Tide-Dominated Deltas

7

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Abstract

Among tidally influenced sedimentary environments, tide-dominated deltas are perhaps the most variable and difficult to characterize. This variability is due in part to the major role that fluvial systems play in defining their delta, with rivers differing widely in discharge, sediment load, seasonality, and grain size. Tide-dominated deltas also tend to be large systems that can extend hundreds of kilometers across and along the continental margin. The associated sediment transport regimes are typically high energy, but they vary considerably at the scale of tidal cycles and seasonal river discharge. As a consequence of varying transport energy, the sedimentary successions formed in tide-dominated deltaic settings tend to be heterolithic, with interbedded sands, silts, and clays and both fining- and coarsening-upward facies associations. The deltaic nature of tide-dominated deltas that distinguishes them from other tidally influenced settings is defined by the cross- or along-shelf progradation of a clinoform, or 'S' shaped, sedimentary deposit. Under the influence of strong bed shear in tidally dominated margins, this prograding clinoform is often separated into two distinct units, one associated with the subaerial deltaplain and one with an offshore subaqueous delta. Onshore, the large, fertile deltaplains built by many modern tide-dominated deltas, especially in South and East Asia, are heavily populated and sustain large economies, making them global important settings. However, the reduction of fluvial inputs by damming and water extraction, as well as intense agricultural, urban, and industrial land uses, threaten the stability and sustainability of these environments.

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7.1 Introduction

River deltas are variably defined by their geography, morphology, or stratigraphy, but are most generally considered to be a sedimentary deposit formed by a river at its mouth. Here, to distinguish deltas from rivermouth estuaries that also receive fluvial sediment

R.A. Davis, Jr. and R.W. Dalrymple (eds.), *Principles of Tidal Sedimentology*,
DOI 10.1007/978-94-007-0123-6_7, © Springer Science+Business Media B.V. 2012

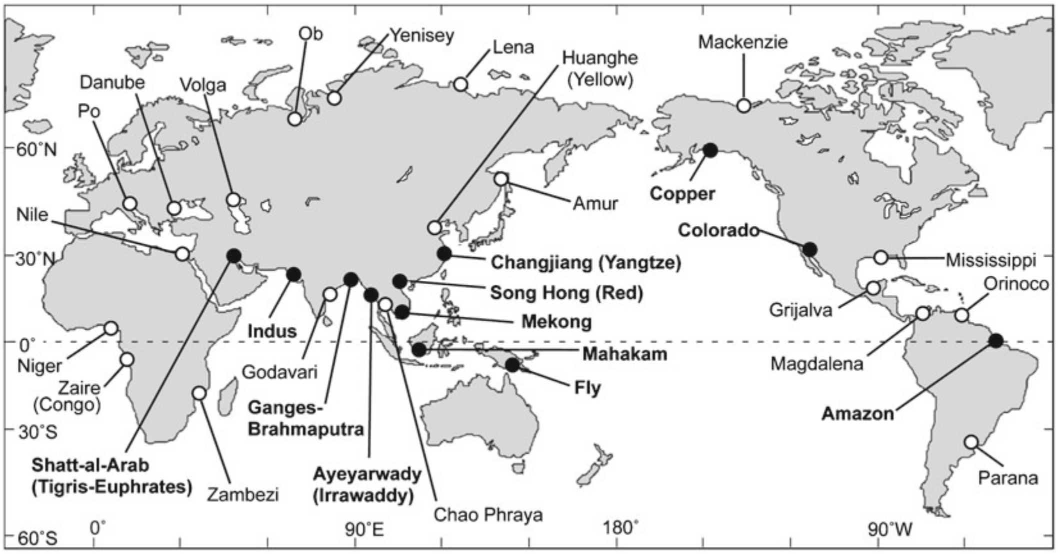

Fig. 7.1 Map of the world's major river delta systems, with those forming tide-dominated deltas indicated (*bold type; filled circle*) (Modified after Hori and Saito 2007)

input (see tide-dominated estuaries chapter), river deltas must receive adequate sediment from the river to build a clinothem, which is a sedimentary deposit having characteristic topset-foreset-bottomset morphology, often in a sigmoidal or 'S' shape. In this way river-fed coastal systems may be depositional, but they are not deltaic if lacking a definable clinoform morphology and progradational features. The surfaces defining many deltaic clinothems are very low-gradient (<3°) for fine-grained deltas and may be difficult to recognize in core or outcrop, so other criteria discussed in this chapter may be important in recognizing deltaic settings from such data. In simplest terms, it is expected that large volumes of heterolithic mud will be found offshore of deltaic rivermouths, which should be a distinguishing character from most other river-influenced settings. Inherent in this definition, deltaic systems will be controlled at a first order by river discharge and fluvial sediment load and secondarily to the rate of reworking by marine processes, primarily waves, tides, and coastal currents.

Although modern and ancient deltas may share a general clinoform morphology, examples from around the world show considerable variability in their surface geomorphology, lithology, process, and response to external forcing. To account for some of this variability, deltas are commonly classified by the dominant process controlling sediment dispersal, and hence surface geomorphology (Galloway 1975). The end-members in this ternary classification scheme are river-, wave- and tide-dominated delta systems, with many examples exhibiting intermediate characteristics that can be classified as mixed-energy (Figs. 7.1 and 7.2). Large deltas may also comprise a composite system, where different portions of the delta are morphologically distinct and controlled differently by fluvial, wave, or tidal processes (Bhattacharya and Giosan 2003). More recent variations of this scheme have in addition considered grain size (Orton and Reading 1993), sediment supply, and sea level (Boyd et al. 1992), although the original Galloway classification arguably remains the most useful for large river deltas.

7.2 Background

7.2.1 Past Research

Although the study of river deltas was active during the first half of the twentieth century (e.g. Russell and Russell 1939), comparatively little research was done on tidally dominated systems, due in part perhaps to their large size, remote locations, and challenging navigation. In the 1970s when delta classification models were first emerging (e.g. Wright and Coleman 1971; Galloway 1975), the only "tide-dominated" end-members that had been studied in any detail were the very small Klang-Langat delta of Malaysia

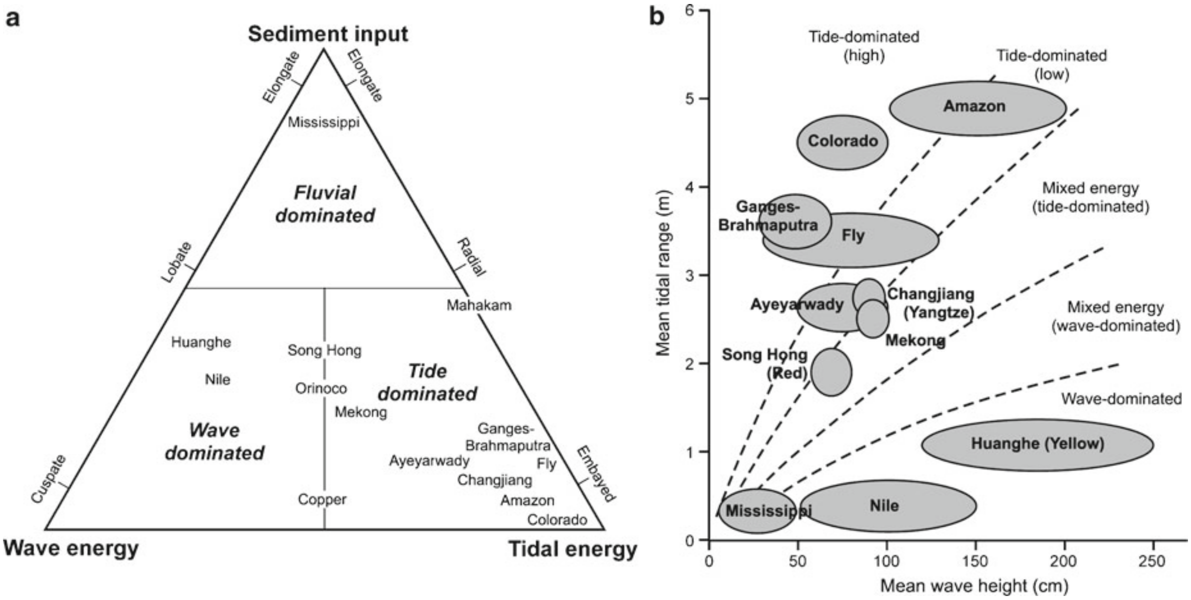

Fig. 7.2 (**a**) Major river deltas classified by the relative influence of river, wave, and tidal processes (After Galloway 1975). (**b**) Mean wave height versus mean tidal range for major large river deltas. The areas are grouped into five morphological classes after the classification of Davis and Hayes (1984) (Modified after Hori et al. 2002a)

(Coleman et al. 1970) and the Yalu and Ord rivers of Korea and Australia, respectively (Coleman and Wright 1978). None of these systems are discussed at length in this chapter as they are best reclassified as tide-influenced deltas (Klang-Langat) or as tidal estuaries (Yalu and Ord; see Chap. 5). In the 1980s the Amazon and Changjiang (i.e. Yangtze) were the first large tide-influenced deltas to be studied in detail through large, comprehensive, and multidisciplinary investigations. The Amazon project, called AMASEDS, collected observational data simultaneously at the seabed and water column over different phases of the river hydrograph and tidal conditions, demonstrating the tremendous benefits of such an integrated approach (Nittrouer and DeMaster 1986). Combined with sediment coring and seismic-reflection surveys, AMASEDS defined the modern approach for studying complex, river-fed continental margin systems. A similar comprehensive study was done for the Changjiang in Asia (Milliman and Jin 1985). However research of tide-dominated deltas remained limited as most studies were of river- or wave-dominated examples (e.g. Mississippi, Nile, Ebro, Rhine).

Middleton (1991) pointed out that a majority of very large rivers in terms of sediment load discharge along meso- to macrotidal coasts, forming tide-dominated or tide-influenced deltas (Fig. 7.1). In response, research was initiated in several tidally affected deltas, with the Fly river being among the first major tide-dominated deltas to be studied in detail (Harris et al. 1996; Wolanski et al. 1995). Since that time the rate of investigation has accelerated and today most major tide-dominated delta systems have received some formal investigation. Most studies have employed stratigraphic or seismic-reflection approaches, but observational and hydrodynamic data remain rare for many systems. Among several coordinated research programs, recent efforts have focused on the Changjiang, Mekong, and other nearby Asian deltas (e.g. Hori et al. 2001; Ta et al. 2005), and the Gulf of Papua 'continuum' that includes the tide-dominated Fly and Kikori deltas (e.g., Ogston et al. 2008; Walsh et al. 2004). The Ganges-Brahmaputra has been reasonably well studied by individual working groups (Goodbred and Kuehl 2000; Kuehl et al. 2005; Michels et al. 1998), and to a lesser extent the Indus (Giosan et al. 2006) and Colorado (Carriquiry and Sanchez 1999; Thompson 1968) deltas. The Ayeyarwady (i.e., Irrawaddy) and Tigris-Euphrates deltas, however, remain notable exceptions with very little published research.

Other more general studies have advanced our understanding of continental margin systems with great implications for tide-dominated deltas, including developments in shelf hydrodynamics and sediment transport (Wright and Friedrichs 2006), and the quantitative modeling of delta evolution, stratigraphy (Fagherazzi and Overeem 2007), and clinothem development (Swenson et al. 2005; Slingerland et al. 2008). One continuing challenge, though, is the difficulty in numerically modeling tidal sediment transport due to complications of the bidirectional flow, thus limiting our ability to assess impacts of environmental changes such as discharge variations, sediment loading, and sea-level change. Although effective modeling of tidal sediment transport remains elusive, progress is being made in understanding hydrodynamics of the complex network of tidal channels (Fagherazzi 2008) and compound clinoform morphology (Swenson et al. 2005; Wright and Friedrichs 2006) that characterize tide-dominated delta systems. These topics are discussed in detail later in this chapter.

7.2.2 Modern Examples

In this chapter we focus primarily on tide-dominated deltas, including examples of the Colorado, Fly, Ganges-Brahmaputra, Indus, Irrawaddy, and Changjiang, with some discussion of tide-influenced deltas such as the Amazon, Mahakam, and Mekong. Overall these systems are best characterized by their wide river mouths that have a pronounced upstream taper and well-developed channel bars and islands. All examples are subject to mesotidal to macrotidal conditions with spring tidal ranges typically ≥3 m. Because of this continual exposure to tidal exchange and sediment transport, tide-dominated deltas along open shorelines are typically fed by large rivers that discharge high sediment loads, although smaller rivers may form deltas in more embayed settings (e.g. Gironde River, France). Indeed, 10 of the river deltas listed above (excluding the Mahakam) rank among the world's top 25 rivers in terms of their fluvial sediment discharge (Milliman and Meade 1983; Milliman and Syvitski 1992). Rankings for the Colorado, Tigris-Euphrates, and Indus rivers are based on historical estimates prior to major damming and sediment trapping.

Most tide-dominated deltas today are located in tectonically active, low-latitude regions, including South Asia, East Asia, and Oceania (Fig. 7.1). Many factors relevant to the development of tide-dominated delta systems are common to these areas. First, amplification of the M2 tidal component in high tidal-range areas is supported by broad, relatively shallow continental shelves and seas that are well connected to the open ocean, and in many instances taper in width toward their apex. Prominent examples include the Arabian Sea (Indus), Bay of Bengal (Ganges-Brahmaputra), Andaman Sea (Ayeyarwady), Gulf of Papua (Fly), and East China Sea (Changjiang). A second factor common to most tide-dominated deltas, and many deltas in general, is that they drain high-standing, tectonically active mountains. Such active orogens yield the abundant sediment required for deltas to form in high-energy coastal basins. In particular the Himalayan-Tibetan uplift and Indonesian archipelago sustain among the world's highest sediment yields (Milliman and Syvitski 1992).

7.2.3 Humans and Deltas

Many tide-dominated deltas are among the world's largest in areal extent (Woodroffe et al. 2006), and the immense, agriculturally rich, lowland delta plains that have formed at the mouths of the Ganges-Brahmaputra, Indus, Ayeyarwady, Mekong, and Changjiang rivers support nearly 200 million people. These populations, like those in all deltas, are at risk from flooding, tropical cyclones, sea-level rise and related environmental hazards. Unfortunately, our current understanding of the process-response (morphodynamic) relationships in tide-dominated deltas is inadequate to assess the likely outcome of various environmental-change scenarios. Much may be learned by further investigation of the several tide-dominated deltas that have already been severely degraded due to river damming, water extraction, and reduced sediment discharge, notably the Indus, Colorado, and Tigris-Euphrates (Syvitski et al. 2009). Despite risk and uncertainty, major dams continue to be constructed on rivers that feed high-energy, tide-dominated delta systems, such as the Three Gorges Dam on the Changjiang and the Xiaowan Dam on the Mekong (Yang et al. 2006; Kummu et al. 2010). Not all tide-dominated deltas are strongly human-impacted, however, with the Amazon, Copper, and Fly river systems draining relatively natural catchments and having sparsely populated delta plains. Similarly, the Ganges-Brahmaputra and Ayeyarwady rivers remain undammed despite their heavily populated catchments, and so their large water discharge and sediment loads sustain stable, if still locally dynamic, delta systems.

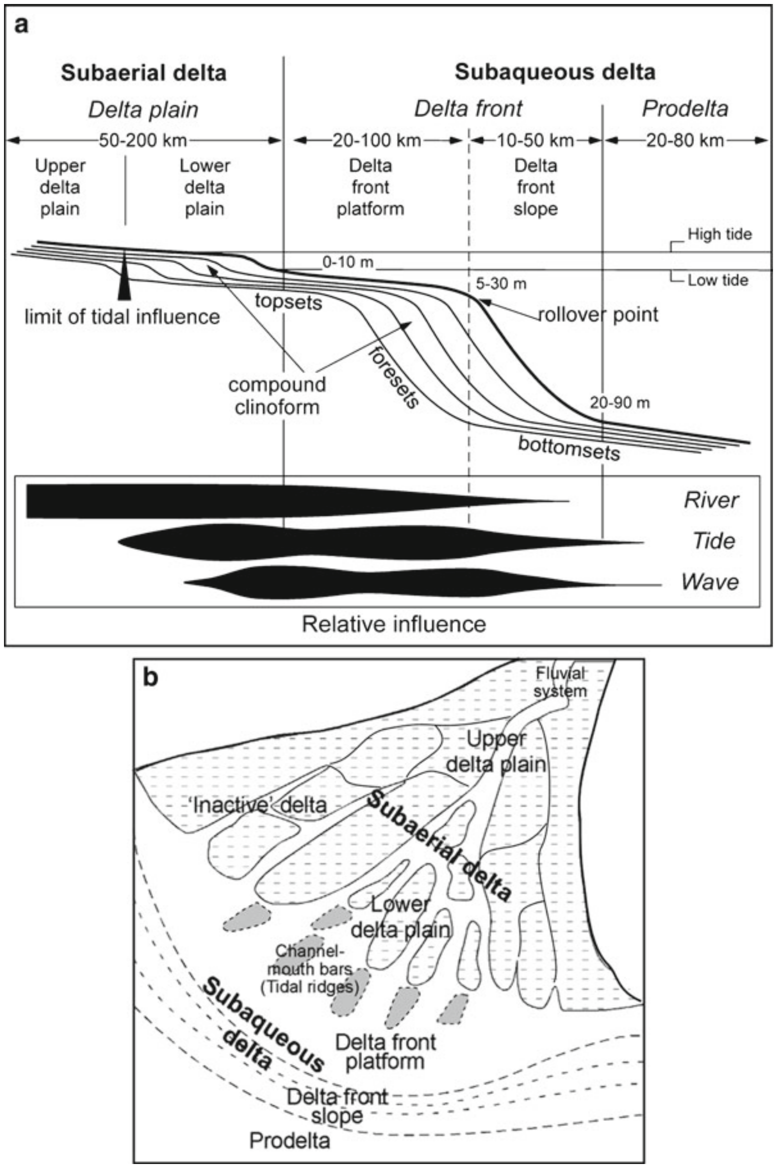

Fig. 7.3 Major physiographic and morphologic features of tide-dominated delta systems shown in (**a**) cross-section and (**b**) planform. Note the well developed subaerial and subaqueous portions of the delta, each represented by a prograding clinoform. The rivermouth is also characterized by channel-mouth bars that build just seaward of the shoreline, and in many cases become emergent and amalgamate into large channel-mouth islands (Modified from Hori and Saito 2007)

7.3 Hydrodynamics

Tide-dominated deltas have complex hydrodynamics that are strongly influenced by river discharge, tidal exchange, and other marine processes such as waves and storms (Fig. 7.3). Each of these controls varies considerably with time (e.g., fortnightly, seasonal, episodic) and location (e.g. active rivermouth, 'inactive' delta plain, subaqueous delta). By definition, tides are perhaps the overarching control on tide-dominated delta systems, but the fact that these are prograding deltas and not transgressing tidal estuaries also reflects the tremendous influence of large fluvial systems feeding them. In addition, large riverine

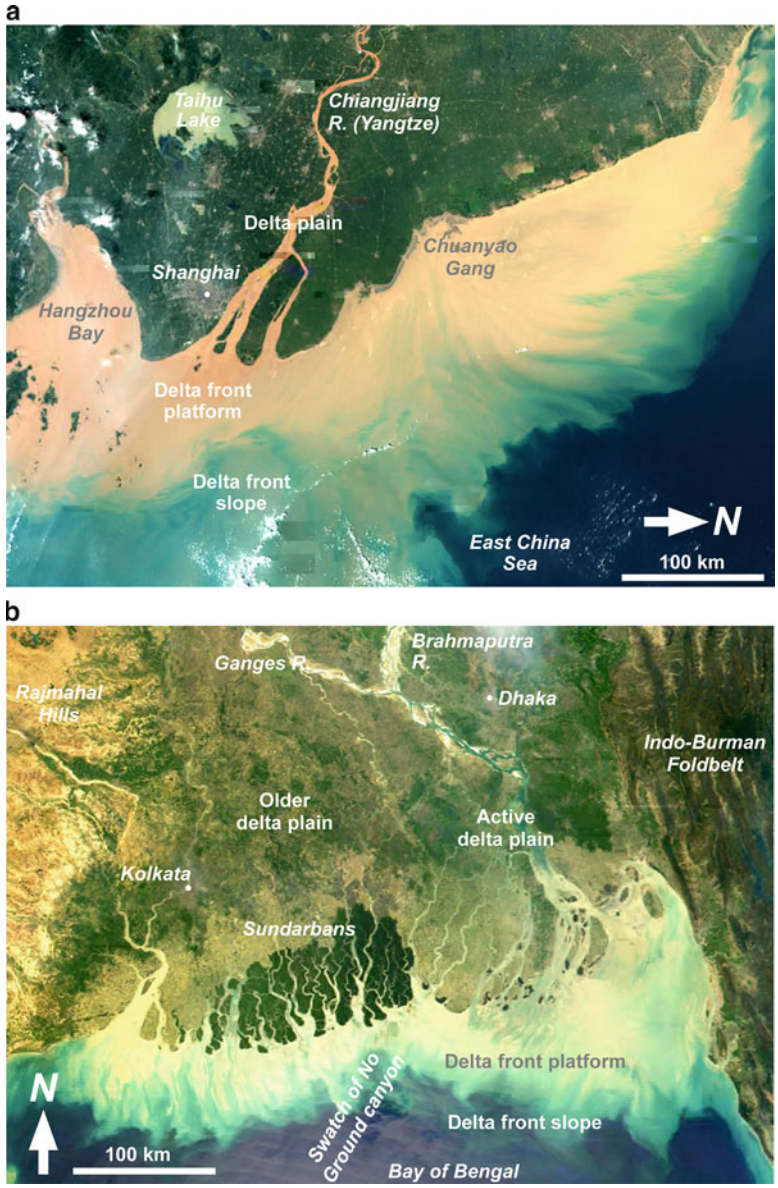

Fig. 7.4 MODIS satellite images of two major tide-dominated delta systems, (**a**) the Changjiang river delta taken near the end of the flood season on 25 October 2000 and (**b**) the Ganges-Brahmaputra river delta taken late in the dry season on 19 March 2002. Major geographic and physiographic features of the delta and surrounding areas are labeled. Both images show high suspended sediment concentrations that extend 50–100 km offshore and hundreds of kilometers alongshore, largely due to suspension by tidal currents (Images from NASA MODIS, http://modis.gsfc.nasa.gov/)

sediment fluxes and persistent tidal energy sustain high suspended-sediment concentrations offshore, where these particulates are subject to widespread dispersal by coastal and ocean currents that are normally too slow for entraining sediments without the addition of a tidal-velocity component (Fig. 7.4). Overall, though, tide-dominated deltas bear the mark of not only strong tidal influence, but also fluvial and marine processes that play critical roles in defining the character and behavior of these complex margin systems.

7.3.1 Tidal Processes

7.3.1.1 Tidal Amplification

At the offshore limits of the delta system, the incoming ocean tide first interacts with the clinoform delta-front, where water depths shoal from 20 to 90 m at the bottomsets to 5–30 m at the topset-foreset rollover point, a distance typically of a few tens of kilometers for megadeltas to a few kilometers for smaller deltas (Fig. 7.3; Storms et al. 2005). Tidal currents accelerate across this zone from <20 cm/s on the open shelf to 30–80 cm/s on the outer delta-front platform (ie., topsets), still tens of kilometers offshore. This acceleration across the prograding delta-front represents an important morphodynamic feedback that in large part is responsible for forming the compound clinoform that is typical of most tide-dominated delta systems. In this case strong bed shear on the inner shelf (i.e., delta platform) defines a zone of limited deposition that separates the prograding subaqueous and subaerial clinoforms (Fig. 7.3a; see also Sect. 7.3.3.2).

After crossing the delta-front platform (i.e. topsets) the progressive tide wave becomes channelized as it propagates upstream of the shoreline, inducing a second phase of energy focusing that accelerates tidal currents to velocities of 50 to >100 cm/s. This acceleration continues for a significant distance upstream (10s of km) due to tidal amplification. Although tidal energy is lost to friction, the local tidal power is actually amplified by the decreasing cross-sectional area of the narrowing channels. This is called a hypersynchronous channel system, whereby tidal height and current velocities increase steadily upstream before declining to zero as tidal energy becomes increasingly attenuated by frictional forces.

Due to this positive feedback of tidal amplification across the shallow prograding delta-front and tapering delta-plain channels, tides actually influence a much larger reach of the continental margin than they would in the absence of the delta. In larger tide-dominated deltas, this enhanced tidal influence may extend 100–200 km across the margin (Fig. 7.5). In general tidal-bed shear in this broad reach is sufficient to impart a strong influence on sediment transport and deposition, although preservation of tidal signatures in the sedimentary record is less certain (see 7.4.2).

7.3.1.2 Tidal Asymmetry

An important consequence of hypersynchronous tidal amplification is the development of an asymmetry in the ebb and flood limbs of the tidal wave. In this case the wave crest (high tide) propagates faster than the wave trough (low tide), causing the flood period (low to high tide) to shorten and ebb period (high to low tide) to lengthen. This time asymmetry requires higher current velocities for the flooding tide to accommodate the tidal prism, and is described as being a flood-dominant tidal system.

Given that the rate of sediment transport (y) increases as a power function (b) of current velocity (x), where $y = ax^b$ with $b = 1.6$–2.0, most flood-dominant tidal systems result in a net onshore-directed transport of sediment, an effect called "tidal pumping" (Postma 1967). This effect may have fundamental implications for the morphology and behavior of tide-dominated delta systems (see Sect. 7.4.1), but its nfluence likely varies spatially and temporally with such factors as river discharge. For example, where river discharge is high the net flow and sediment transport patterns may be significantly altered or even reversed from the tidal signature alone. In general low river discharge allows a net upstream (landward) transport of sediment (e.g., during the dry season), whereas high discharge weakens this tidal-pumping effect and forces net offshore transport. These natural patterns in tidal pumping and sediment transport may be considerably altered on rivers with large dams used to artificially control water discharge (Wolanski and Spagnol 2000).

7.3.2 Fluvial and 'Estuarine' Processes

The evolution of tidal hydrodynamics at the coast is not only influenced by seabed and shoreline morphology but also by interactions with freshwater discharge. In the case of most tide-dominated deltas, the interaction of large river-water fluxes and meso- to macro-tidal regimes tend to generate strong horizontal shear, turbulent eddies, and vigorous vertical mixing. Such dynamic flows are generally adequate to preclude density stratification and result in a well-mixed estuary at the delta rivermouth. Therefore buoyancy-driven gravitational circulation is not as significant in

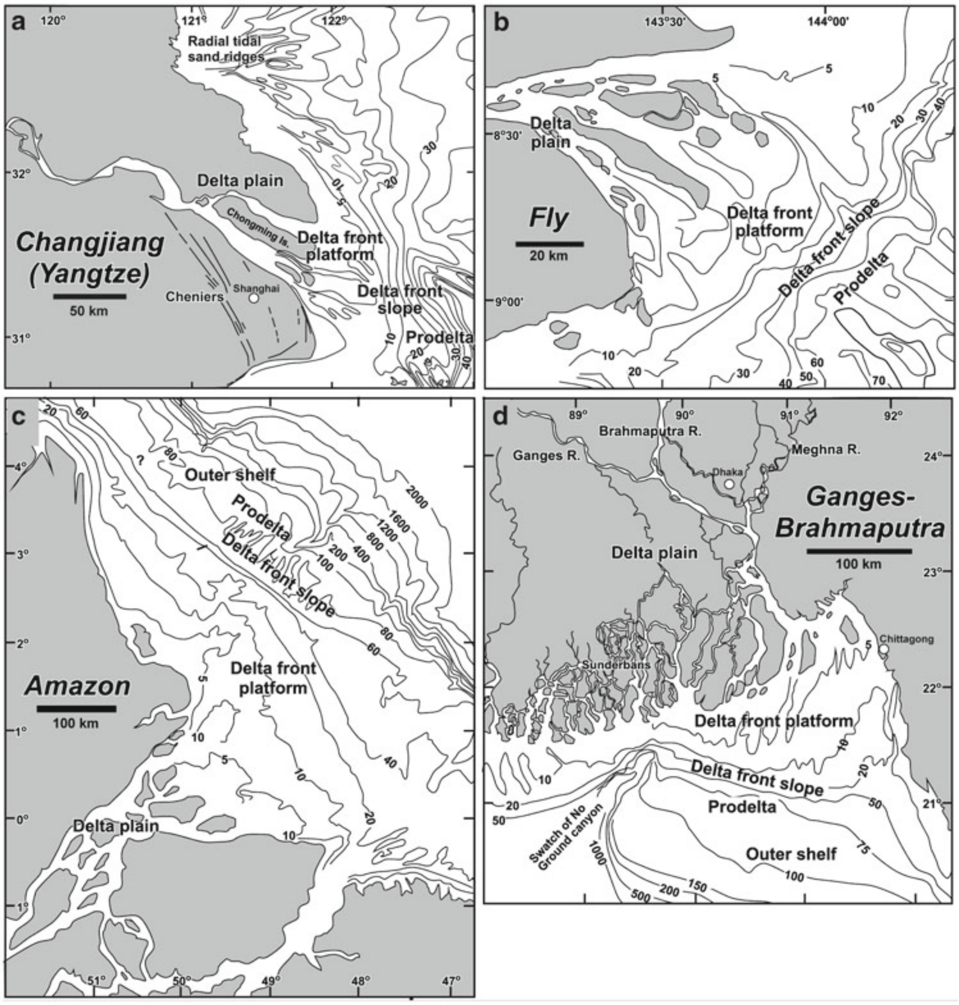

Fig. 7.5 Physiographic maps of four major tide-dominated delta systems, including the (**a**) Changjiang, (**b**) Fly, (**c**) Amazon, and (**d**) Ganges-Brahmaputra. Note the variable scale but similar funnel-shaped morphology of the rivermouths, each with characteristic channel-margin bars that are many tens of kilometers long. Each delta system is also characterized by a large muddy clinothem deposit that is forming off the rivermouth, at a similar length-scale of many tens of kilometers offshore (Compiled after Hori et al. 2002a; Harris et al. 2004; Nittrouer et al. 1986; Goodbred and Kuehl 2000)

tide-dominated deltas as it is at many less energetic river mouths. As with any complex natural system, though, partially mixed stratification and weak estuarine circulation may develop locally within tide-dominated deltas given spatiotemporal differences in tidal energy (spring vs. neap) and river discharge (seasonality and flow splitting amongst the distributary channels).

7.3.2.1 Sediment Transport Convergence

Although stratification is not generally important in tide-dominated delta systems, river discharge plays at least two other key roles in defining system-scale hydrodynamics. First, the flux of freshwater from the river relative to the incoming tidal prism determines the position of sediment transport convergence within the rivermouth or on the shelf. Sediment convergence occurs where sediments are trapped by outflowing river discharge and onshore tidal transport, causing a high concentration of suspended sediment, often referred to as the turbidity maximum, and high deposition rates on the underlying seabed. In general, high river discharge relative to the tidal prism forces the location of this sediment convergence further seaward and defines an important location of dynamic-scale sediment accretion (i.e., where sediments may be stored for short time periods, less than a year, and subject to later reworking). In contrast to tide-dominated estuaries where the flux convergence of suspended sediment tends to be located near the apex of the rivermouth embayment, the convergence in tide-dominated deltas is typically near the mouth of the embayment or slightly seaward (e.g. Fly, Ganges-Brahmaputra, Changjiang; Dalrymple and Choi 2007). The convergence may shift many kilometers upstream during the low-discharge dry season (Wolanski et al. 1996), but, with the majority of sediment delivered during high river flow, the wet-season transport regime is more important to delta evolution. In an extreme case the Amazon River, with more discharge than any other river on Earth, actually forces its tide-river flux convergence 60–90 km offshore onto the middle continental shelf where most sediment accumulates in the subaqueous clinothem (Kuehl et al. 1986; Nittrouer et al. 1986). Although depositional patterns here are strongly tide influenced, no saltwater enters the Amazon rivermouth at any time of the year despite a spring tidal range of ~7 m. Finally, it is important to note that the location of flux convergence for coarser-grained bedload may lie considerably landward of that for suspended load (Montaño and Carbajal 2008).

7.3.2.2 Residual Flow

The second important interaction of river discharge with tidal hydrodynamics is that river flow, at least seasonally, dominates the residual flow in tide-dominated deltas. Residual flow is the resultant current vector (i.e., 'net drift') that emerges from averaging all flow components (tidal, fluvial, and marine) over a period of weeks to a year. Residual flow can be difficult to determine from short-term instrumental deployments because of the dominance of non-steady synoptic-scale forces (e.g., waves, storms, flood discharge), and thus results may differ depending on the time-scale over which observations or calculations are made. Ultimately, though, it is the asymmetry in tidal currents and the unidirectional flow of river discharge that tend to generate residual flows and dominate the net *fluid* transport in tide-dominated delta systems (Barua et al. 1994).

Because residual flow is a purely fluid transport phenomenon, its role in sediment transport will vary depending on the timing, magnitude, and duration that sediments are suspended in the water column. Thus, along lower-energy margins where suspended sediment concentrations are comparatively low and much of the sediment is relatively coarse (i.e., sand-sized) bedload, time-averaged residual flows may not be important to overall morphologic development. However, on high-energy, tide-dominated deltaic margins where suspended-sediment concentrations are consistently high, the weak but persistent residual flows may account for much of the long-term net sediment transport and resulting morphological evolution of the rivermouth delta and adjacent tidal delta plain.

7.3.3 Marine Processes

The large rivers that feed most modern tide-dominated deltas export much of their sediment load to the shelf, where it is subject to a suite of marine processes – tides, waves, storms, geostrophic currents – that ultimately define the morphology and development of the subaqueous portion of the delta (Walsh and Nittrouer 2009). Often the greatest effect of these processes on sediment dispersal and development of the subaqueous delta occurs when they are coincident with high river discharge. Complex, non-linear interactions that emerge during high-energy stochastic events (e.g., storms, floods) may account for large-scale transport and redistribution of fine-grained sediment to all portions of the delta, but has been demonstrated to be especially important to offshore transport (e.g. Ogston et al. 2000). In this case the importance of such offshore mud transport has long been recognized (Swift et al. 1972) from the widespread occurrence of accreting mud wedges on the shelf, but the mechanisms of such transport remained uncertain and controversial until recently (Hill et al. 2007). In the past two decades direct instrumental observations have revealed the regular occurrence of gravity-driven cross-shelf transport occurring off the mouths of most of the world's major rivers (Wright and Friedrichs 2006). This transport phenomenon, which is generated by the interaction of fluvial and marine processes, shares many of the same conditions shown to be necessary for the development of a subaqueous muddy clinothem (Swenson et al. 2005), and probably defines much of the shelf morphology found offshore of large rivers in high-energy settings.

7.3.3.1 Gravity-Driven Sediment Transport

Widespread occurrence of mud deposits and active mud accretion on the middle of continental shelves has long drawn speculation as to the mechanisms responsible for their emplacement (Swift et al. 1972). General observations of focused, rapid accumulation imply an association of these deposits with sediment-laden density currents, which are near-bottom fluid flows that are denser than the overlying water column because of a high concentration of suspended sediment. Turbidity currents are an example of gravity-driven transport, but the gradient of the shelf is typically too low to sustain the high flow velocities needed to maintain continuous sediment suspension and the downslope propagation of such gravity flows. Not only are shelf gradients low, but very few rivers discharge sediment plumes that are hyperpycnal (i.e., denser than the ambient coastal seawater), and this is especially true of the larger, relatively dilute rivers offshore of which shelf mud deposits are most prevalent.

In the past two decades, though, repeated synoptic-scale observations of seabed and water column dynamics during storms and high-discharge flood events have demonstrated that gravity-driven near-bed density flows are a common mode of cross-shelf mud transport (Wright and Friedrichs 2006). The controlling processes and boundary conditions can vary widely, but the fundamental requirements are hyperpycnal near-bed sediment concentrations and a mechanism for maintaining sediment suspension on the low-gradient shelf, typically accomplished by waves and/or tidal currents. These specialized requirements are most typically met when rivers are discharging peak sediment loads onto an energetic shelf, which arguably occurs with the greatest regularity along tide-dominated deltaic margins (Harris et al. 2004). It is uncertain whether this assertion is true because gravity-driven transport is recognized in many margin systems, but it can be said that gravity-driven transport has been documented in all tide-dominated deltas with adequate observations (Wright and Friedrichs 2006).

7.3.3.2 Compound Clinoform Development

As gravity-driven transport is generally associated with high-discharge and high-energy conditions, so too is the development of a compound-clinoform morphology in delta systems (Fig. 7.3; Swenson et al. 2005). The concept of compound clinoforms emerged from investigations of tide-dominated and tide-influenced deltas in the 1980s (e.g. Amazon, Huanghe), when it became clear that these systems supported actively accreting subaqueous deltas that are located substantial distances offshore of, and separate from, their better recognized subaerial landforms (Fig. 7.5; Nittrouer et al. 1986; Prior et al. 1986). The presence of well-developed subaqueous deltas has also been documented for the tide-dominated Ganges-Brahmaputra, Indus, and Changjiang river deltas (Chen et al. 2000; Kuehl et al. 1997; Giosan et al. 2006). In these systems the subaerial clinoform includes primarily the lower delta plain and advancing shoreline that form at the convergence of onshore-directed marine processes and river discharge, whereas the subaqueous clinoform develops at the boundary between shallow-water and deep-water processes (i.e., wave-tide-current transport vs. gravity-driven transport; Swenson et al. 2005).

7.3.4 Sediment Budgets

Tide-dominated deltas are commonly large sediment dispersal systems controlled both by high-energy coastal processes and high-discharge rivers. Their sediment load is widely dispersed with active deltaic sedimentation occurring tens to hundreds of kilometers across and along the continental margin. Therefore, developing sediment budgets for these systems is inherently useful in understanding how they respond to external forcings (e.g., climate, sea level) and how their fluvial, coastal, and marine reaches interact.

One of the first budgets developed for a tide-dominated delta was in the Fly River system, where Harris et al. (1993) could only account for about half ($55 \pm 20\%$) of the annual sediment load of ~85×10^6 metric tons within the tide-dominated portion of the delta (note: load estimate prior to construction of the Ok Tedi mine). Of the sediment that could be located, roughly equal volumes were apportioned to the lower delta plain (i.e., subaerial clinothem) and deltafront/prodelta system (i.e., subaqueous clinothem). Subsequent work has shown that most of the 'missing' fraction is split between deposition on the Fly's vast lowland river floodplain (Swanson et al. 2008) and the actively growing alongshelf clinothem (Slingerland et al. 2008). A similar distribution of sediment was determined for the Ganges-Brahmaputra river delta, where both modern and Holocene budgets show that ~40% of the annual load is trapped within the prograding subaerial and subaqueous clinothems of the tide-dominated portion of the delta. The remaining 60% is distributed about evenly to the fluvial deltaplain through overbank sedimentation and to the Swatch of No Ground canyon that feeds the deep-sea Bengal Fan (Goodbred and Kuehl 1999).

Liu et al. (2009) recently developed budget approximations for several tide-dominated or tide-influenced deltas, showing that 30–40% of the sediment load for the Huanghe (Yellow), Mekong, and Changjiang rivers escape the deltaic depocenters located in the vicinity of the river mouth, similar to the portion observed for the Fly and Ganges-Brahmaputra dispersal systems. In the case of these East Asian examples, though, sediments are advected distances of up to 500–800 km before being deposited as an alongshelf clinothem at inner- to mid-shelf water depths. Prior to these recent studies, it was thought that only the Amazon dispersal system supported such long-distance alongshelf-export of sediment from its river delta (Allison et al. 2000). Aside from their distance, though, these remote clinothems share nearly all characteristics of a prodelta mud wedge, raising the question of whether they should be considered part of the delta system. Regardless of their classification, these findings emphasize that tide-dominated deltas are only part of a larger source-to-sink continuum of interacting continental-margin components (e.g., Goodbred 2003).

7.4 Sedimentary Environments

The sedimentary environments of tide-dominated delta systems can be largely divided into those associated with the 'subaerial' and 'subaqueous' portions of the compound clinoform (Figs. 7.3 and 7.5). The subaerial delta can be further subdivided into a 'lower delta plain' that is influenced by tides and other marine processes and an 'upper delta plain' that is above the tidal influence and dominated by fluvial processes. Offshore the subaqueous delta has often been subdivided into the 'delta front' and 'prodelta', but here we subdivide the clinothem into the 'delta-front platform' (or subtidal delta plain), the 'delta-front slope', and 'prodelta' based on both morphology and sediment facies (Fig. 7.3a). In river-dominated delta systems the subaerial delta, together with the delta-front platform, comprises the topsets of a single deltaic clinoform, with wave-dominated systems often having a definable but closely spaced double clinoform. In the case of most tide-dominated deltas though, these environments are separated by a broad high-shear zone of limited sediment accumulation that separates the prograding subaerial and subaqueous clinoforms of the compound delta system (Nittrouer et al. 1986; Swenson et al. 2005). Beyond the rollover point (i.e. topset-foreset transition) the 'foreset' and 'bottomset' regions of the clinoform correspond to the delta-front slope and prodelta, respectively. Another feature of tide-dominated deltas is that this zonation is irregular along the coast with multiple, wide distributary channels and islands occurring within a funnel-shaped embayment (Fig. 7.5), as compared with wave-dominated deltas where environmental zonation is roughly parallel to the shoreline.

7.4.1 Subaerial Delta

As noted by Middleton (1991) many of the largest rivers discharging to tide-dominated coasts have a principally fine-grained sediment load that forms a mud-dominated delta system. The shoreline of such deltas is often fringed by expansive tidal flats, marshes, and/or mangroves threaded by tidal channels (see Chaps. 8–10). These tidally-dominated environments are characteristic of the intertidal to shallow subtidal zone, particularly at the rivermouth and along adjacent coasts, and may include salt marshes, mangroves, muddy tidal flats, tidal channels, and channel-mouth bars. In tropical to subtropical tide-dominated deltas the subaerial deltaplain comprises broad mangrove-colonized plains that extend from the limits of salt intrusion downward to the upper half of the intertidal zone, where they merge with wide intertidal mud and sand flats in the lower intertidal zone.

This transition between subtidal and supratidal environments is the principal zone of subaerial delta progradation and is largely defined by the development of channel-mouth bars within and just seaward of the active river mouth (Allison 1998). These bars are generally large (10^2–10^4 m) elongate features that extend from shallow subtidal to supratidal elevations, forming within or along the active distributaries of the rivermouth estuary and comprising muddy, sandy, to heterolithic sediments (Fig. 7.5; Chen et al. 1982; Dalrymple 2010). For rivers discharging large sediment loads, such tidal ridges accrete vertically and horizontally, and ultimately merge to form shallow, intertidal flats. These flats eventually become emergent and vegetated to form new delta-plain environments. In this way the growth of tidal ridges marks the incipient stage of delta-plain progradation and is a defining process in tide-dominated deltas (Allison et al. 2003).

The sedimentary facies that characterize the tide-influenced distributaries comprise laminated to thinly bedded sand-mud alternations with tidal signatures, although these are not always well preserved or statistically definable (Dalrymple et al. 2003). Due to the saltwater intrusion into distributary and tidal channels, marine to brackish fauna (e.g. molluscs, foraminifera and ostracods) can be found >100 km upstream of the shoreline. Foraminifera transported by flood tides are recognized even further upstream, presumably transported during low river discharge and high astronomical tidal conditions. However, such patterns are expected to be temporally and spatially variable in complex delta systems, where differences in discharge among active and abandoned distributary may strongly affect onshore transport distances for marine-derived particles.

Along the distributary channel margins, inclined sand-mud alternations are reported from channel slope to tidal flats, which are termed inclined heterolithic stratification (IHS) (Choi et al. 2004). Rhythmic climbing-ripple cross-lamination and neap-spring cycles may also be associated with IHS (Choi 2009). These distributary-channel deposits contain well-sorted fine silt to clay, often derived from near-bed fluid muds (e.g. Fly River; Ichaso and Dalrymple 2009). These sediments with high accumulation rate and large sediment supply can provide indirect evidence of river deltas in the rock record, although they do not necessarily distinguish them from tide-dominated estuaries unless other indicators, such as a progradational stacking of facies, can also be recognized.

Muddy tidal flats are one of the most important components of tide-dominated deltas. The typical sediment facies of this environment comprises sand-mud alternations with flaser, lenticular and wavy laminations or bedding, especially close to the river mouth where sedimentation rates are high and bedding is well preserved (Reineck and Singh 1980). Bidirectional features of sand-layer stacking and cross-laminations, and mud-drapes or double mud-drapes, indicate tidally influenced deposition. These sand-mud layers are basically controlled by cycles of flood-slack-ebb-slack tidal currents, where slack periods produce the draping muds and flood and ebb currents form planar to ripple-laminated sand layers. However, neap-spring tidal cycles are not often recorded in the laminations (Dalrymple and Makino 1989), as much of the record is destroyed by bioturbation, waves, storms, and other events (Fan and Li 2002; Fan et al. 2004, 2006). From the subtidal to intertidal zones, these sediment facies typically show an upward-fining and thinning succession. The thicker and coarser layers in the lower intertidal zone result from more mud settling from the water column at slack tide and stronger currents during flood and ebb for sand transport. The migration of tidal channels and creeks across tidal flats may also generate a typically fining-upward and thinning-upward succession (e.g., Gulf of Papua, Walsh and Nittrouer 2004). Toward the top of the succession in the upper intertidal zone, plant rootlets and peat/peaty sediments become common and reflect transition to a vegetated delta-plain facies with subaerial soil formation (Allison et al. 2003). In tropical to subtropical areas woody mangroves dominate these environments, with tree roots, leaves, and other plant fragments forming peats and organic-rich sediments.

Alternating sand-mud layers also commonly occur within subtidal shoals that form on the delta-front platform and likely represent the incipient phase of channel-mouth bar formation. In the Amazon and Ganges-Brahmaputra deltas these deposits are interbedded or interlaminated sand and mud that are formed under the strong influence of tides, especially the neap–spring cycle (Jaeger and Nittrouer 1995; Michels et al. 1998). The daily tidal exchange is not typically recorded, though, either not being formed or not preserved. The sand layers within the delta-front platform develop through erosion and bedload transport during spring tides, whereas muddy layers are produced under relatively low-energy conditions during neap tides. In case of the Gulf of Papua shelf of the Fly and Kikori deltas, the delta-front platform (topset) shows massive mud with laminated sandy mud, interbedded mud and sand, and bioturbated sandy mud (Dalrymple et al. 2003; Walsh et al. 2004). Some of these thick mud sets

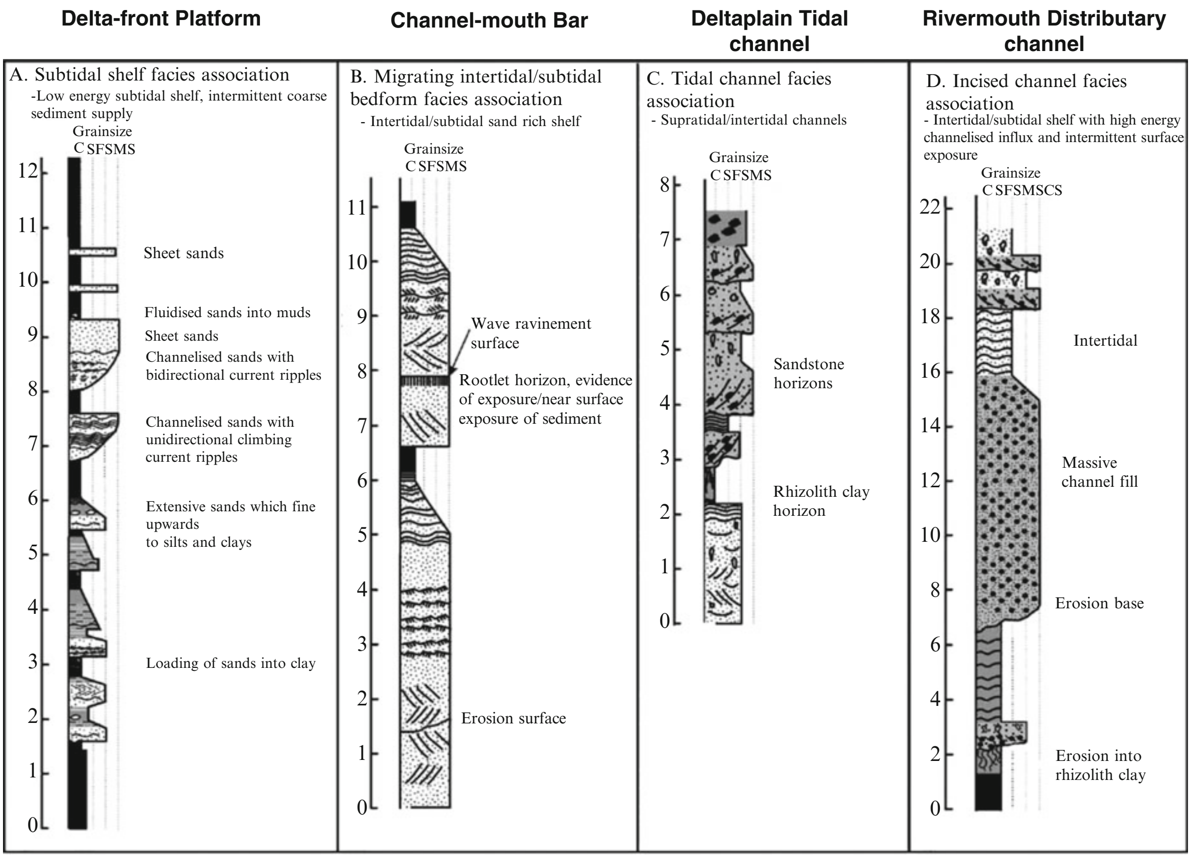

Fig. 7.6 Sketch logs of major facies associations identified from a 500-m thick Miocene-age sequence of the tide-dominated Ganges-Brahmaputra river delta. These facies associations comprise juxtaposed deltaic environments (see Fig. 7.3) that can be found within 50 km of one another in the modern Ganges-Brahmaputra delta system (see Figs. 7.4b and 7.5d). Note that neither the fluvially dominated upper delta plain nor the marine-dominated delta-front slope or prodelta are represented in this thick deltaic section, suggesting limited transgression/regression during this time (After Davies et al. 2003)

on the delta-front slope are likely formed by wave-supported hyperpycnal flows during storm events (Kudrass et al. 1998) and may be correlative with local wave-scoured erosion surfaces on the delta-front platform.

Where wave influence is high at the shoreline, sediment facies in the intertidal zone change significantly with the development of sandy beaches and longshore bars. The Mekong and Red river deltas of Vietnam both have beach ridges with aeolian dunes and foreshore with longshore bars in an intertidal zone in parts of the delta (Thompson 1968; Ta et al. 2005; Tanabe et al. 2006; Tamura et al. 2010). Portions of these deltas are also tide-dominated and characterized by mangroves and tidal channels. Where changes in river, wave, and tidal influence vary through time, reductions in sediment supply to muddy tidal flats can induce erosion and the downdrift formation of sand/shell-mound along the shoreline, called ‘cheniers’. Such episodic changes locally form a series of cheniers on the prograding delta plain (Fig. 7.5a; e.g., Changjiang, Mekong).

7.4.2 Subaqueous Delta

Seaward of the muddy subaerial delta and inner delta-front platform, sediments typically coarsen again on the outer delta-front platform toward the rollover point (e.g., Changjiang, Gulf of Papua, Mekong; Hori et al. 2001; Ta et al. 2005). This situation is common for deltas with a relatively shallow rollover where abrupt shoaling across the delta-front slope exposes the outer platform to high wave energy and tidal-current acceleration (Figs. 7.5 and 7.6). Structures on this outer portion of the delta-front platform include fine to medium-scale bedding with wave ripples, hummocky and trough cross-stratification and frequent sharp-based erosional contacts formed by storm-wave scour. Subaqueous dunes are also occasionally reported from this zone of the delta-front platform (Gagliano and McIntire 1968; Kuehl et al. 1997). Overall tidal signatures are not well developed in these deposits despite the strong cross-shelf tidal currents, because of generally lower sedimentation rates and frequent bed resuspension by waves.

At water depths below fair-weather wave base (~5–30 m), sedimentary facies of the delta-front slope are characterized by a coarsening-upward succession of alternating sand and mud deposits (e.g., Changjiang, Mekong, Ganges-Brahmaputra) or laminated to bioturbated muds (e.g., Gulf of Papua, Amazon). Individual bedding units often comprise graded (upward fining) and finely laminated sand–silt layers with sharp basal contacts, such as in the Ganges-Brahmaputra (Michels et al. 1998) and Changjiang deltas. Ripples are also found on the seabed of the delta front of the Changjiang (Chen and Yang 1993). However, clear tidal signatures are not always present in the delta-front slope sediments of tide-dominated deltas, because tidal currents are not usually well-developed this far offshore. Similarly, prodelta sediments even further offshore are often highly bioturbated and intercalated with silt stringers and thin shell beds. The shell beds result primarily from storms, which may also transport coarser-grained sediments to the prodelta. In contrast to the prevalent tide-dominated facies formed in the delta-plain distributaries and the adjacent intertidal to subtidal delta-front platform, the delta-front slope to prodelta environments are mostly influenced by waves, ocean currents, and storms.

7.4.3 Facies Associations

Because many factors can influence the formation of stratigraphic sequences over 10^3–10^5 years, it is also useful to consider mesoscale facies associations that characterize the various subenvironments of tide-dominated deltas (Fig. 7.6; Gani and Bhattacharya 2007; Heap et al. 2004). A facies association is a group of sedimentary facies that are typically found together and define a particular environment, but also allow for local variability in lithology, structure, and stratal relationships. In deltaic settings where accretion rates are relatively high, facies associations record delta progradation and lobe development that typically occurs at timescales of 10^1–10^3 years . For tide-dominated deltas the most frequently described facies association is that of the lower delta plain, which captures the advancing deltaic shoreline and subtidal to supratidal transition (Allison et al. 2003; Harris et al. 1993; Hori et al. 2002a, b; Ta et al. 2002; Dalrymple et al. 2003). As described from numerous delta-plain systems, the facies association comprises an 8–10 m thick, fining upward succession starting with sandy, cross-stratified subtidal shoals, which grade into heterolithic intertidal mud-sand couplets and are capped by a rooted mud-dominated supratidal soil (Fig. 7.7).

Other facies associations that have been described for tide-dominated deltas include tidal bars, tidal gullies and channels, incised distributary channels, and the subtidal shelf (Fig. 7.7; Davies et al. 2003; McCrimmon and Arnott 2009; Tänavsuu-Milkeviciene and Plink-Björklund 2009). The tidal-bar facies association is variably described as a fining-up or coarsening-up succession of cross-stratified sand with bidirectional flow indicators and inclined planes that is very similar to, if not the same as, the portion of the delta-plain facies association (Fig. 7.6b). The difference between the upward-fining and upward-coarsening descriptions is likely related to their proximity to the active distributary mouth, the fining-up example being more proximal to the rivermouth and receiving abundant sediment to make a rapid transition from subtidal to vegetated intertidal setting, whereas the coarsening-up succession may be a more wave-tide dominated downdrift littoral deposit. The tidal gullies and distributary channels are regularly described as fining-up, current-rippled to planar-bedded deposits with a sharp, often incised, lower contact. However, the most characteristic features of these facies associations is the regular occurrence of mud clasts that reflect the local reworking of shallow intertidal and supratidal delta-plain deposits as channels migrate, avulse, and incise (Fig. 7.6c; Dalrymple et al. 2003; Davies et al. 2003; Tänavsuu-Milkeviciene and Plink-Björklund 2009). On average, though, tidal channels are relatively laterally stable (e.g. Fagherazzi 2008) and so the muddy delta-plain deposits that cap tidal-channel sands are commonly preserved in the upper stratigraphy of the subaerial delta clinothem.

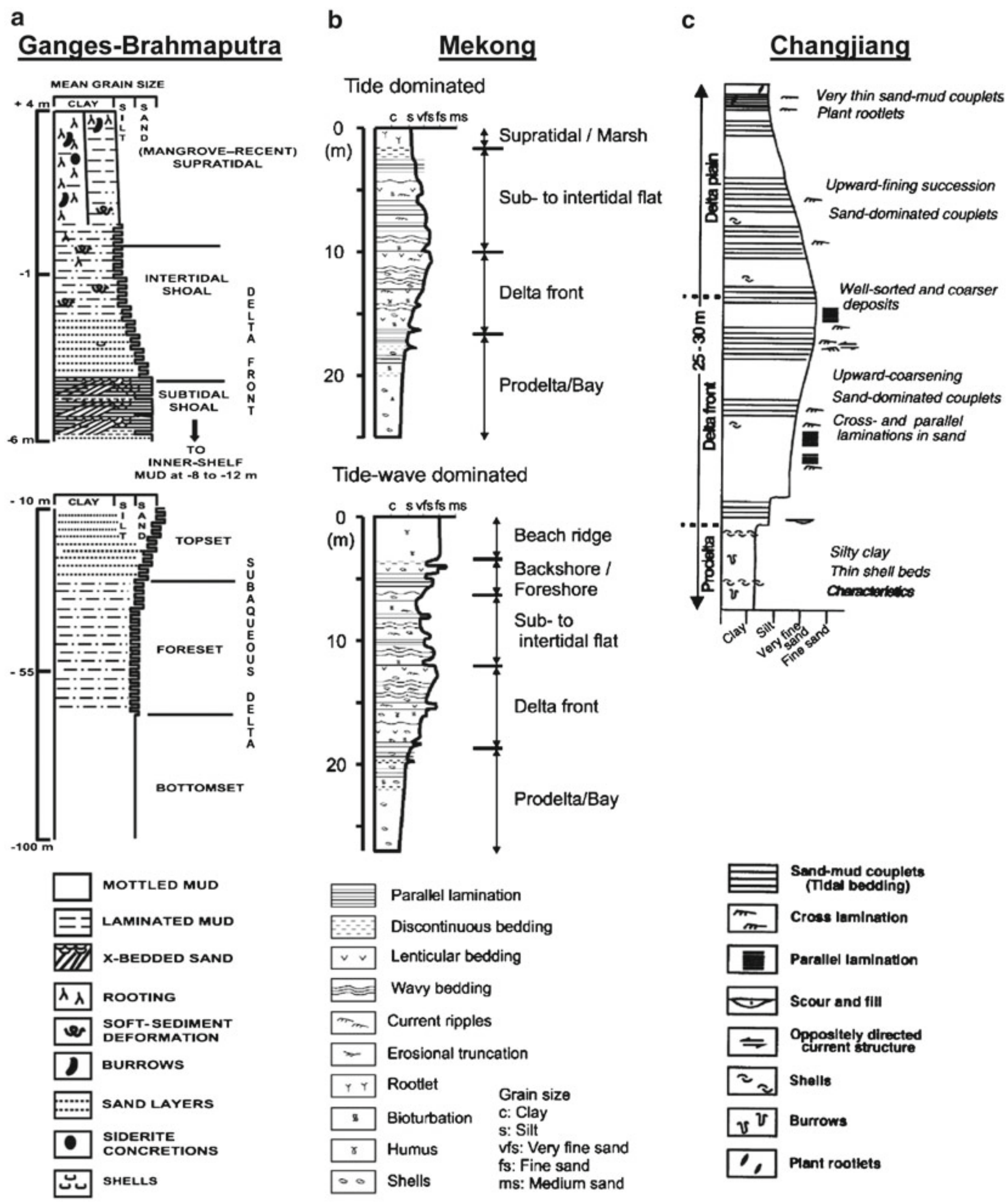

Fig. 7.7 Stratigraphic succession models for three major tide-dominated delta systems, (**a**) the Ganges-Brahmaputra, (**b**) the Mekong, and (**c**) the Changjiang. Each model includes the lower coarsening-up subaqueous clinothem overlain by the upper, generally fining-up, subaerial clinothem. The Mekong example also shows an alternate coarsening-up model that is characteristic of more wave-influenced portions of the delta where beach ridges are well developed at the shoreface (Modified after Kuehl et al. 2005; Ta et al. 2002; Hori et al. 2002a, respectively)

Offshore facies associations are less frequently described for tide-dominated deltas, in part because of sampling constraints in modern examples, but also because tidal signatures become increasingly weak offshore and may not be recognized in the rock record. This potential bias may explain early confusion with interpreting the Sego sandstones (Book Cliffs, USA), which are incised into marine shales and thus described as various types of forced regression deposits in a tidally influenced setting (Van Wagoner et al. 1991; Yoshida et al. 1996). Willis and Gabel (2001, 2003) have since argued that the Sego Sandstone actually represent the tidal channels and inner shelf sand sheet of a tide-dominated delta system, which incised into its own muddy delta-front platform and prodelta deposits during progradation. Such a mud-incised succession of progradating tidal channel deposits has also been described from the Miocene-age record of the Ganges-Brahmaputra delta (Fig. 7.6d; Davies et al. 2003).

7.5 Stratigraphy

7.5.1 Stratigraphic Successions

Deltas are defined as discrete shoreline deposits formed where rivers supply sediment more rapidly than can be redistributed by basinal processes (Elliott 1986); thus shoreline advance is essential for distinguishing them from estuaries, which also occur at river mouths but are transgressive depositional systems. As defined, deltas are regressive prograding to aggrading systems (Boyd et al. 1992; Dalrymple et al. 1992). Therefore deltaic successions will overall shallow upward, ideally including facies associations from prodelta, delta-front slope, delta-front platform, and delta-plain environments, in ascending order (Fig. 7.7; Dreyer et al. 2005).

In tide-dominated deltas that support a compound clinothem with prograding subaerial and subaqueous deltaic units, the idealized stratigraphic succession can be subdivided into two major intervals (Fig. 7.7). The lower portion shows an upward-coarsening facies succession from the prodelta to delta-front slope and outer platform deposits that is marked at its top by sharp-based wave and current scours. This lower interval is overlain by an upward-fining succession of prograding deposits from the inner delta-front platform and shoaling to subaerial delta-plain facies. The upper interval is most typically represented by the delta-plain facies association (see Sect. 7.4.1), but may also include local sub-environments such as tidal channel bars or estuarine distributary associations. Within the overall deltaic succession, the coarsest and most well-sorted deposits typically occur in the boundary zone between the delta-front platform and slope, and secondarily in the prograding, distributary-mouth channel bars (Coleman 1981; Hori et al. 2001, 2002b; Dalrymple et al. 2003; Tänavsuu-Milkeviciene and Plink-Björklund 2009). With only modest variation this general succession of an upward-coarsening subaqueous-delta unit overlain by an upward fining subaerial-delta unit has been documented in many of the world's modern tide-dominated delta systems, including the Ganges-Brahmaputra (Allison et al. 2003), Mekong (Ta et al. 2002), Changjiang (Hori et al. 2001), and Fly (Harris et al. 1993; Dalrymple et al. 2003). Such similarity suggests that this stratigraphic succession may be a useful tool in distinguishing tide-dominated deltas in the rock record (Willis 2005). Local variation in the tide-dominated delta succession has been recognized in the Mekong system, which has become increasingly wave influenced in the late Holocene and shows an upward-coarsening succession ending in wave-swept foreshore to aeolian beach-ridge deposits (cf. Fig. 7.6b, lower profile; Ta et al. 2002). In the Mahakam delta, alongshore heterogeneity in stratigraphic successions arises from the greater fluvial influence relative to tidal reworking (Gastaldo et al. 1995).

7.5.2 Delta Progradation

The rate of delta progradation can strongly influence the delta facies succession. As the subaerial delta progrades basinward, the tidal distributary channels can incise up to 20 m into the delta-front platform deposits, and a relative rise of sea level (e.g., commonly through subsidence) is important in order to preserve topset deposits of the outer delta-front platform. The Ganges-Brahmaputra and Mahakam deltas are examples of such progradational and aggradational deltas that display a largely continuous and conformable Holocene succession from prodelta to delta-plain facies (Goodbred et al. 2003; Storms et al. 2005). If distributary channels are stable relative to delta progradation, a delta succession will form as described above. However, if the lateral migration of distributaries is fast relative to delta progradation, then much of the delta-front facies will be replaced by distributary-channel fill, which is thought to occur in the Fly river delta (Dalrymple et al. 2003).

7.5.3 Role of Sea-Level Change

Sea-level change can also force environmental changes that may appear similar to delta progradation in the stratigraphic record. During periods of sea-level fall there is a forced regression of the shoreline that drives delta progradation and potentially downward incision. If the drop in sea level is relatively fast compared to the rate of delta progradation, then the succession should shift toward a more fluvially dominated stratigraphy with decreasing marine and tidal influence (Bhattacharya 2006). However, with further sea-level fall and a narrowing of the shelf, tidal range will ultimately drop and tidal energy will decrease considerably relative to a growing wave influence. It might therefore be inferred that tide-dominated deltas are more generally highstand features, as adequate tidal energy is less well developed during lowstands due to narrow shelf widths. Indeed meso- to macrotidal conditions in the modern are associated exclusively with broad shelves or large drowned valleys and embayments. Regional morphology of the continental margin (e.g. rift settings, epicontinental seas) could maintain tidal amplification even during lowstand, though, in such settings as the Cretaceous Western Interior Seaway (Bhattacharya and Willis 2001) and the Gulf of California.

Sea-level rise following a lowstand leads to the transgression and marine inundation of incised valleys formed during the previous fall of sea level. Riverine sediments are effectively trapped in these valleys to form fluvial and coastal plains, resulting in sediment starvation on the adjacent shelf and the formation of a ravinement surface and condensed section (Hori et al. 2004; Goodbred and Kuehl 2000). Continued sea-level rise and transgression of the shelf and valleys will tend to favor tidal amplification and the development of tide-influenced or tide-dominated environments (Uehara et al. 2002; Uehara and Saito 2003), although such responses are also dependent on shelf and shoreline physiography. If sediment supply is sufficient relative to the rate of sea-level rise, though, then these transgressive estuarine settings will evolve into deltas with an associated change in shoreline trajectory from landward to seaward. When constrained within the incised valleys, such highstand deltaic successions typically overlie transgressive estuarine sediments along the maximum flooding surface (Hori et al. 2002a, b; Tanabe et al. 2006). Where deltas have infilled their lowstand valley, channel avulsion and migration to interfluve areas will lead to delta-lobe formation directly on the lowstand exposure surface and sequence boundary (Goodbred and Kuehl 2000; Ta et al. 2005). In some cases, such as the Mekong and Red river deltas, tidal dominance may wane as the delta progrades into the estuarine embayment and coastal morphology shifts from concave to convex, making the system more wave-dominated as the delta lobe faces more open ocean (Ta et al. 2005; Tanabe et al. 2006).

7.6 Summary

Tide-dominated deltas are an end member of the river-wave-tide ternary delta classification and have been studied in earnest only since the 1970s. Several comprehensive research programs during the 1980s and 1990s developed a sound knowledgebase on the hydrodynamics, sediment transport and marine processes, and strata formation in tide-dominated deltaic settings. More recent research on modern deltas, particularly studies involving the drilling of cores and the collection of observational data, have accelerated our understanding of the specific sedimentary environments, processes, and stratigraphic successions found within and around tide-dominated deltaic settings.

Today most modern tide-dominated deltas are building seaward through modestly prograding deltaplains and more rapidly prograding muddy subaqueous clinothems. The sedimentary facies within these settings are typically, perhaps characteristically, heterolithic and often mud-dominated (e.g. Changjiang, Fly), although some systems may have an appreciable sand component (e.g. Ganges-Brahmaputra). In contrast, most sections of the rock record that have been interpreted as tide-dominated deltas comprise sand-dominated, or alternating sand-mud, sedimentary facies. This apparent bias toward coarse-grained ancient examples may arise from the difficulty of distinguishing deltaic successions from other mud-dominated sedimentary facies, many of which may lack clear indicators of fluvial origin due to the strong overprint of tidal processes. The broad distances across which many modern tide-dominated deltas develop also present a challenge at the outcrop scale, and differences in fluvial sediment input (e.g., coarse vs. fine) may further limit the recognition of unique facies characteristics.

In terms of human impacts, more than 200 million people live in tide-dominated delta systems today, ranking them among the world's most economically and culturally important environments. In many systems the mangroves, salt marshes, and tidal flats typical of tide-dominated delta systems are threatened by human activities. Several modern deltas are already severely degraded due to decreases in sediment and freshwater delivery caused by damming and water extraction, respectively (e.g. Colorado, Indus). Similar modifications and activities have been implemented along the Yangtze river system, with anticipated negative impacts; damming and water consumption remain likely threats to the heavily populated Ganges-Brahmaputra and Ayeyarwady basins as well. Regardless, sustainable ways to conserve and use these environments will be a continuing challenge.

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