increasing terrestrial contributions. The preservation of multiple incised-valley-fill sequences is controlled by the different regional tectonic characteristics. Vertically superimposed valleys are preserved beneath the Changjiang delta, whereas the Luanhe fan delta is characterized by lateral juxtaposition of valley as a result of channel switching.

INTRODUCTION

Incised-valley deposits form hydrocarbon reservoirs of economic importance in many parts of the world (Zaitlin et al., 1994). They also contain valuable information on regional depositional processes and sea-level changes. Numerous studies of incised-valley deposits have been conducted over the last two decades (e.g., Posamentier and Vail, 1988; Posamentier et al., 1988; Van Wagoner et al., 1990; Dalrymple et al., 1992, 1994; Allen and Posamentier, 1993; Pattison and Walker, 1994; Zhang and Li, 1994; Nichol et al., 1996; Gupta, 1997, 1999; Blum and TÖrnqvist, 2000; Ardies et al., 2002; Li, C.X., et al., 2002; Plint and Wadsworth, 2003). Fisk (1944) and Fisk and McFarlan (1955), on the basis of the studies of the Mississippi delta, suggested that the filling of incised valleys resulted from fluvial sedimentation coping with sea-level rise. Zaitlin et al. (1994) conceived a widely accepted and applied model for the development of incised-valley-fill sequences during a transgression and the subsequent regression.

Four sediment-rich incised-valley systems in China, which underlie the Luanhe fan delta, the Changjiang delta, the Qiantangjiang estuary, and the Zhujiang delta, are examined in this study. The rivers feeding the studied deltas and estuary originate from mountainous areas and are strongly influenced by the monsoon. These result in very large water and sediment discharges (Li, C.X., et al., 1991; Li, C.X., et al., 2004). The abundant water and sediment supplies have a significant influence on the incision and infilling of the valleys. The control of late Quaternary sea-level change leads to a similar overall trend in the formation and infilling of the incised valleys. However, different tectonic, morphological, hydrological, oceanographical, substrate, and sediment properties result in different local environmental conditions and facies characteristics. The stretch of the incised valleys examined in this study coincides with segment 2 and the outer part of segment 3 in the model of Zaitlin et al (1994).

The main goal of this paper is to summarize the similarities and differences in the Late Quaternary incised-valley fill underlying several sediment-rich deltas and estuaries in China. A general depositional model is developed to summarize the processes of valley incision and infilling that reflects the specific characteristics of the hydrodynamics and morphodynamics.

REGIONAL SETTINGS AND INCISED-VALLEY CHARACTERISTICS

Regional Settings

The Chinese coast extends through several tectonic uplift and subsidence zones (Fig. 1). Grabens commonly exist within the uplift areas, such as those underlying the Zhujiang and the Hanjiang deltas (Li, C.X., et al., 1991; Huang et al., 1982; Li, P.R., et al., 1991). Major Chinese rivers, including the Changjiang, the Huanghe, and the Zhujiang enter the marginal seas at coastal subsidence areas or by way of the grabens. The incised valleys that underlie three deltas and one estuary are studied here. From

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FIG. 1.—Study areas and their general tectonic characteristics.

north to south, they are the Luanhe fan delta, the Changjiang delta, the Qiantangjiang estuary, and the Zhujiang delta (Fig. 1). These four systems were selected because they represent a variety of tectonic and hydraulic conditions, in addition to abundant available data. River discharge and suspended-sediment load differ among the examples by up to two orders of magnitude, with tidal ranges varying from microtidal to macrotidal (Table 1). On the basis of the classification of deltas and estuaries (Galloway, 1975; Dalrymple et al.,1992), the Qiantangjiang estuary is tide-dominated, the Zhujiang delta is river-dominated, the Changjiang delta is mixed river- and tide-dominated, and the Luanhe fan-delta is mixed river- and wave-dominated (Huang et al., 1982; Li, C.X., 1985, 1986; Li, C.X., et al., 1991; Li, C.X., et al., 1993; Zhang and Li, C.X., 1996; Long, 1997; Li, C.X., and Wang, 1998; Li, C.C., 2004).

A large portion of the continental shelf in the study areas was exposed during the last glacial maximum, when sea level was approximately 120 to 150 m below the present sea level (Zhu et al., 1979; Wang, Y., 1996). Numerous cores have revealed that incised valleys exist below each of the modern deltas and estuaries (Huang et al., 1982; Li, C.X., 1985; Li, P.R., et al., 1991; Li, C.X., et al., 1993b; Zhang and Li, 1996; Li, C.X., et al., 1996; Li, C.X., et al. 2002; Long, 1997; Li, C.X., and Wang, 1998).

The Incised Valley in the Changjiang Delta Area

The Changjiang delta is located in a tectonic subsidence zone controlled by W–E faults along both sides (Chen, Z.Y., and Stanley, 1995). The basin tilts slightly from southwest to northeast, reflecting an increase in subsidence rate from the margin to the center (Wu and Li, 1987). The Changjiang River enters the coastal plain through the Zhenjiang–Yangzhou hilly area, extending eastward and covering a coastal plain of approximately 22,800 km^2 (Li, C.X.,1986). The studied subaerial Changjiang delta can be divided into a main delta body and two flanking areas (Fig. 2; Li, C.X., et al., 2002). The Quaternary unconsolidated sediments are 100 to 450 m thick in the studied section. The last glacial Changjiang incised valley, extending southeastward, is approximately 250 km long, 10 to 60 km wide, and 60 to 100 m deep. The thickness of postglacial deposits increases seaward, with the maximum located in the incised valley (Fig. 3). The paleosol formed on the flanking interfluves during the last sea-level lowstand, representing the interfluve sequence boundary, is typically 3–25 m below the present surface and approximately 50 to 60 m higher than the corresponding erosional surface at the base of the incised valley (Li, C.X., and Wang, 1998).

The Incised Valley in the Qiantanjiang Estuary Area

The Qiantangjiang estuary has a typical funnel shape. Its southern side overlies bedrock hills with colluvial deposits in the valleys, whereas the northern side covers the coastal plain adjacent to the southern flank of the Changjiang delta. Tidal range increases landward from the mouth, reaching a maximum of 8.9 m at Jianshanzui Station (Fig. 4), where one of the world's largest tidal bores occurs. Tidal-current velocities increase landward along with the increase of tidal range. A maximum flood-tide velocity of nearly 4.0 m/s was measured at Jianshanzui (Table 2). Flood currents are stronger along the northern side of the estuary, whereas ebb currents tend to be concentrated along the southern side (Fig. 5). The archipelago of bedrock islands at the entrance

TABLE 1. —General background information on the studied deltas and estuary.

	Luanhe Fan Delta	Changjiang Delta	Qiantangjiang Estuary	Zhujiang Delta
River length (km)	1200	6300		2214
Water discharge ($10^9 m^3$)	4.6	924	31.2	326
Suspended load (10^6 tons)	19.0	486.0	9.4	83.4
Suspended load / Water discharge (10^6 ton /$10^9 m^3$)	4.2	0.53	0.30	0.26
Delta (estuary) area* (km^2)	2100	22,800	7100	9600
Tidal range (m)	1.4–1.5	2.6–4.5	5.0–8.9	1.1–3.4
Tectonic position	Uplift	Subsidence	Graben in uplift belt	Transition from uplift to subsidence

* Delta area is the area of the subaerial delta. Estuary area is the area from the estuary mouth to the apex.

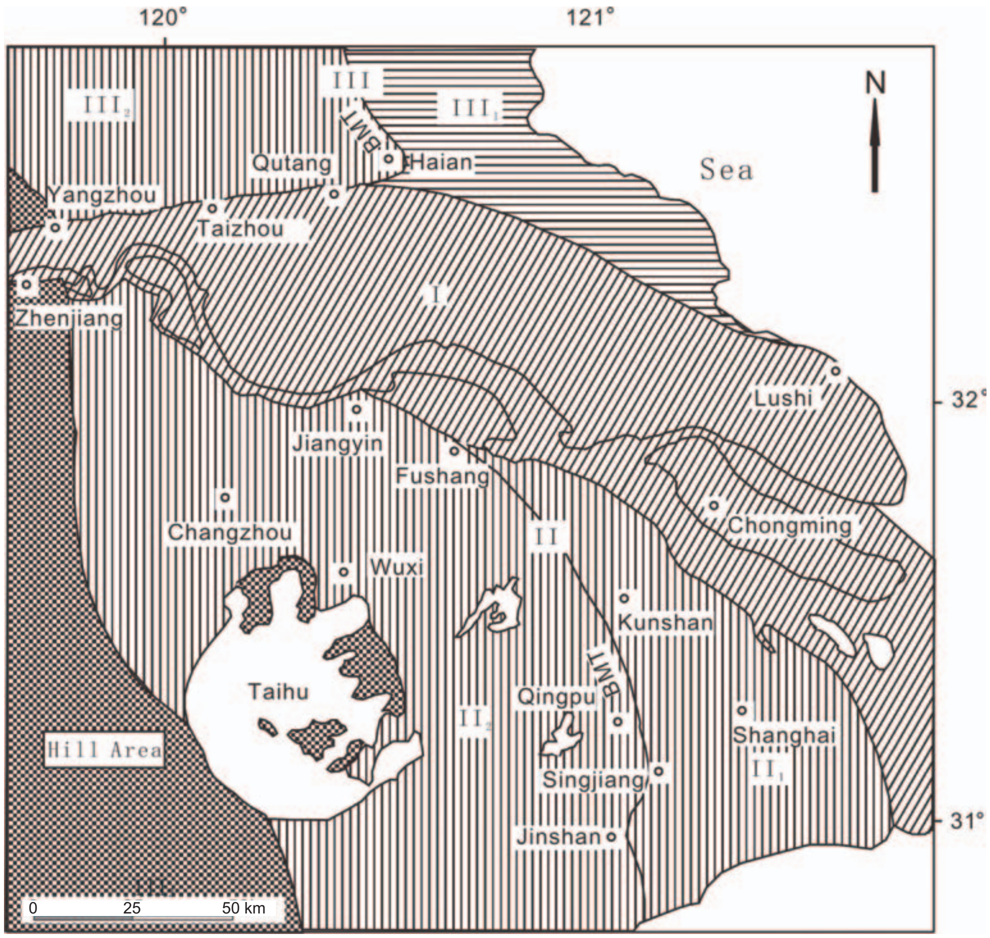

FIG. 2.—Changjiang incised valley (I) and paleo-interfluves along the two flanks (II and III). II1: Frontal zone of southern flank; II2: Back zone of southern flank; III1: Frontal zone of the northern flank; III2: Back zone of the northern flank; BMT: Boundary of maximum transgression (After Li et al., 2002).

significantly damps the incident wave energy. Tidal currents in the vicinity of the islands are locally intensified, resulting in subaqueous sandy sediments around them. Wave action along the seaward side of the islands leads to the development of coarse-grained pocket beaches. This locally distributed coarse sediment does not substantially alter the overall landward coarsening trend in the estuary as a whole (Zhang and Li, 1996).

The Qiantangjiang estuary is located in a transition zone between tectonic uplift to the south and a zone of subsidence to the north. Its incised valley, which has a shape similar to that of the modern estuary, is approximately 50 to 100 m deep and 10–100 km wide. Near the apex, two or three tributary valleys are present, separated by buried bedrock and hills (Figs. 6, 7). These valleys converge into one main valley downstream. This valley was incised into the undulating bedrock or the weathered rock along the southern side and in the apical area. Along the northern side and seaward end, the incision developed in unconsolidated Quaternary deposits.

Incised Valley in the Luanhe Fan-Delta Area

The Luanhe River (Fig. 1) originates in a mountainous area. Active tectonic tilting occurs in the study area, with uplift occurring at a higher rate in the west than in the east. The river flows out of the mountain area into a relatively steep coastal zone, depositing an alluvial fan and then feeding a delta. Due to the tilting, the Luanhe River has switched from west to east in stages, flowing out of the mountain in three places during various phases of the Quaternary, forming three fan deltas (Fig. 8; Li, C.X., 1985). The active Luanhe fan delta (phase III), formed since the postglacial maximum transgression, is embedded in the eastern part of the late Pleistocene fan delta (phase II). The middle Pleistocene fan delta (phase I) is located to the east of the later phases and at a higher elevation. The present fan delta (phase III) is bounded by steep slopes along both sides. The ratio of annual sediment discharge to water discharge is the highest of the four studied river systems (Table 1).

The incised valley underlying the Luanhe fan delta extends southward from the mountain area for approximately 70 km to the river mouth. The valley, 20 to 60 m deep, is 0.5 to 4 km wide at the apex and 90 km wide at the mouth. Maximum thickness of postglacial sediments was measured in the central portion of the incised valley, with thicker sediments near the upper fan-delta area and an overall seaward thinning (Fig. 9). The plan shape and dimensions of the incised valley are similar to those of the modern fan delta. The valley is incised into bedrock at the apical area and

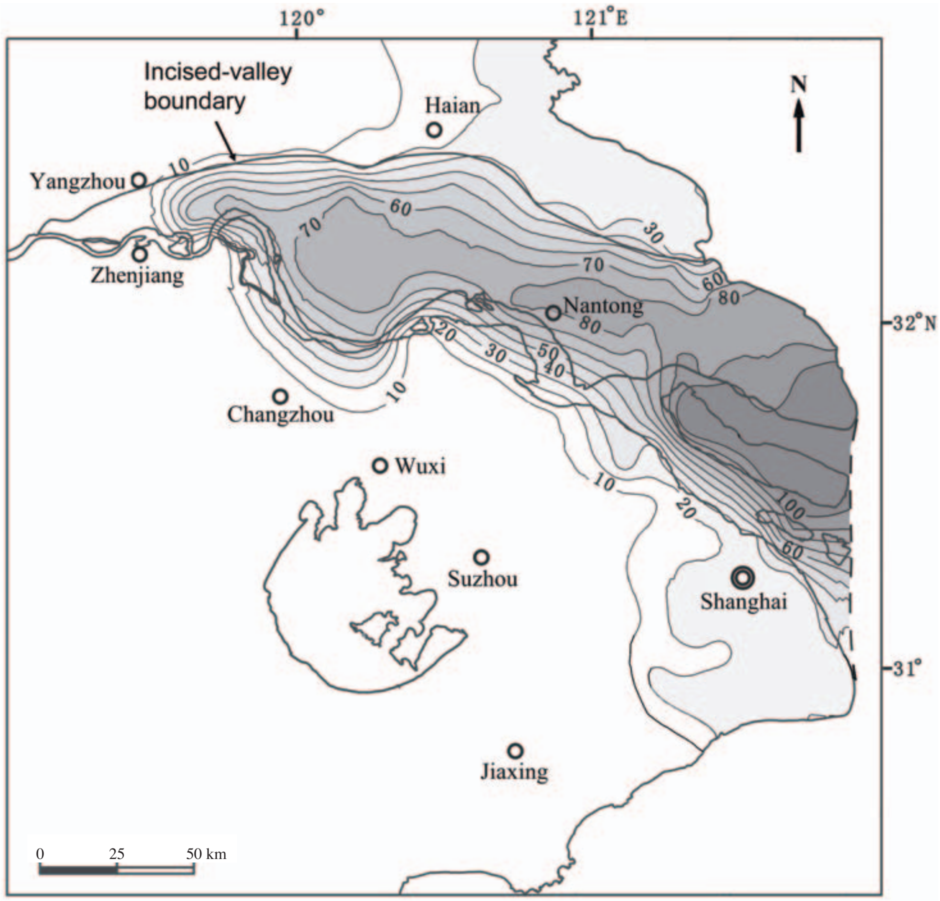

FIG. 3.—Isopach map of the postglacial sediment in the Changjiang delta area. Zero contour line coincides roughly with the boundary between the hilly area and the incised-valley system shown in Figure 2 (Modified from Li et al., 2003).

yellowish-brown Late Pleistocene consolidated sediments in the middle and lower fan-delta area with an easily identifiable contact (Fig. 10; Li, C.X., 1985).

Incised Valley in the Zhujiang Delta Area

The modern Zhujiang delta is located in a graben and covers 9,600 km^2, of which 81% is plain area and 19% is bedrock hills. There are numerous bedrock islands in the shallow river-mouth area. The delta is river-dominated because of the relatively low tidal range (Table 1) and damped wave energy (Huang et al., 1982; Li, C.X., 1986; Li, C.X., et al., 1991; Huang, 2000). The Zhujiang delta is a complex delta formed by the coalescence of the Xijiang, Beijiang, and Dongjiang deltas, with eight distributaries entering the South China Sea (Fig. 11).

The Zhujiang incised-valley system is 16 to 64 m deep and composed of several narrow elongated valleys formed by independent rivers flowing into the same graben. The valleys were separated by bedrock hills and were connected at places through secondary valleys (Fig. 12). The modern delta started developing in the estuary during the postglacial transgression maximum. The erosional surface is cut into Precambrian metamorphic rocks or granite, Cenozoic sedimentary rocks, and thin unconsolidated late Pleistocene deposits (Huang et al., 1982; Long, 1997; Li, C.C., 2004).

CHARACTERISTICS OF THE INCISED-VALLEY-FILL SEQUENCES

Depositional Facies in the Incised-Valley Fill

There are similarities and differences in the depositional facies among the four incised-valley fills. The following discussion summarizes mostly the similarities. This allows the comparison of the four different systems. Regional differences are also indicated.

River-Channel Facies.—

This facies is composed of fine sand, medium-fine sand, medium-coarse sand, sandy gravel, or coarse sand with mud clasts. For a large river system (e.g., the Changjiang River), this facies is composed mainly of fine sand with gravel finer than 0.5 cm in the lag deposits. For short rivers draining a tectonically active region, such as the Luanhe River and the Qiantangjiang River, the channel facies tends to be coarser and is dominated by sandy gravel, with up to 10 cm gravel in the lag deposits. The gravels are typically subrounded or subangular. Cross-bedding is common, and no marine microfossils are found. This facies fines upward gradationally and contains 1–2 m of coarser sediments at the base. The thickness of the river-channel facies is

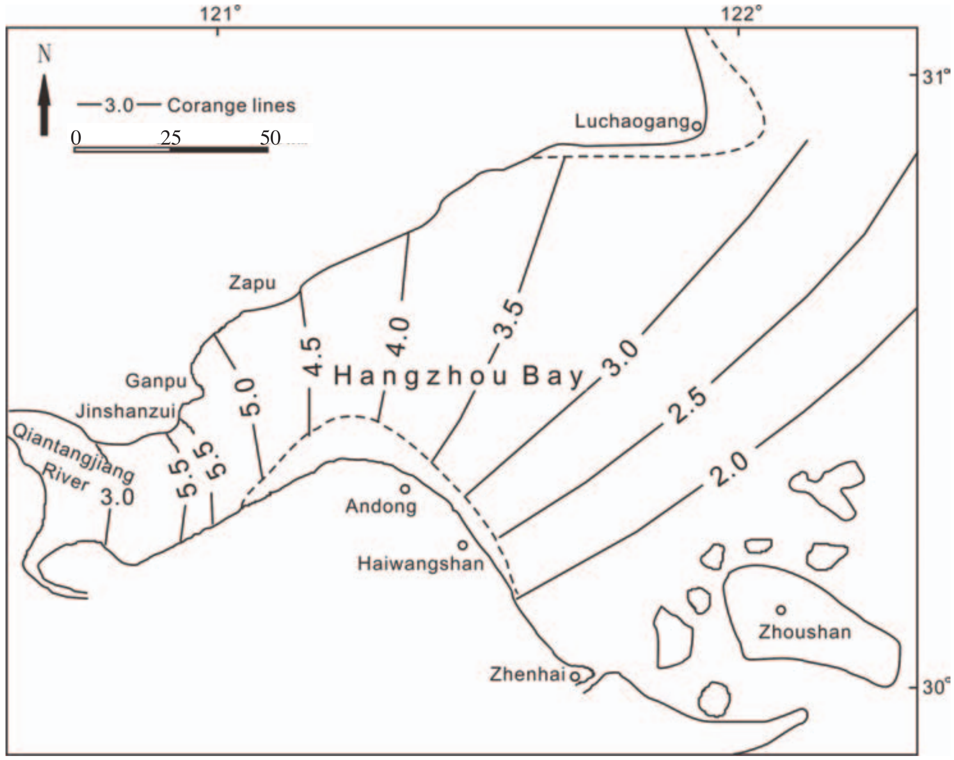

FIG. 4.—Distribution of tidal range in the Qiantangjiang estuary (modified from Lin and Cao, 2000).

typically 15–30 m, with a maximum of 49 m, and constitutes approximately 20 to 25% of the total incised-valley fill in each example (Huang et al., 1982; Li, C.X., 1985; Li, P.R., et al., 1991; Li, C.X., et al., 1993b; Zhang and Li, 1996; Long, 1997; Li, C.X., et al., 2000; Li, C.X., et al., 2002).

Marine-Influence Floodplain Facies.—

This facies is typically composed of gray massive mud with brownish to reddish spots. Plant debris and roots, thin peat layers, sand lenses, organic-rich mud lenses, and small amounts of marine microfossils are common (Li, C.X., et al., 1993b). It is interpreted as a marine-influenced floodplain facies because of the presence of the marine microfossils. It is usually 15–20 m thick, with a maximum thickness of 30 m. This facies is broadly distributed in the Qiantangjiang estuary, the Luanhe fan delta, and the Zhujiang delta (Huang, et al., 1982; Li, C.X., 1985; Long, 1993; Zhang and Li, 1996). In some places, this facies contains well-developed sandy-muddy laminae with horizontal, wavy, lenticular, and flaser bedding, indicating tidal influence. Small foraminifera with great variation in abundance are combined with terrestrial ostracoda, which represents an interaction of marine and terrestrial factors (Wang, 1985). The boundary between this facies and the overlying and underlying facies is gradual.

Shallow Marine Facies.—

This facies is typically composed of gray muddy deposits with a high water content and poorly developed lamination. Sandy

TABLE 2. —Average measured tidal ranges and tidal currents in the Qiantangjiang estuary.

Station	Tidal range (m)	Peak flood Tidal current (m/s)
Zapu	4.55	1.46
Ganpu	5.48	3.20
Jianshanzui	5.33	3.85
Haineng	2.28	3.72
Qibao	0.37	0.68
Hangzhou	0.35	0.48

Station locations are shown in Figure 4. The last three stations are farther west of that figure.

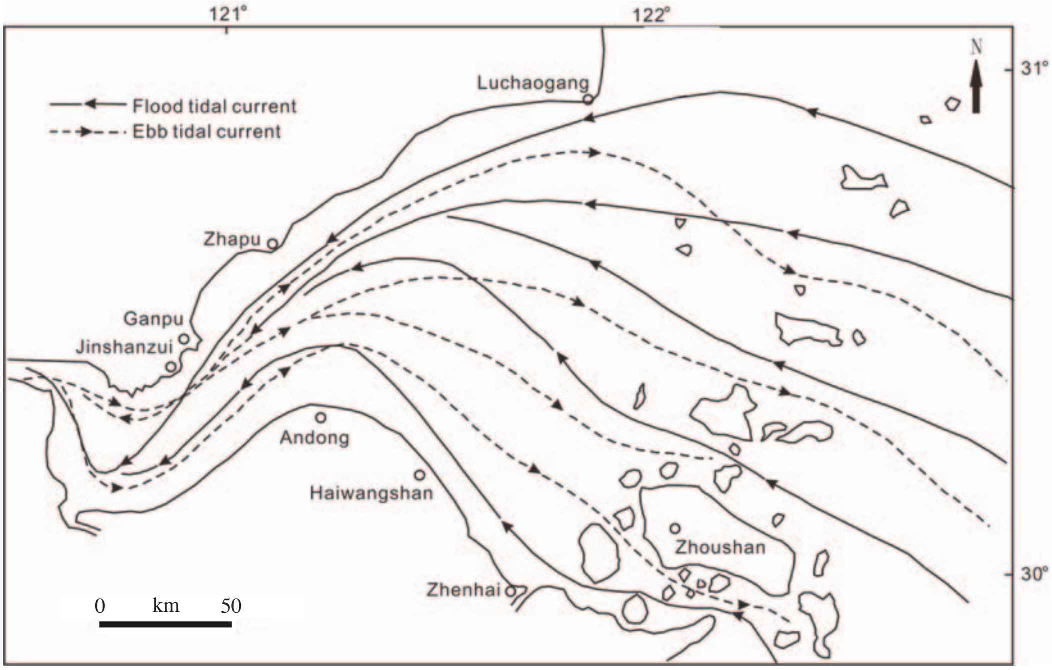

FIG. 5.—Flood and ebb tidal-current patterns in the Qiantangjiang estuary (modified from Lin and Gao, 2000).

laminae 1–2 mm thick are found in muddy layers several centimeters thick. The characteristics of this facies include shell debris and vertical burrows. Normal-size benthic foraminifera, together with a few terrestrial ostracoda, are found in the muddy deposits. This facies is interpreted as shallow marine facies near the estuary mouth (Wang, 1985; Li, C.X., and Wang, 1998). The contacts between this facies and the underlying and overlying facies are typically gradual. Locally, a sharp boundary with overlying facies, due to erosion by strong fluvial or tidal currents, is observed.

Deltaic Facies.—

This facies is composed of silt, fine sand, clayey sand, and sandy clay, containing horizontal and wavy bedding, bidirectional cross-bedding, reactivation surfaces, and a foraminifer

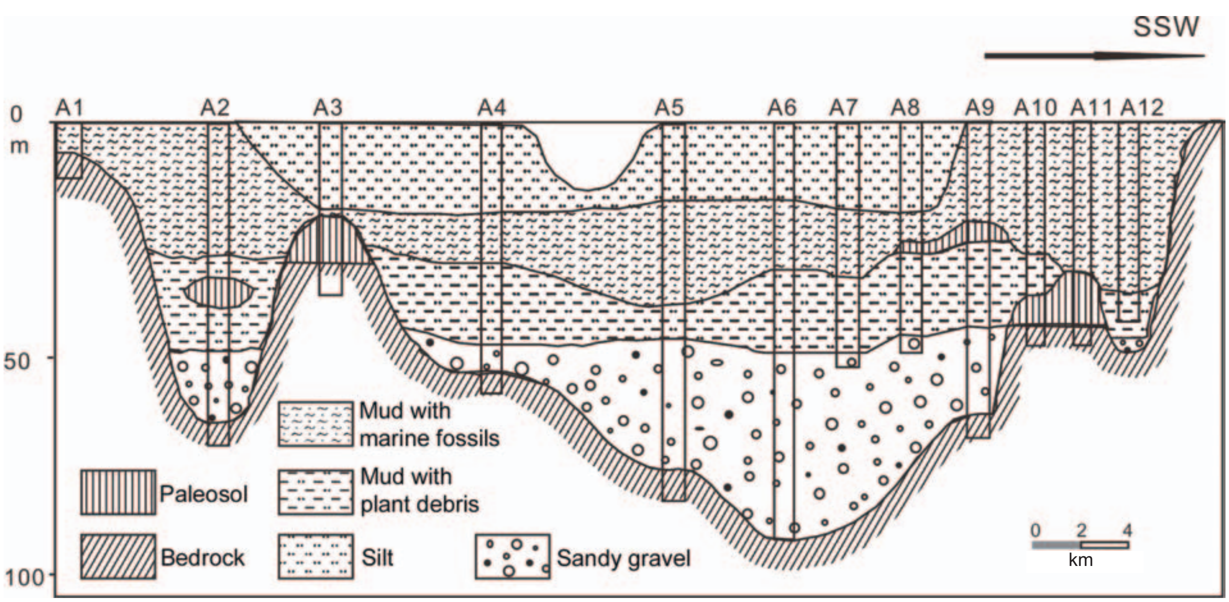

FIG. 6.—The Qiantangjiang incised valley subdivided by bedrock hills in the apical area of the estuary. The location of the section (A-A') is shown in Figure 7 (After Zhang and Li, 1996).

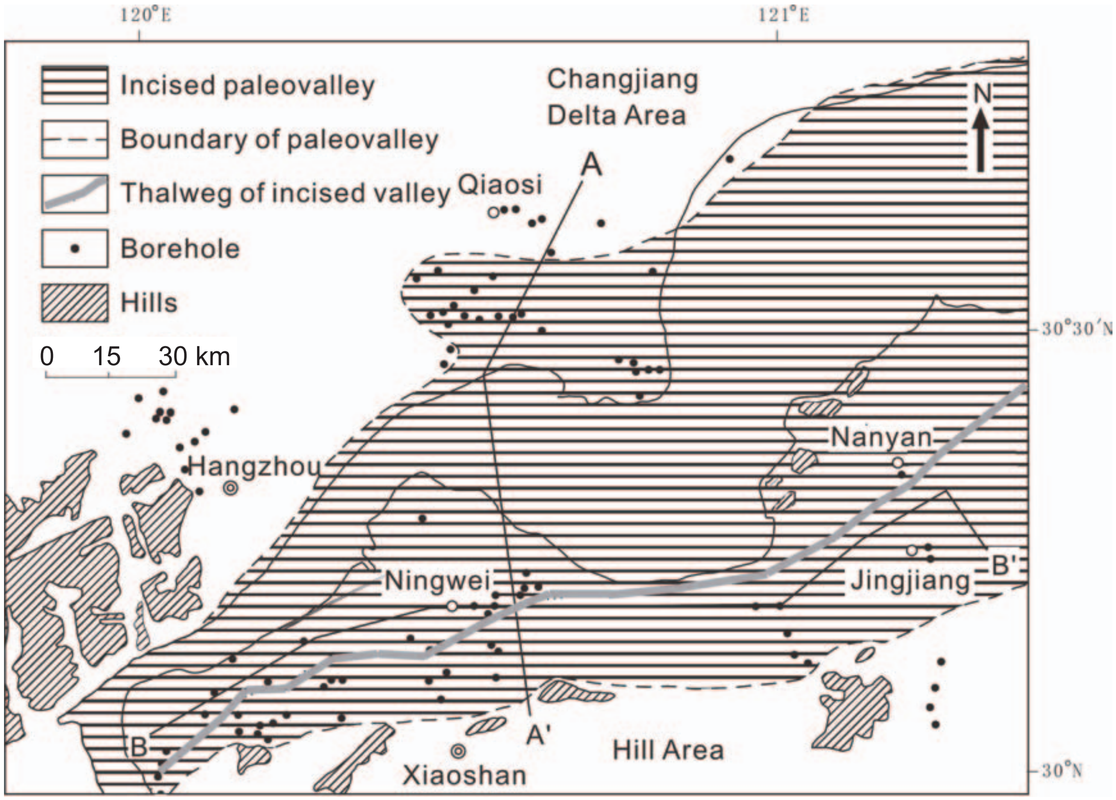

FIG. 7.—The Qiantangjiang incised valley (Modified from Zhang and Li, 1996).

assemblage characteristic of a river mouth. The sedimentary structures indicate the influence of tidal currents. This facies is usually coarsening upward with a gradual contact with underlying strata, and is interpreted as having accumulated in a river mouth bar. In some places, it is fining upward with an erosional surface at the base, in which case it is interpreted as a distributary-channel deposit. A tidal-flat facies often exists toward the upper part of the deltaic facies. The fining-upward tidal-flat facies is characteristic of various tidal bedding (Huang et al., 1982; Li, C.X., 1984, 1985, 1986; Li, P.R., et al., 1991; Long, 1997; Li, C.X., and Wang, 1998).

Tide-Dominated Facies.—

This facies is composed mainly of well-sorted silt and fine sand containing abundant foraminifera of low diversity. It is underlain by an erosional surface and is generally 20 to 30 m thick. Discrete millimeter-scale muddy laminae are found in sand beds several centimeters thick. No vertical grain-size trend can be detected in the sandy deposits. This sandy deposit occurs in the apical area of the modern Qiantanjiang estuary (Li, C.X., et al., 1993b; Zhang and Li, 1996) and the paleo-Changjiang estuary (Li, C.X., 1984; Li, C.X., and Wang, 1998). Better sorting is measured in the Qiantanjiang estuary relative than in the paleo-Changjiang estuary, because the sandy deposits in the former are believed to have been transported from the Changjiang delta and reworked by strong tidal currents (Chen, J.Y., et al., 1964; Qian et al., 1964, 1989; Zhang and Li, 1996). The difference between the tide-dominated facies and the deltaic facies is that the former is composed largely of well sorted sandy and silty deposits and is underlain by an erosional surface scoured by strong tidal currents.

Vertical Facies Successions in the Incised-Valley Fills

Four facies successions (FS), FS-I through FS-IV, are summarized based on numerous drill-core analyses. FS-I, from bottom to top, is composed of river-channel, marine-influenced floodplain, shallow marine, and deltaic facies (Fig 13A). This succession is transgressive at the base but becomes regressive toward the top. FS-I summarizes the succession observed in cores obtained from the coastline areas of the Changjiang and Zhujiang deltas and the Luanhe fan delta. This succession is absent in the Qiantangjiang estuary. FS-II is composed of, from bottom to top, river-channel, marine-influenced floodplain, shallow marine, and tide-dominated facies (Fig. 13B). This succession is also transgressive at the base and becomes regressive toward the top. FS-II occurs in the cores from the apical areas of the Qiantanjiang and paleo-Changjiang estuaries. FS-III, from bottom to top, consists of river-channel and floodplain facies throughout the entire succession (Fig 13C). Marine microfossils and tidal sedimentary structures are absent. FS-III summarizes the cores collected from the inland portions of the Luanhe fan delta (Li, C.X., 1985, 1986) and Zhujiang delta (Li, C.C., and Yang, 1981; Long, 1997). FS-IV synthesizes cores at the apical area of the Luanhe fan delta and is composed of sandy gravel intercalated with thin discontinuous muddy deposits without marine fossils. It is interpreted as superimposed fluvial facies dominated by river-channel deposits (Fig. 13D).

The distribution patterns of the facies successions are different along the longitudinal profile of the four incised valleys. FS-

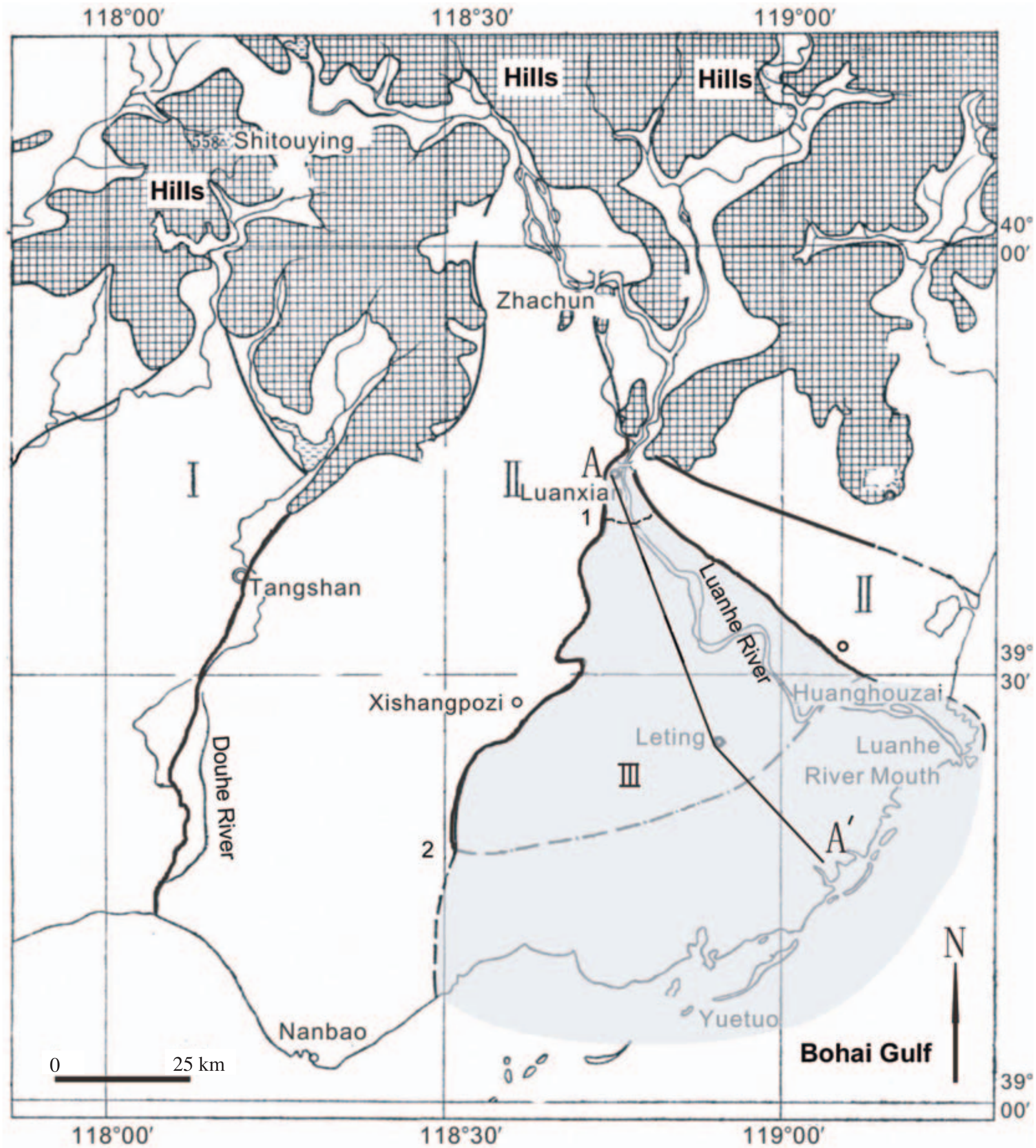

FIG. 8.—Three phases of the incised valleys in the Luanhe fan-delta area. I: Fan-delta of the middle Pleistocene; II: Fan-delta of the Late Pleistocene; III: Postglacial fan-delta; 1: seaward boundary of FS-IV succession; 2: seaward boundary of FS-III succession (Modified from Li, C.X., 1985).

I occurs near the modern coastline and passes landward into FS-II in the Changjiang incised valley (Li, C.X., and Wang, 1998; Li, C.X., et al., 2002). Along the Luanhe valley, the landward distribution pattern includes FS-I, FS-III, and FS-IV. In the apical area of the Qiantangjiang estuary, only FS-II is found (Li, C.X., et al., 1993b; Zhang and Li, 1996). Along the Zhujiang incised valleys, the successions consist of FS-I and FS-III (Huang et al., 1982; Li, C.X., et al., 1991; Long, 1997; Li, C.C., 2004).

Based on the relative dominance of marine or fluvial processes, the idealized longitudinal organization of the four facies successions (Fig. 14) begins with the marine-dominated FS-I near the modern coastline. FS-II and FS-III represent a gradual strengthening of fluvial process and weakening of marine processes. FS-IV occurs at the apex area; marine influence is minimal and fluvial processes dominate sedimentation. It is worth noting that the above model is based on core data obtained largely from the subaerial parts of the model deltas; the subaqueous offshore portion of these valleys is beyond the scope of this paper.

Characteristics of Transgressive and Regressive Successions

Although the postglacial sea-level history consists only of the rising half of a complete sea-level cycle, the incised-valley succession includes both a transgressive and a regressive succession because of the tremendous fluvial sediment supply. An erosional surface, formed during the sea-level lowstand, lies at the bottom of all the studied incised-valley sequences. This erosional surface

FIG. 9.—Isopach map of postglacial sediment in the Luanhe fan-delta area. Contours of less than 20 m are not included due to lack of data near the incised-valley boundary (Modified from Li, C.X., 1985).

represents a sequence boundary as commonly accepted (Van Wagoner et al., 1990; Dalrymple et al., 1992; Dalrymple and Zaitlin, 1994; Zaitlin et al., 1994; Blum et al., 2000; Ardies et al., 2000; Plint and Wadsworth, 2003). The placement of the boundary between transgressive and regressive successions is subject to some debate. The maximum flooding surface (MFS) is located within the shallow marine facies when the facies is present in the incised-valley fill with gradual transition to the overlying and underlying strata. In the case that the shallow marine facies is partly eroded, the erosional surface at the top of the muddy deposits may be accepted as the MFS. In the case of complete erosion of the shallow marine facies, the erosional surface at the top of the marine influenced facies can be considered as the MFS. When the incised-valley fill is composed of transgressive and

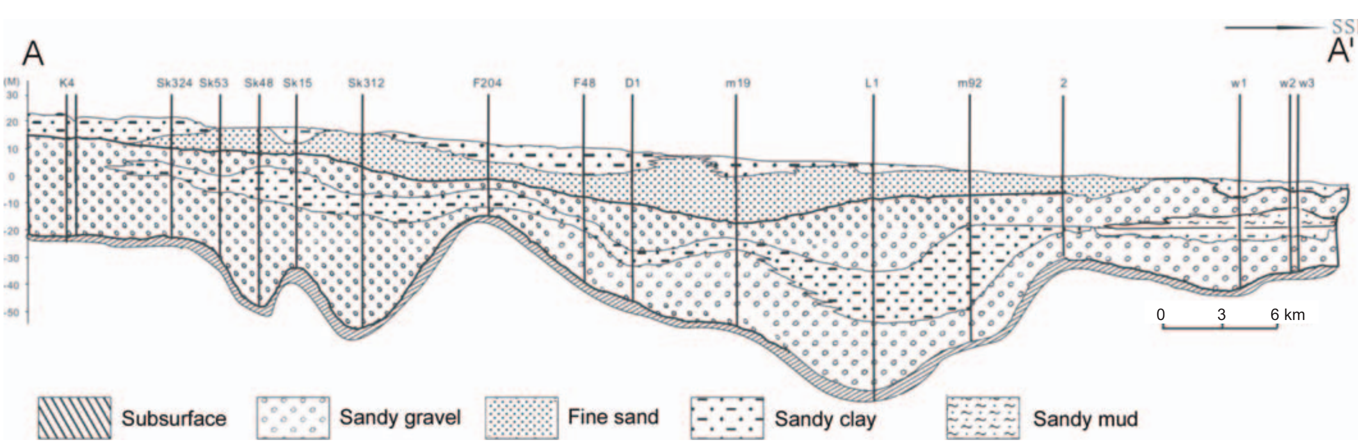

FIG. 10.—Longitudinal section of the incised valley beneath the Luanhe fan-delta. The location of the section (AA') is shown in Fig. 8.

FIG. 11.—Zhujiang delta and its main distributaries: 1: Humen; 2: Jiaomen; 3: Hongqili; 4: hengmen; 5: modaumen; 6: Jitimen; 7: Hutiomen; 8: Yemen.

regressive fluvial successions, the MFS is put at the top of the transgressive fluvial succession.

The above determination of the MFS is summarized on the basis of our data from the studied deltas and estuary. Sedimentation characteristics on the continental shelf, as commonly used in the determination of MFS, is not considered here due to lack of data. Some studies put the MFS within the muddy marine deposits (Zaitlin et al., 1994; Shanley et al., 1992), whereas others argue that the boundary should be at the base of the muddy deposits (Allen and Posamentier, 1993). Theoretically and ideally, this boundary is the maximum flooding surface, which is synchronous and should be located within the muddy deposits and represents a transition from the deposition at the end of transgression to that at the beginning of regression. On the other hand, the regressive succession extends gradually seawards and overlies the transgressive succession. In this sense, the boundary represents a diachronous surface. In the present context, the boundary between the transgressive and regressive successions is positioned within the muddy shallow marine facies. However, it is difficult to determine the exact position of the boundary because of limited age data for most of the drill cores used in this study. In addition, the shallow marine facies may be eroded partially or completely by fluvial and / or tidal flows, leaving an erosional surface. In this case, the erosional surface is used to separate the transgressive and regressive successions (Fig. 13, FS II and FS III). The exact boundary is difficult to identify at the apex area, because of the superposition of layers, a lack of marine signatures, and the presence of multiple erosional surfaces.

The river-channel facies at the bottom of the incised-valley fill is usually identified as belonging to the lowstand systems tracts (Allen and Posamentier, 1993; Van Wagoner et al., 1990), or partially as lowstand systems tracts (Zaitlin et al., 1994). In the incised valleys studied here, this facies fines upward and lacks any through-going and regionally correlative erosional surfaces within the fluvial deposits. Its thickness greatly exceeds the water depth in any channel. Existing ^{14}C dates are all younger than 15,000 years (Huang et al., 1982; Li, C.X., 1985; Zhang and Li, 1996; Long, 1997; Hori et al., 2001; Li, C.X., et al., 2000, 2002). Thus, the lower channel facies was formed under the influence of base-level rise, as discussed in the following sections, and thus belongs to the transgressive succession. Therefore, the transgressive succession here is equivalent to the transgressive systems tract and the regressive succession is equivalent to the highstand systems tract.

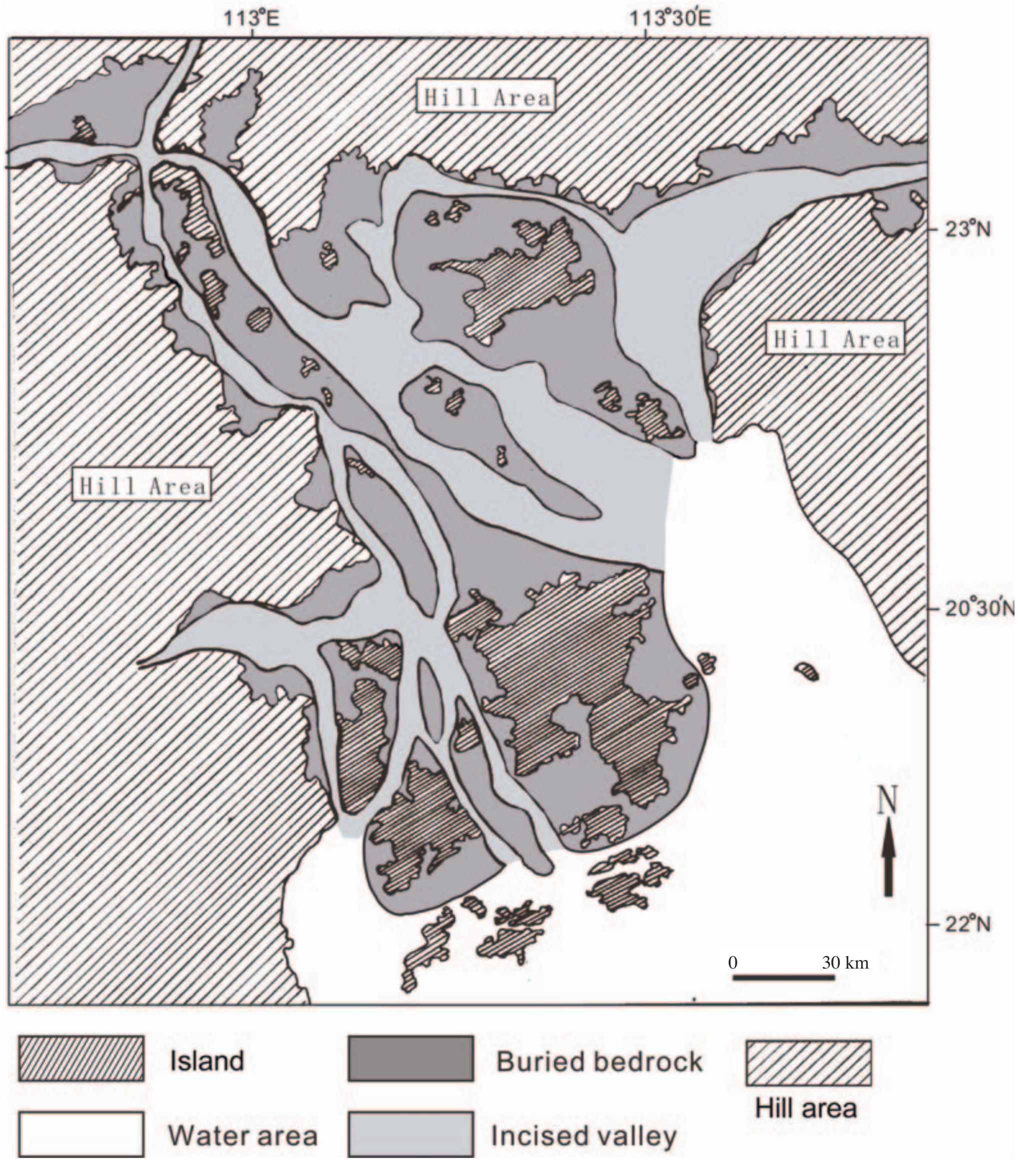

FIG. 12.—Distribution of incised valleys beneath the Zhujiang delta (modified from Long, 1997; and Huang et al., 1982).

A through-going erosional surface created by initial transgression was not found: the transition between river-channel facies and marine-influenced floodplain facies is generally gradual. In the case of a funnel-shaped estuary, strong tidal currents in the inner estuary area tend to create tidal ravinement surfaces at the base of the tidally scoured channels, such as those observed in the modern Qiantanjiang estuary and the paleo-Changjiang estuary. This erosional surface, although diachronous, also serves as the boundary separating transgressive and regressive successions. Erosion by wave forcing is typically local. Therefore, the initial transgressive erosional surface is not a significant component in the studied incised-valley fills.

The thickness and volume of the transgressive and regressive successions in the Changjiang and the Qiantangjiang incised valleys were calculated based on the numerous cores. The thickness of the transgressive succession constitutes more than 50% of the total incised-valley fill and represents roughly 60 to 70% of the total volume (Table 3). Similar numbers are also obtained for the Luanhe and Zhujiang incised valleys (Huang et al., 1982; Li, C.X., 1985; Long, 1997). Therefore, the transgressive succession is an important component of the incised-valley fill for these sediment-rich rivers (Fig. 13).

FORMATION OF THE INCISED-VALLEY-FILL SUCCESSIONS

The surface sediments in the Qiantangjiang estuary display a fining-seaward trend (Fig. 15; Zhang and Li, 1996). Based on various studies on tidal current pattern and mineralogical assemblages, the sediments in the Qiantangjiang estuary come mainly from the neighboring Changjiang River, transported by tidal currents (Chen, J.Y., et al., 1964; Qian et al., 1964; Yan and Hu, 1989; Shen, 2001). At the wide mouth, the tidal currents are relatively weak, allowing the deposition of a relatively large

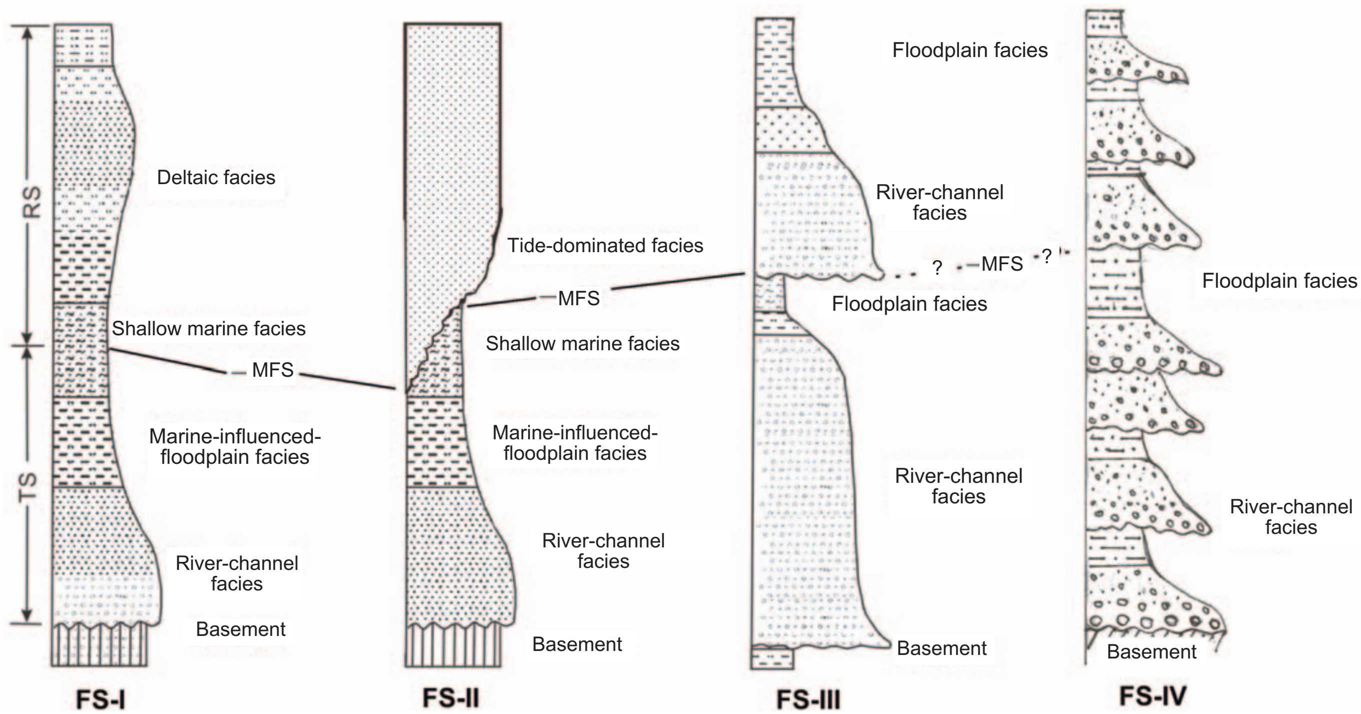

FIG. 13.—Facies-succession types summarized from the studied sediment-rich incised-valley systems.

portion of the clay and silt from suspension and forming muddy sediments. In the middle and apical areas where the tidal bore intensifies, the relatively strong currents allow only sandy material to be deposited, forming well-sorted sand bodies. The strong tidal currents also create an erosional surface at the bases of the tidal sand bodies. These sand bodies also demonstrate a rather homogeneous vertical grain-size distribution. Similar sand bodies formed by strong tidal currents were also interpreted in the upper part of the regressive succession in the apical area of the Changjiang delta. Based on a large amount of core data, the sediments of the paleo-Changjiang estuary also display a fining-seaward trend (Fig. 16; Li, C.X., and Wang, 1998).

The incised valley under the Luanhe fan delta is fan-shaped, with an apical area several hundred meters wide and a mouth area tens of kilometers wide. At the present coastal area, the regressive succession is composed of deltaic facies with coarsening-upward deposits and marine signatures. Upstream from the coastal area, the incised-valley deposits consist of superimposed transgressive and regressive fluvial successions without marine signatures. The active erosion by the fluvial flow makes it difficult to clearly distinguish transgressive and regressive succession. The apical area of the Luanhe fan delta is several kilometers long. The superposition of multiple channel deposits contrasts with the typical deltaic succession.

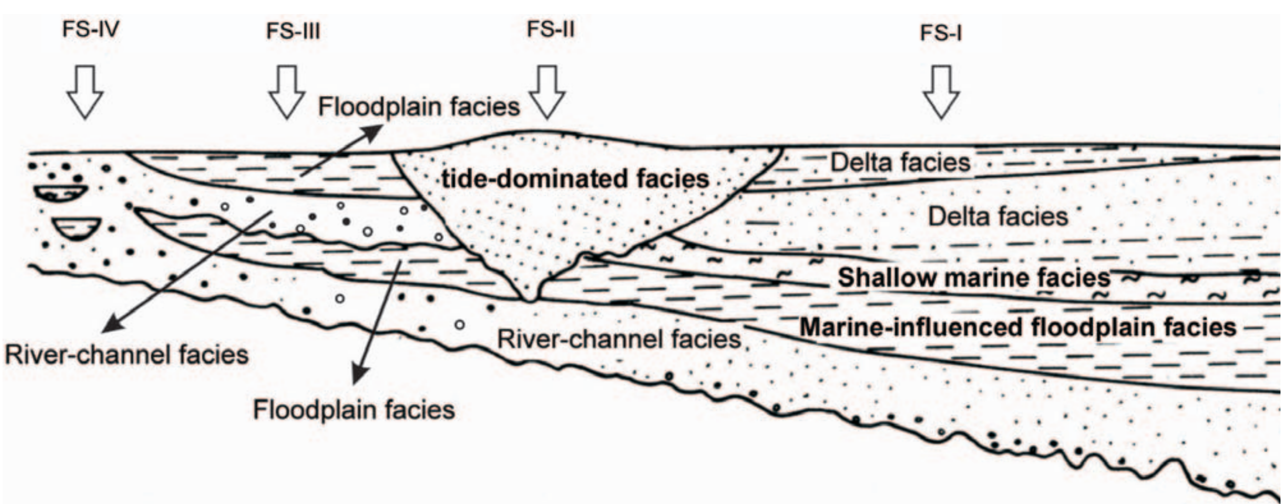

FIG. 14.—Idealized longitudinal distribution of facies successions along an incised valley.

TABLE 3. —Average thickness (m) and sediment volume ($10^9 m^3$) of the transgressive succession in the incised-valley fills of the Changjiang delta and Qiantangjiang estuary

	Thickness	%	Volume	%
Changjiang delta	44.2	54.2	558.0	63.6
Qiantangjiang estuary	45.5	54.6	207.6	69.5

Calculated on the basis of the data from Zhang and Li, 1998; and Li, B.H., et al., 2003.

In the Zhujiang delta area, several narrow incised valleys are separated by buried bedrock hills. The landward delta area is characteristic of the superimposed fluvial successions (Li, C.C., and Yang, 1981; Huang et al., 1982; Long, 1997; Li, C.C., 2004). The regressive succession is composed of fluvial deposits containing a few marine and brackish algae (Huang et al., 1982). The modern delta area was occupied by a unified paleo-estuary at the time of maximum transgression, although the Zhujiang incised-valley system consists of several valleys of independent rivers.

Overall, in the studied estuary and the paleo-estuaries, the sediment distribution is different from that shown in the Dalrymple et al. (1992) model. The coarse bay-head facies is absent from the regressive succession, perhaps because it was not formed or was reworked by fluvial processes. The bay-head delta facies is also not developed in the apical parts of the transgressive successions. In the following, we propose a modified model for the development of incised-valley deposits in a sediment-rich environment, especially for the transgressive succession.

Depositional Processes in the Lower Reaches of the Rivers

One of the factors controlling the depositional processes in the lower stretches of the rivers is the interaction between fluvial and tidal currents. In the Changjiang and Qiantangjiang Rivers, tidal currents can be measured 200 to 300 km upstream from the river mouth during spring tides in the dry season (Fig. 17). The duration of the flooding tide decreases from 4–5 hours near the river mouth to 1–2 hours ~ 200 km upstream, and eventually becomes zero 230 and 290 km upstream on the Changjiang and Qiantanjiang rivers, respectively (Li, C.X., et al., 1983; Li, C.X., et al., 1993a). The distance of saltwater intrusion is about 100 km in both rivers, which is much shorter than the limit of flood tidal currents. Dead and light foraminifer tests can be transported easily by flood tidal currents (Wang, P.X., 1985; Cheng, 1987). The upstream limit to find foraminifer tests coincides with that of flood tidal currents (Fig. 18).

Another factor controlling the depositional processes in the lower stretches of the rivers is base-level fluctuations. Base-level rise reduces the hydraulic gradient, creating a backwater affect in the lower reach of the river. The extent of the backwater can be calculated from the river gradient and the magnitude of the base-level rise (Qian et al., 1989). For the Changjiang River, the average gradient of the lower reach is about 1/140,000; therefore, a 3 m rise of tide induces a backwater of ~ 420 km, which greatly exceeds the 230 km upstream limit of the flood tidal currents. The reduced water-surface gradient leads to a slower river flow, which in turn results in sediment accumulation. The sedimenta-

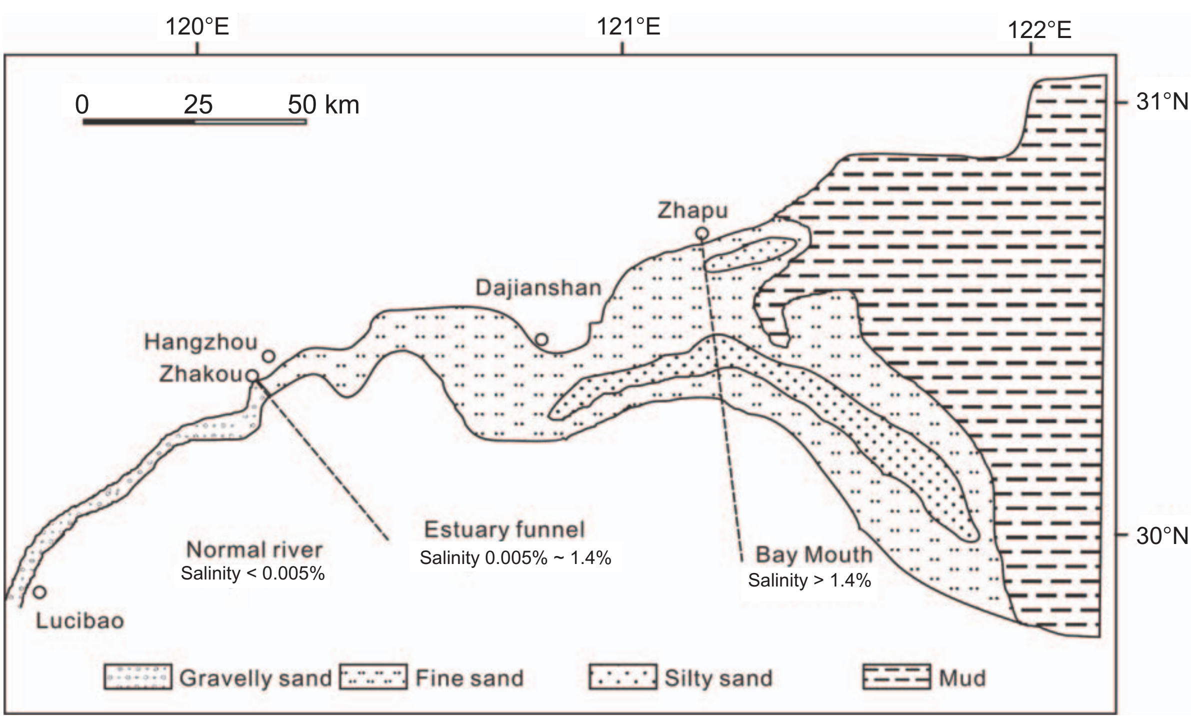

FIG. 15.—Sediment distribution in the present-day Qiantangjiang estuary (modified from Zhang and Li, 1996).

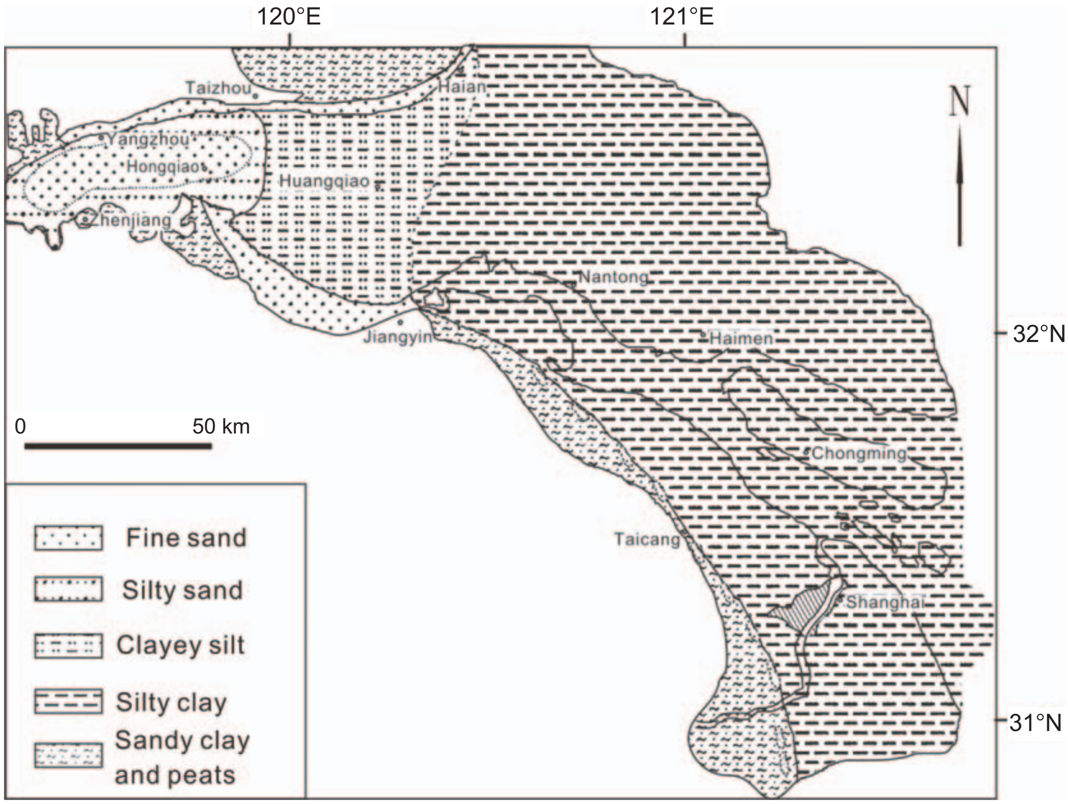

FIG. 16.—Sediment distribution in the Changjiang paleo-estuary, reconstructed from drill cores (modified from Li, C.X., 1984).

tion rate decreases gradually in the upstream direction along the backwater river reach. The sedimentation at the upper limit of the backwater results in an elevated water surface, assuming that the river cross-sectional area remains the same. This elevated water surface at the upper limit of the backwater then becomes a new raised base level, inducing sedimentation farther upstream. This retrogressive aggradation results in sedimentation in the upstream direction. The rate of retrogressive aggradation reduces in the upstream direction and eventually diminishes. The retrogressive aggradation extends farther upstream than the original extent of backwater (Makkaveev, 1960; Borland, 1971; Qian et al., 1989). The relationships among the above parameters are illustrated in Figure 19. The extent of saltwater intrusion is the smallest, followed by flood tidal current and backwater, with the extent of retrogressive aggradation being the greatest. The term "tidal influence" should specify that of flood tidal current or tidal water-level fluctuation. The flood tidal current may transport marine fossils and create relevant sedimentary structures. These two distances can be very different, as demonstrated by the Changjiang River (Fig. 20). Among these parameters, the limits of flood tidal current and retrogressive aggradation are more important factors controlling the incised-valley fill.

The Transgressive Succession in the Incised-Valley Fill

The transgressive succession plays a significant, and sometimes dominant, role in the filling of the incised valley (Table 3). Thus, it is crucial to understand the processes responsible for its deposition. The rising sea level induces retrogressive aggradation and filling of the incised valleys in the lower reach of the river (Schumm, 1993). River-channel deposits typically demonstrate a coarsening-upstream trend. Therefore, landward retreat of the river mouth, induced by rising sea level, produces a superposition of channel deposits with an overall fining-upward trend (Fig. 21). Marine microfossils are rare in the studied transgressive river-channel facies, which was deposited largely by the retrogressive aggradation beyond the upstream limit of flood tidal currents. Marine microfossils and tide-generated sedimentary structures are present in the upper portion of the transgressive succession when the flood tidal currents reach the location of the present delta/estuary. The studied incised valleys are wider than the river channel, and the main river channel may migrate within the incised valley, thereby allowing the development of both river-channel facies and floodplain facies. Migration of the main river channel within the incised valley may also rework the previous floodplain deposits, forming the muddy clasts found in some channel facies. A small number of marine microfossils were found in the floodplain deposits, where they were probably transported by storm events. Continued sea-level rise then caused the estuary to migrate landward, forming the tide-influenced floodplain facies.

Retrogressive aggradation appears to be a continuous process and is not sensitive to small hiatuses and short-term reversals in sea-level change. A regionally correlative and continuous erosional surface was not found in the transgressive succession. This is characteristic of the studied sediment-rich systems and is different from the discontinuous transgressive events documented in other areas (Gupta, 1999; Thomas and Anderson, 1994). The strata formed by retrogressive aggradation are fundamentally different from those of deltaic deposits (Table 4).

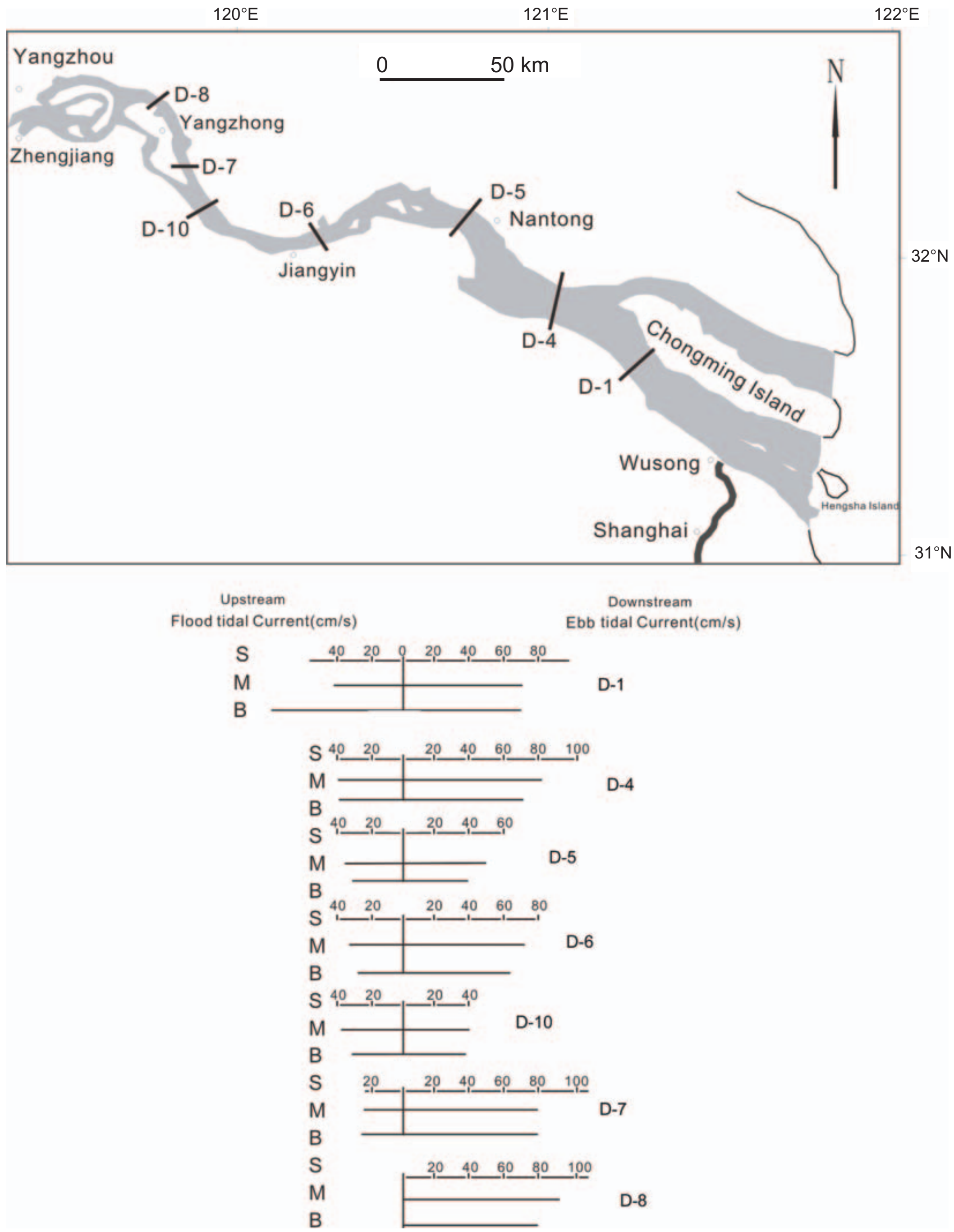

FIG. 17.—Velocities of flood and ebb tidal currents (lower panel) at the observation stations (upper panel) in the lower reach of the Changjiang River. S: Flow velocity at the water surface; M: Flow velocity at mid-depth; B: Flow velocity near the channel bottom.

The Regressive Succession in the Incised-Valley Fill

When the transgression reached maximum extent, estuaries of various sizes and shapes were present in the study areas. A huge paleo-Changjiang estuary, similar to the modern Qiantangjiang estuary, reached its maximum extent during the maximum transgression. The deposits that accumulated in the apical areas at the time of maximum transgression consist of well-sorted sandy deposits, 15 to 25 m thick, with marine microfossils and tidal sedimentary structures. A regional erosional surface exists at their base, representing the amalgamation of many tidal-channel erosion surfaces. These sandy deposits are commonly exposed, forming sand lenses that extend parallel to the paleo-flow direction and are raised 1–2 m above the surrounding areas as a result of differential compaction. This slight elevation difference is shown schematically in Figure 14. Historical records

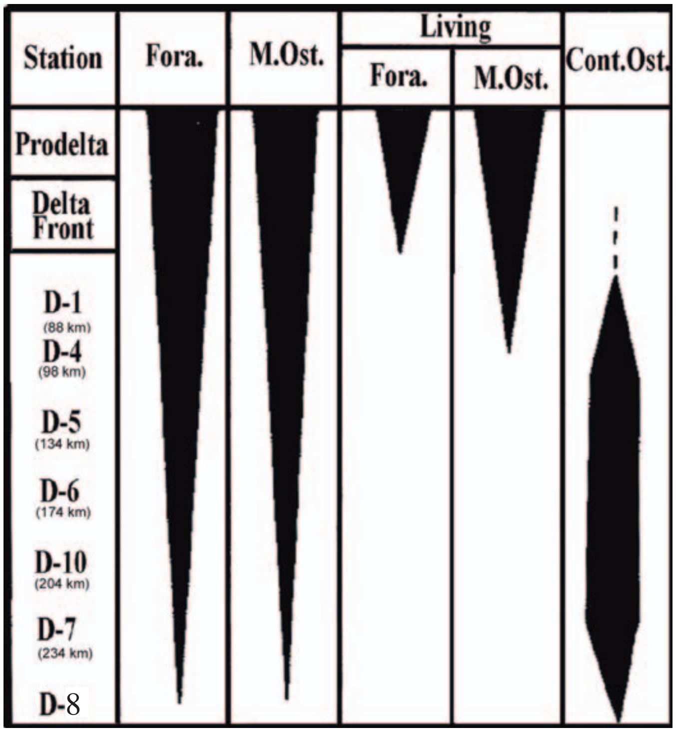

FIG. 18.—Distribution of marine microfossils in the Changjiang River. Locations of observation stations are shown in Figure 17. Fora.: foraminifera; M. Ost.: marine ostracoda; Cont. ost.: terrestrial ostracoda.

describe spectacular tidal bores at the ancient city of Guangling (present Yangzhou) in the apical area of the paleo-estuary, similar to those that occur in the modern Qiantangjiang estuary (Chen, 1989). This suggests that the paleo-Changjiang estuary during postglacial transgressive maximum was macrotidal. Since then, it has evolved from macrotidal to mesotidal as the depositional environment evolved from a concave estuary to a protruding delta. The sand body in the emerged apical area of the paleo-estuary does not show an upward-coarsening deltaic succession and should be interpreted as a coastal plain. By contrast, a deltaic succession is identified in the outer part of the Changjiang delta, demonstrating the evolution of the coastal plain during the progradation. The boundary between the two is gradual.

Both abrupt and gradual boundaries are distinguished between the regressive and transgressive successions. Two types of extensive erosional surface are distinguished. One is interpreted as a tidal ravinement surface and typically occurs in the apical part of an estuary or paleo-estuary with strong tidal currents. The other type is believed to be created by river flow and occurs mostly in the apical and inner delta areas in tectonically uplifted areas with steep gradient (e.g., the Luanhe fan delta; Fig. 10). The gradual boundary between the regressive and the transgressive successions typically occurs in areas where shallow marine muddy facies is well preserved. Erosional surfaces with limited spatial extent can also be found underneath the distributary-channel deposits.

Preservation of the Incised-Valley Fill Deposits

The studied incised-valley-fill deposits were formed during the transgression since the last glacial period. Several transgressions occurred during the Quaternary along the Chinese coast (Wang, P.X., 1985). Whether successive incised valleys are superimposed or are located far apart at approximately the same stratigraphic elevation is controlled by local tectonic conditions. The Changjiang incised valleys are located in a zone of tectonic subsidence controlled by W–E faults (Wu and Li, 1987). Each of the preceding incised-valley fills was reworked by the following incision, such that in many cases only the coarse river-channel facies at the bottom are preserved. This results in the superposition of several phases of river-channel deposits separated by erosional surfaces (Fig. 22). The sediments at the bottom of the postglacial incised-valley fill were deposited approximately 10,000 to 12,000 years BP. The age of the strata below the erosional surface is about 100,000 years BP, whereas the age of the deposits below the next boundary is approximately 200,000–250,000 years BP (Qin et al., 1987; Li, C.X., and Wang, 1998). The erosional surfaces separating each sequence can be correlated with paleosol horizons on both flanks of the incised valley, further confirming the multi-phase superposition of several incised-valley sequences (Fig. 22).

Because the Luanhe system is located in an uplifted area with differential uplift rates (higher in the west and lower in the east), the Luanhe incised valleys are preserved in a different manner than those of the Changjiang system. This tectonic condition encourages river switching by means of avulsion. Three river switches, each forming an incised valley at a different location and elevation, have been documented (Li, 1985). The valley of the last glacial lowstand was incised into the eastern half of the large, late Pleistocene fan delta (Fig. 8). Each of the older incised-valley deposits is preserved more completely than in the Changjiang system because erosion by the later incision was limited.

CONCLUSIONS

The incised valleys beneath the Luanhe fan delta, the Changjiang delta, the Qiantanjiang estuary, and the Zhujiang

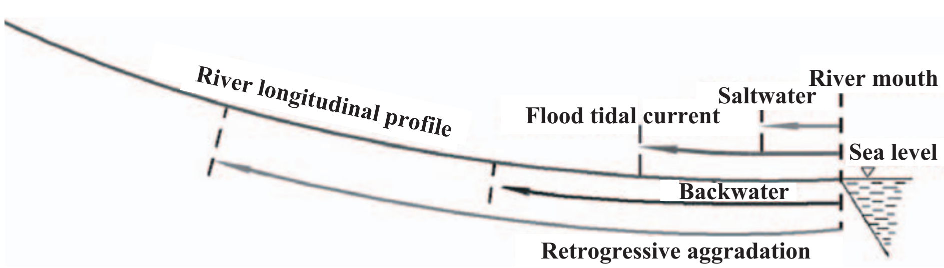

FIG. 19.—Schematic comparison of the upstream limits of saltwater intrusion, flood tidal currents, backwater, and retrogressive aggradation.

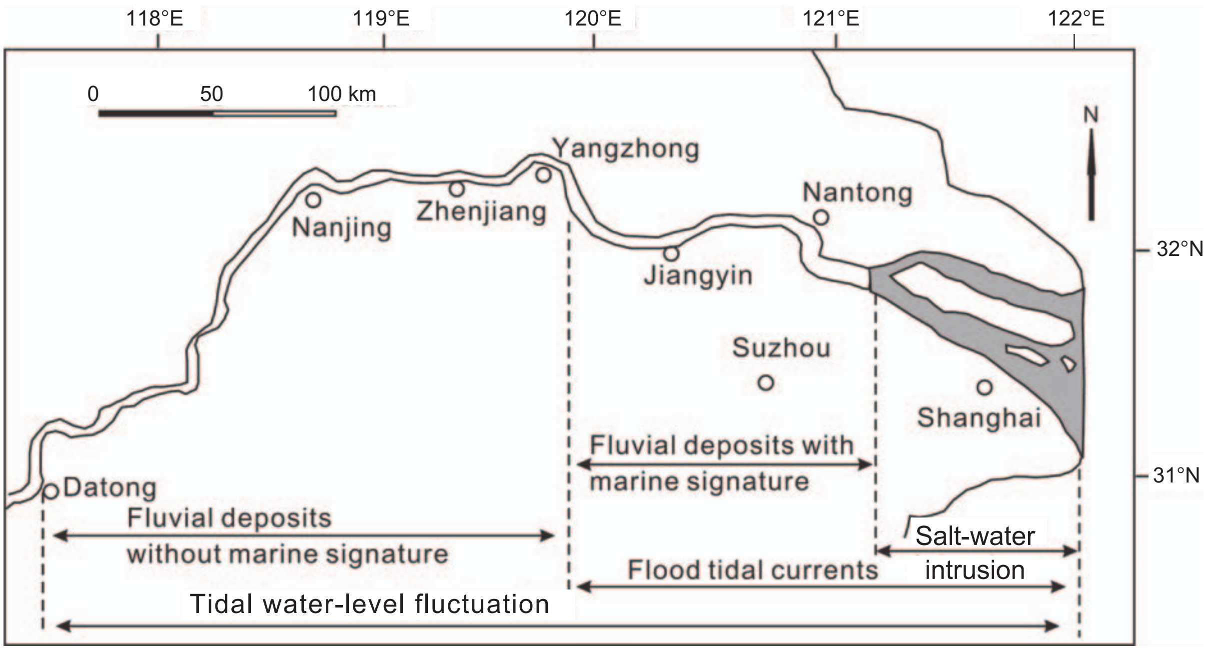

FIG. 20.—Upstream limits of measured saltwater intrusion, flood tidal currents, and tidal water-level fluctuations in the Changjiang River.

delta were formed during the last-glacial sea-level fall and were filled by the following sea-level rise. Estuaries were formed during the transgression and were filled and converted to deltas when sediment supply overwhelmed sea-level rise. Controlled by different tectonic influences, substrate characteristics, sediment supplies, morphology, and relative strength of fluvial and marine processes, the shapes of the postglacial incised valleys are significantly different, including a single long valley for the Changjiang delta, a fan-shaped valley with steep slope for the Luanhe fan delta, and a system divided into several valleys by bedrock hills for the Zhujiang delta.

Four facies successions (FS-I to FS-IV) are summarized from the incised-valley-fill deposits of the four systems. An idealized model is developed with FS-I near the present shoreline, FS-II and FS-III in the middle, and FS-IV at the apex of the present-day deltas/estuaries. This reflects a gradual landward decrease of marine influence, and a gradual increase, to dominance, of fluvial influence. The incised-valley fills are underlain by a basal erosional surface formed by river incision at the lowstand of sea level.

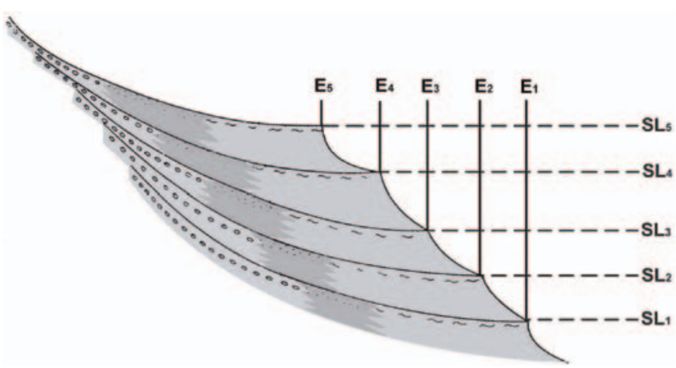

FIG. 21.—Formation of a retrogressive incised-valley fill succession. SL1…SL5: sea-level elevations at various stages; E1…E5: corresponding mouth positions during the sea-level rise.

The boundary between the transgressive and regressive successions is located within the shallow marine facies. This boundary is typically gradual except in the apical areas of the Qiantanjiang estuary and the paleo-Changjiang estuary, where erosion by the intensified tidal currents produced an erosional surface. In the area where FS-III and FS-IV occur, the transgressive and regressive succession boundary occurs entirely within fluvial deposits; there are no shallow marine or estuarine facies in this inland location. Such deposits lie within Zaitlin et al.'s (1992) segment 3. Compared to the regressive succession, the transgressive succession is thicker with a greater volume in the overall incised-valley fills. This is caused by the tremendous rate of sediment supply and serves as a distinct character of sediment-rich incised-valley-fill deposits.

A fining-seaward trend of sediment grain size exists in modern Qiantanjiang and paleo-Changjiang estuaries. Bayhead deltas were not found in all of the four cases. The studied transgressive successions were formed mainly by retrogressive aggradation. During the postglacial transgression, the incised valleys were gradually inundated, with the largest estuary formed at the time of transgression maximum. The regressive succession formed as the sediment supply overwhelmed the sea-level rise.

The preservation of multiple incised-valley fills is controlled by the different regional tectonic characteristics. Within the Changjiang valley, the older incised-valley-fill deposits are commonly partially eroded and reworked by the younger valley incision, resulting in a superposition of river channel deposits of different ages. For the Luanhe fan delta, river switching formed incised valleys and fan deltas that are widely separated and at various elevations.

TABLE 4. —Differences between the transgressive estuarine succession and regressive deltaic succession in the studied incised valleys.

	Transgressive succession	Regressive succession
Sediment characteristics	Fining-upward	Coarsening-upward
Position of development	Lower river reach upstream from mouth	Seaward of the river mouth
Shoreline trend	Transgression	Regression
Depositional process	Retrogressive aggradations due to sea-level rise	Deposition due to jet-flow spreading

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REFERENCES

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

ARDIES, G.W., DALRYMPLE, R.W., AND ZAITLIN, B.A., 2002, Controls of the geometry of incised valley in the Basal Quartz unit (Lower Cretacereous), Western Canada Sedimentary Basin: Journal of Sedimentary Research, v. 72, p. 602–618.

BLUM, M.D., AND TORNQVIST, T.E., 2000, Fluvial response to climate and sea-level change: a review and look forward: Sedimentology, v. 47 (Supplement), p. 2-48.

BORLAND, W.M., 1971, Reservoir sedimentation, *in* Shen H., ed., River Mechanics, vol. 1, p. 29-1–29-38.

CHEN, J.Y., 1989, Formation and evolution of the morphology in the Changjiang Delta, *in* Chen, J.Y., Shen, H.T., and Yun, C.X., eds., Processes of Dynamics and geomorphology of the Changjiang Estuary: Shanghai, Shanghai Scientific & Technical Press, p. 38–47 (in Chinese).

CHEN, J.Y., LUO, Z.D., CHEN, D.C., XU, H.G., AND QIAO, P.N., 1964, Formation and evolution of the tidal sand body in the Qiantanjiang Estuary: Acta Geographic Sinica, v. 30, no. 2, p. 112–123 (in Chinese).

CHEN, Z.Y., AND STANLEY, D.J., 1995, Quaternary subsidence and river channel migration in the Yangtze Delta Plain, eastern China: Journal of Coastal Research, v. 11, p. 927–945.

CHENG, X., 1987, A preliminary study of distribution of living foraminifera in surface sediments of the Changjiang (Yangtze) Estuary: Marine Geology and Quaternary Geology, v. 7(1), p. 73–78 (in Chinese with an English abstract).

DALRYMPLE, R.W., ZAITLIN, B.A., AND BOYD, R., 1992, Estuarine facies models: conceptual basis and stratigraphic implications: Journal of Sedimentary Petrology, v. 62, p. 1130–1146.

DALRYMPLE, R.W., AND ZAITLIN, B.A., 1994, High-resolution sequence stratigraphy of a complex, incised valley succession, Cobequid Bay–Salmon River estuary, Bay of Fundy, Canada: Sedimentology, v. 44, p. 1069–1091.

FISK, N.H., 1944, Geological investigation of the alluvial valley of the lower Mississippi River: Technical Report, Mississippi River Committee, Vicksburg, Mississippi.

Fisk, H.N., and McFarlan, E., Jr., 1955, Late Quaternary deltaic deposits of the Mississippi River, *in* ______, Geological Society of America, Special Paper 62, p. 279–302.

GALLOWAY, W.E., 1975, Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems, *in* Brousssard, M.L., ed., Deltas: Models for Exploration: Houston Geological Society, p. 87–98.

GUPTA, S., 1997, Tectonic control on paleovalley incision at the distal margin of the early Tertiary Alpine foreland basin, southeastern France: Journal of Sedimentary Research, v. 67, p. 1030–1043.

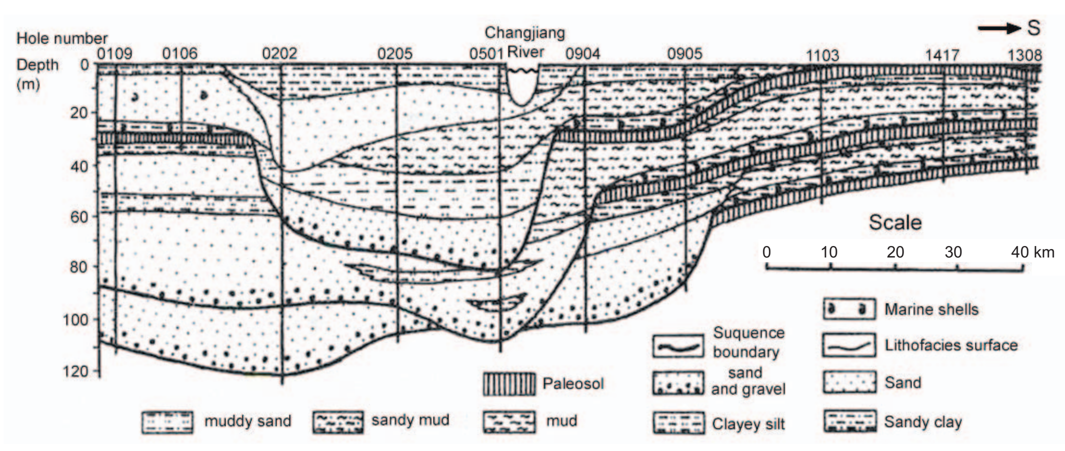

FIG. 22.—Superposition of incised valleys of various stages beneath the Changjiang delta (modified from Li, C.X., and Wang, 1998).

Gupta, S., 1999, Controls on sedimentation in distal margin palaeovalley in the Early Tertiary Alpine foreland basin, southeastern France: Sedimentology, v. 4, p. 357–384.

Hori, K., Saito ,Y., Zhao, Q.H., Cheng, X.R., Wang, P.X., Sato, Y., and Li, C.X., 2001, Sedimentary facies of the tide-dominated paleo-Changjiang (Yangtze) Estuary during the last transgression: Marine Geology, v. 177, p. 331–351.

Huang, Z.G., Li, P.R., and Zhang, Z.Y., 1982, Zhujiang (Pearl) Delta: Formation, Development and Evolution: Guangzhou Popular Science Press, 274 p (In Chinese).

Huang, Z.G., 2000, Sea Level Changes in Guangdong and Its Impacts and Strategies: Guangdong Science and Technology Press, 386 p. (in Chinese).

Li, B.H., Li C.X., and Shen, H.T., 2003, A preliminary study on sediment flux in the Changjiang Delta during the postglacial period: Science in China (Series D), vol. 32, no. 9, p. 776–782.

Li, C.C., 2004, Estuarine Processes and Evolution in South China: China Science Press, 248 p. (in Chinese).

Li, C.C., and Yang, G.R., 1981, Some problems of formation and evolution of the Zhujiang Delta: Collected Papers on Oceanology and limnology, China Science Press, p. 115–122.

Li, C.X., 1984, Sedimentary processes in the Yangtze Delta since Late Pleistocene: Collected Oceanic Works, v. 7, p. 116–126 (in Chinese, with English abstract).

Li, C.X., 1985, The Luanhe Fan-Delta Depositional System: Beijing, Geological Publishing House, 169 p. (in Chinese).

Li, C.X., 1986, Deltaic sedimentation, *in* Ren, M.E., ed., Modern Sedimentation in Coastal and Nearshore Zone of China: China Ocean Press and Springer-Verlag, p. 253–378.

LI, C.X., Chen, G., Yao, M., and Wang, P., 1991a, The influences of suspended load on the sedimentation in the coastal zones and continental shelves of China: Marine Geology, v. 96, p. 341–352.

Li, C.X., Li, P., and Chen, X.R., 1983, The influence of marine factors on the Yangtze River channel below Zhenjiang: Acta Geographica Sinica, v. 38, p. 128–140 (in Chinese, with English abstract).

Li, C.X., Su, H.P., and Tang, G.L., 1993a, Upstream transportation of sediment and longitudinal division of estuaries, in Degens, __, ed., Transport of Carbon and Nutrients in Lakes and Estuaries, Part 6: University of Hamburg, v. 74, p. 209–216.

Li, C.X., Chen G., Zhong, H.X., and Liu, B.Z., 1993b, Sedimentary sequence and environmental evolution of Qiantangjiang estuary during postglacial period: Quaternary Sciences, no. 1, p. 16–24 (in Chinese with an English abstract).

Li, C.X., Chen, Q.Q., and Li, P., 1996, Late Quaternary buried paleosols and their parent materials in the Yangtze Delta: Journal of Tongji University, v. 24, p. 439–444 (in Chinese with English abstract).

Li, C.X., and Wang, P.X., 1998, Late Quaternary stratigraphy of the Yangtze Delta: Beijing, China Science Press, 222 p. (in Chinese).

Li, C.X., Chen, Q.Q., Zhang, J.Q., Yang, S.Y., and Fan, D.D., 2000, Stratigraphy and paleoenvironmental changes in the Yangtze Delta during the late Quaternary: Journal of Asian Earth Sciences, v. 18, p. 453–469.

Li, C.X., Wang, P., Sun, H.P., Zhang, J.Q., Fan, D.D., and Deng, B., 2002, Late Quaternary incised-valley fill of the Yangtze delta (China): its stratigraphic framework and evolution: Sedimentary Geology, v. 152, p. 133–158.

Li, C.X., Fan, D.D., Deng, B., and Korotaev, V., 2004, The coasts of China and issues of sea-level rise: Journal of Coastal Research, SI (43), p. 36–49.

Li, P.R., Qiao, P.N., Zheng, H., Fang, G., and Huang, G.Q., 1991b, The environmental evolution of the Zhujiang (Pearl River) Delta in the last 10000 years: Beijing, China Ocean Press, 154 p. (in Chinese with an English abstract).

Lin, B., and Cao, Y., 2000, Analysis of tidal characteristics in the Hangzhou Bay (Qiantangjiang Estuary): Estuary and Coast Engineering, v. 2, p. 16–25.

Long, Y.Z., 1997, Sedimentary Geology of the Zhujiang (Pearl) Delta: Beijing, China Geological Publishing House, 165 p. (in Chinese).

Makkaveev, N.E., 1960, Experimental Geomorphology: Moscow, Moscow University Press, 166 p. (In Russian).

Nichol, S.L., Boyd, R., and Penland, S., 1996, Sequence stratigraphy of a coastal-plain incised valley estuary: Lake Calcasieu, Louisiana: Journal of Sedimentary Research, v. 66, p. 847–857.

Pattison, S.A.J., and Walker, R.G., 1994, Incision and filling of a lowstand valley: late Albian Viking Formation at Crystal, Alberta, Canada: Journal of Sedimentary Research, v. B64, p. 365–379.

Plint, A.G., and Wadsworth, J.A., 2003, Sedimentology and Palaeogeomorphology of four large valley systems incising delta plains, western Canada Foreland Basin: implication for mid-Cretacerous sea-level change: Sedimentology, v. 50, p. 1147–1186.

Posamentier, H.W., Jervey, M.T., and Vail, P.R., 1988, Eustatic controls on clastic sedimentation I—conceptual framework, *in* Wilgus, C.K., Hasting, B.S., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C., and Kendall, C.G.St.C., eds., Sea-Level Change: An Integrated Approach: SEPM, Special Publication 42, p. 109–124.

Posamentier, H.W., and Vail, P.R., 1988, Eustatic controls on clastic sedimentation II—sequence and systems tract models, *in* Wilgus, C.K., Hasting, B.S., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C., and Kendall, C.G.St.C., eds., Sea-Level Change: An Integrated Approach: SEPM, Special Publication 42, p. 125–154.

Qin, Y., Zhao, Y., and Chen, L., 1987, Geology of East China Sea: Beijing, Science Press, 274 p. (in Chinese).

Qian, N., Xie, H.X., Zhou, Z.D., and Li, G.B., 1964, Present process of formation of the sand body in the Qiantanjiang Estuary: Acta Geographic Sinica, v. 30 (no. 2), p. 124–141.

Qian, N., Zhang, R., and Zhou, Z., 1989, Evolution of River Channel: Beijing, China Science Press, 584 p. (in Chinese).

Schumm, S.A., 1993, River response to baselevel changes: Implications for sequence stratigraphy: Journal of Geology, v. 101, p. 279–294.

Shanley, K.W., McCabe, P.J., and Hettinger, R.D., 1992, Tidal influence in Cretaceous fluvial strata from Utah, USA: a key to sequence stratigraphic interpretation: Sedimentology, v. 39, p. 905–930.

Shen, H.T., 2001, Material Flux of the Changjiang Estuary: Beijing, China Ocean Press, 176 p. (in Chinese).

Thomas, M.A., and Anderson, J.B., 1994, Sea-level controls on the facies architecture of the Trinity/Sabine incised-valley system, Texas continental shelf, *in* Dalrymple, R.W., Boyd, R., and Zaitlin, B.A., eds., Incised-Valley Systems: Origin and Sedimentary Sequences: SEPM, Special Publication 51, p. 63–82.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops: Concepts for High-Resolution Correlation of Time and Facies: American Association of Petroleum Geologists, Methods in exploration series, 7, 55 p.

Wang, P.X., 1985, Marine Micropaleontology of China: China Ocean Press and Springer-Verlag, 370 p.

Wang, Y., 1996, Marine Geography of China: Beijing, China Science Press, 535 p. (in Chinese).

Wu, B.Y., and Li, C.X., 1987, Quaternary Geology of the Changjiang Delta: Beijing, Geological Publishing House, 127 p. (in Chinese).

Yan, S.Z., and Hu, F.X., 1989, Relationship between heavy mineral assemblage and hydrodynamics in the Qiangtanjiang Estuary, *in* Chen, J.U., Wang, B.C., and Yu, Z Y., eds., Development and Evolution of China's Coast: Shanghai Scientific & Technical Press, p. 208–214 (in Chinese).

Zaitlin, B.A., Dalrymple, R.W., and Boyd, R., 1994, The stratigraphic organization of incised-valley systems associated with relative sea-level change, *in* Dalrymple, R.W., Boyd, R., and Zaitlin, B.A., eds., Incised-Valley Systems: Origin and Sedimentary Sequences: SEPM, Special Publication 51, p. 45–62.

ZHANG, G.J., AND LI, C.X., 1998, Sources of sediments filling the Qiantangjiang-estuary incised valley since last glaciation: Chinese Science Bulletin, v. 43 (15), p. 1280–1284

ZHANG, G., AND LI, C., 1996, The fills and stratigraphic sequences in the Qiantangjiang incised paleo-valley, China: Journal of Sedimentary Research, v. 66, p. 406–414.

ZHU, Y., LI, C., AND ZENG, C., 1979, On late Pleistocene low stand of sea level in East China Sea: Chinese Science Bulletin, v. 24, p. 317–320 (in Chinese).