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Review Article
Shallow-marine Sandstone Reservoirs, Depositional Environments, Stratigraphic Characteristics and Facies Model: A Review

Numair Ahmed Siddiqui, Abdul Hadi A. Rahman, Chow Weng Sum, Wan Ismail Wan Yusoff and Mohammad Suhaili bin Ismail

Department of Geoscience, Faculty of Geoscience and Petroleum Engineering, Universiti Teknologi PETRONAS, Perak, Malaysia

Abstract
A significant percentage of the world's hydrocarbon reserves are found in shallow-marine sandstone deposits. Understanding the internal characteristics, distribution, geometry and lateral extent of these sandstones in the subsurface is therefore, an essential part of successful exploration and production strategy. The aim of this study was to document a review on the understanding of shallow-marine sandstone reservoirs, depositional environments, stratigraphic characteristics and facies modeling which is quit challenging because of generic hierarchy of different scale and sets of heterogeneities. This review was based on seven different types of clastic coastal depositional environments: Deltas, tide-dominated estuaries, wave-dominated estuaries, barrier-islands and lagoons, strand plains and tidal flats. This study documented a broad examination of these depositional environments and their corresponding stratigraphic and facies models which lead to a better understanding of their impact on reservoir heterogeneities within these settings. The review supports the hypotheses of previous researchers that wave, tide and river power exercise the primary control over the gross geomorphology and facies distribution patterns in clastic coastal depositional environments which can be applicable to any region on earth where clastic coastal depositional environments may be identified from stratigraphic characteristics.

Key words: Shallow-marine deposits, depositional environment, stratigraphy, facies model

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Corresponding Author: Abdul Hadi A. Rahman, Department of Geoscience, Faculty of Geoscience and Petroleum Engineering, Universiti Teknologi PETRONAS, Perak, Malaysia Tel: +60149975114

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Siliciclastic shallow-marine deposits form reservoir in many of the world's major hydrocarbon provinces (e.g., Brunei, Indonesia, Malaysia, Nigeria, North Sea, Venezuela, etc.). These rocks hold the vast majority of the remaining hydrocarbon reservoirs which is quit challenging because of generic hierarchy of different scale and sets of heterogeneities. Identification and prediction of heterogeneities in these reservoirs is therefore a vital to efficiently and economically produce these reservoirs[1-3]. Numerous studies by different groups have investigated the facies characteristics and their impact on reservoir heterogeneity[4-10]. These studies were based on outcrops and field data and also on constructed reservoir simulation models, using detailed geological outcrop and oilfield data[11-15]. Among the objectives are to upscale and capture the effects of small scale heterogeneities on flow performance[16-25]. The outcomes of this study gives a surface-based modeling approach that has been used to construct a reservoir-scale, 3-D model of the facies architecture, used to represent both key stratigraphic horizons and facies boundaries in the model.

Siliciclastic shallow-marine sediments and rocks are product of the depositional environments located between land and sea and their response to a variety of forcing mechanisms[26]. The geomorphic evolution of such depositional environments (including deltas, estuaries, lagoons, strand plains and tidal flats) is controlled by the relative importance of several main factors, which includes; physical process regime, the internal dynamics of coastal and shelf depositional system, relative sea-level, sediment flux, tectonic setting and climate. The main physical processes operating in these settings are river-derived flows, waves, shoreline and tidal-currents. The flow energy in such environments are generally higher[19,27-30]. This resulted in a complex pattern of transportation and deposition of coarse sediments (silt, sand and occasionally conglomerates). The gross geomorphology of clastic coastal depositional environments is affected by the relative importance of long shore currents, waves and tides in controlling the amount, nature, distribution and transportation of sediment along the coast[3,10,31,32] (Fig. 1).

The significant alongshore sediment transport that produces coast parallel sedimentary features is by large swell waves generate, such as spits, barriers, sand bars and barrier

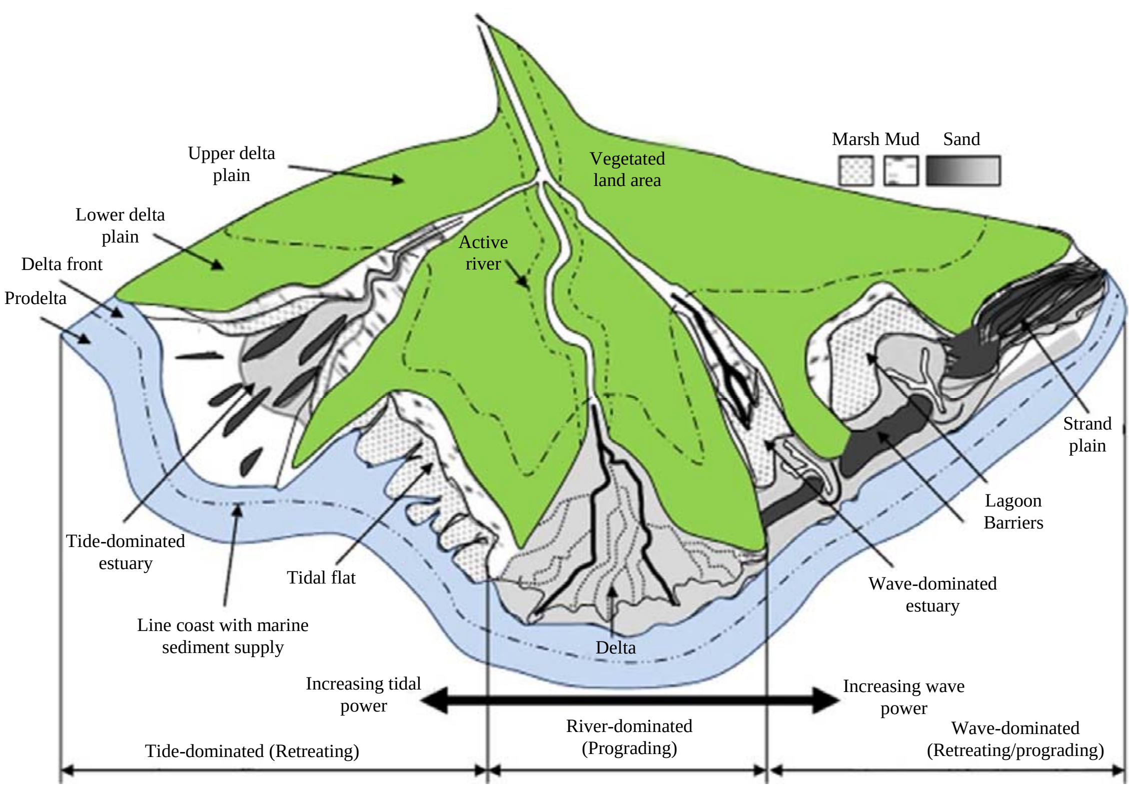


Fig. 1: Significant of coast parallel sedimentary features by large swell waves generate, such as spits, barriers, sand bars and barrier islands

Tidal currents generally produce coast normal sedimentary features, including: Elongate tidal sand banks, wide-mouthed estuaries, funnel-shaped (in plain view) deltaic distributary channels and broad intertidal flats

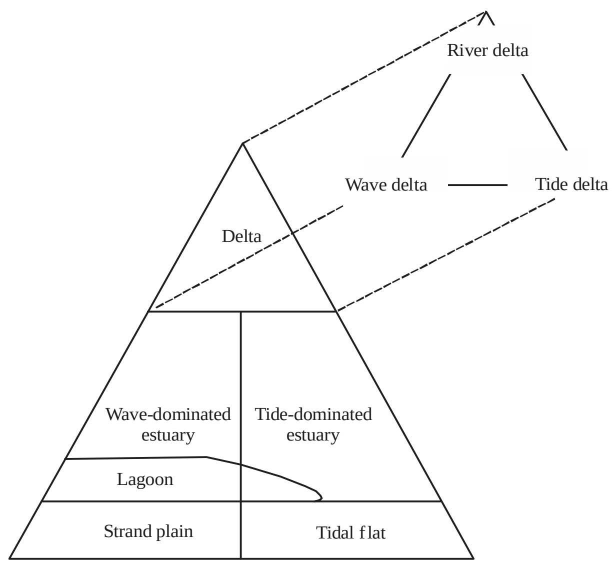


Fig. 2: Classification of six different types of depositional environment in ternary diagram[30]

islands. In contrast, large tidal ranges (>4 m) and strong tidal currents generally produce coast normal sedimentary features, including: Elongate tidal sand banks, wide-mouthed estuaries, funnel-shaped (in plain view) deltaic distributary channels and broad intertidal flats (Fig. 1). These depositional settings are dominantly composed of clastic sediments and has long been studies all over the world[18,22,28,29,33-39], mainly which includes, the Nile river delta, the Mississippian delta, the Ganges/Brahmaputra delta and the Niger delta. These shallow-marine sandstone environments can be characterized by their distinct facies which are reliable indicator of any (river, wave or tide-dominated environment) depositional process (Fig. 2). Having the concept of sedimentary facies and stratigraphy, facies analyses of high quality exposures in several coastal plains, all over the world provide an opportunity to examine the stratigraphic nature of these shallow-marine sandstone deposits. Based on distinct assemblages of physical and biogenic sedimentary structures, the vertical sequence of facies, each depositional environment can be recognized. Some present day examples have recently been described by many researchers[18,27,29]. But the individual facies are of little interpretative value. However, when use in combination as facies models, facies successions highlight lateral and vertical variations between different sedimentary environments. A facies model represents a general summary of a given depositional system which represent a generalization of the physical attributes for a certain type of depositional environment, where the local variations from numerous modern and ancient examples have been ''Distilled away'' to leave only the common features. Since, accurate facies models are an integral part of understanding the stratigraphic evolution of a depositional system.

The aim of this study is to supports the hypotheses of previous researchers and reviews the documented information on shallow-marine siliciclastic depositional environments, the facies and stratigraphic characteristics of the sandstones and facies model and their impact on reservoir heterogeneity for detail analysis and demonstration on present conditions.

KEY CHARACTERISTICS OF SHALLOW-MARINE DEPOSITIONAL ENVIRONMENTS AND SANDSTONE RESERVOIR HETEROGENEITY

The shallow-marine and coastal realm is defined as "The depositional system that exist between the landward influence of the marine processes and the seaward influence of continental, mainly fluvial (river) processes[40,41]". Shallow-marine environments are generally considered and classified according to physical process regime[16]. The main physical processes operating in shallow-marine setting are waves and storms, tidal currents and river-derived flows[20]. Shallow-marine sandstones can be characterized by their distinct features which are reliable indicators of shallow-marine environment. First, the physical processes are generally distinctive: For example, extensive sheets and ridges of cross bedded sand deposited by strong currents, hummocky and swaley cross-stratification are distinctive sedimentary structures that are believed to be unique to storm-deposited sands. Secondly, the organisms, either as body fossils, specifically benthic organisms that are only abundant in shelf environments or as trace fossils (distinct shallow-marine trace fossil assemblage). Third are the lithology and texture, mainly sand and mud with some gravel and moderately to well-sorted.

Therefore, shallow-marine depositional system is based upon the long-term movement of the shoreline and the key depositional processes. This shoreline movement is controlled by the balance between the amount of sediment supplied to the depositional system and the amount of accommodation space created[40,42]. The depositional environment and facies succession of shallow-marine sandstone may preserve indicators of change in sea-level during transgression and regression and are often easily identified, because of the unique conditions required to deposit the different facies successions (parasequences) (Fig. 1). For instance, during transgression the coarse-grained clastics like sand are usually deposited in near-shore, high-energy environments, fine-grained sediments however, such as silt and carbonate muds are deposited farther offshore, in deep, low-energy waters[43]. Thus, a transgression reveals itself in the sedimentary column when there is a change from near-shore facies (such as sandstone) to offshore ones (such as marl) from the oldest to the youngest rocks. A regression will feature the opposite pattern with offshore facies changing to near-shore ones[43]. Regressions are less well-represented in the strata, as their upper layers are often marked by an erosional unconformity. Many studies concentrate on progradational (regression) systems because they are volumetrically most important as reservoirs[44,45], examples include the Niger delta[46], the Palaeo-Baram delta of Borneo and Brunei[18,47] and many others.

The shallow-marine shorelines are subdivided further based upon the dominant depositional process. Six broad types of clastic coastal depositional environment are recognized (Table 1), which divided into two main groups: (1) Those that receive a large sediment supply and are actively prograding seawards (e.g., deltas, strand plains and tidal flats) and (2) Those that receive a small sediment supply and which exhibit geomorphic features associated with the Holocene sea level rise and have yet to completely fill their Paleo valleys[48]. Under conditions of stable sea level, the existence of these types of clastic coastal depositional environments depends on the relative quantities of terrestrial and/or marine sediment supplied in relation to the size of the receiving basin. Because of the close link between the geomorphology of clastic coastal depositional environments and the relative influence of waves and tides at the coast, it is possible to distinguish between wave-dominated coasts (characterized by wave-dominated deltas, wave-dominated estuaries, strand plains and lagoons) and tide-dominated coasts (characterized by tide-dominated deltas, tide-dominated estuaries and prograding tidal flats (Fig. 1). All shallow-marine depositional systems are affected to a greater or lesser degree by all of these six depositional processes classified within a ternary diagram scheme (Fig. 2). Any point within the triangle is defined by the relative importance of depositional environment in controlling the resultant facies (and ultimately, reservoir) architecture for building model.

DELTAS

Deltas are formed from the deposition of the sediment carried by the river as the flow leaves the mouth of the river[22,45,49,50]. Over-long period of time this deposition builds the characteristics geographic pattern in the form of the triangular shape of the fourth letter of the Greek alphabet (Δ). As the sediment-laden, river enters the standing body of water, the flow decelerates, which diminishes the ability of the flow to transport sediment. As a result, sediments drop-out of the flow and deposits. Over time, this single river channel will build a deltaic lobe (such as, the birds-foot of the Mississippi delta, the Nile delta shown in Fig. 3), pushing its mouth further into the standing water. As the river enters the standing water of sea the morphologies of delta changes, the original deltaic shape range from elongate 'finger' building out into the sea (such as the Mississippi delta), to highly prominent sand bars and ridges parallel to river direction (tidal delta) or to highly reworked distributary channels and mouth-bars of river by waves, which form a beach ridge barriers complex that approximately parallel to the shoreline. In this regard, there are three key processes have been identified in delta system, i.e., fluvial, wave and tide-dominated delta system[40,51,52] (Fig. 2).

Depositional environment and process: The formation of delta system consist of three main forms; the delta plain (where river process dominate), the delta front (where river and basinal processes are both important) and the prodelta (where basinal processes dominated)[53] (Fig. 4) from subaerial delta setting to subaqueous delta. This form, from delta plain to prodelta may be influence by tide or wave-dominated processes which change the morphology of depositional environment with subaerial to subaqueous delta. Within this forms the basic depositional environment in a deltaic system is the mouth-bars[41,54], as, if the sediment is not significantly reworked by the wave and tidal-dominated processes. The mouth-bars, which as aggrades, it eventually becomes emergent and diverges the river into two distributary channels

Table 1: Summary of different depositional environments, stratigraphic characteristics and facies model with modern, ancient and oil field examples

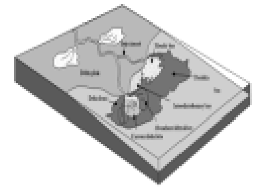
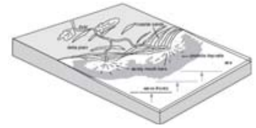
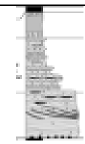
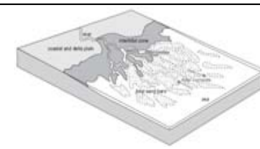
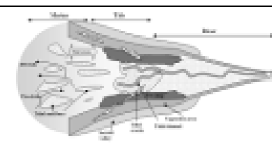
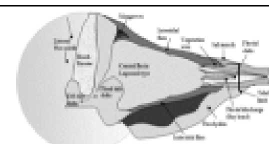
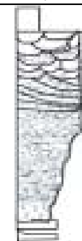
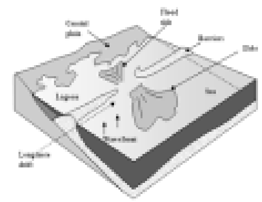
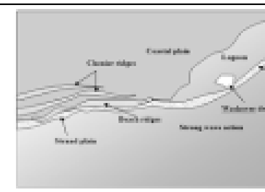
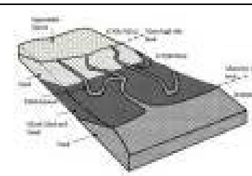
Shallow-marine environments	Distinct environments and facies	Representative stratigraphy	Model		Examples
Deltas	Distributary channels (coarse-to fine-grained), mouth-bars, distal mouth-bars (mudstone and siltstone)	 Source: UGA Stratigraphic lab		Modern: Ancient: Oil-fields:	Nile and Mississippi delta[19,44,35] Battfjellet and Pennsylvanian Perrin delta[35] Nun field Nigeria and Gudao oil field China[81]
Wave-dominated deltas	Wave ripples and hummocky cross-stratification, soft sediment deformation, climbing current ripples, brackish fauna and staked coarsening and fining-upward facies	 Source: Walker and James[53]	 Source: Nichols[74]	Modern: Ancient: Oil-fields	Nile delta and Brazos delta[28] Niger and Baram delta[18,58] Nigeria delta and Budare field, Eastern Venezuela[58]
Tide-dominated deltas	Strata displays coarsening-up of a delta with tidal channels of delta plain and tidal flat of delta top facies, structure includes, cross bedding, tidal bedding, reactive surface and flaser, wavy and lenticular bedding, herringbone cross-stratification, mud drapes and channel erosional base	 Source: UGA Stratigraphic lab	 Source: Nichols[74]	Modern: Ancient: Oil-fields	Ganges-Brahmaputra and Changjiang tidal delta[73] Changjang tidal delta and Fly rive tidal delta[58,73] Troll West field, Norwegian North sea and Lagunillas field Western Venezuela[73]
Tide-dominated estuaries	Flood plain (burrows and mudstone), tidal flat (trough cross, flaser and lenticular bedding) and tidal channels and point bar with erosive base	 Source: UGA Stratigraphic lab		Modern: Ancient: Oil-fields:	Fitzroy and Amazon river[66] Changjang estuary and Gironde estuary[73] Sacha field Ecuador and Aspelintoppen Formation Central Basin of Spitsbergen[65]
Wave-dominated estuaries	Upper shoreface (trough cross sandstone), lower shoreface (proximal storm bed with mudstone interbedded) and offshore (burrowed mudstone with storm bed)	 Source: UGA Stratigraphic lab		Modern: Ancient: Oil-fields:	Danube and Baram estuary[18,77] Hueco formation South-Central New Mexico and Floras lakes South-West Oregon[19] Little Bow field, Canada and Finnmark field, North Norway[37]

Table 1: Continue

Shallow-marine environments	Distinct environments and facies	Representative stratigraphy	Model		Examples
Barrier island and lagoons	Barrier islands are mainly sand and gravel (subhorizontal (planar) stratification and wave reworking structure) and lagoon consist of both mud and sand (interbedded and inter-fingering sandstone, shale, siltstone and coal)			Modern: Ancient: Oil-fields:	Albemarle and Pamlico Ferron beach lagoon in North Carolina[83] Ferron Sandstone Utah and Venice lagoon Italy[13] Sabkha field and Tigre lagoon oil field, Louisiana[78]
Strand plains	Beach ridges (sand and gravel within fine or coarsening coastal plain or upward-fining channel sandstones and cheniers plains of fine-grained sediment			Modern: Ancient: Oil-fields:	Western Louisiana and strand plain, Bahia Province, Brazil (Source: Wikipedia) San Juan basin outcrop, Frio formation Texas at Austin[87] Fario formation field Texas and seventy six West field, South Texas[86,87]
Tidal flats	Burrowed trough cross-laminated sand stone with falser to lenticular bedding and having fining upward trend	 Source: UGA Stratigraphic lab		Modern: Ancient: Oil-fields:	Abu Dhabi Persian Gulf and Oban on Stewart island, New Zealand (Source: Wikipedia) Palmares formations, North-Eastern Brazil and Sabkhas outcrop Utah[27] Sam-Bis oil field Nigeria[94]

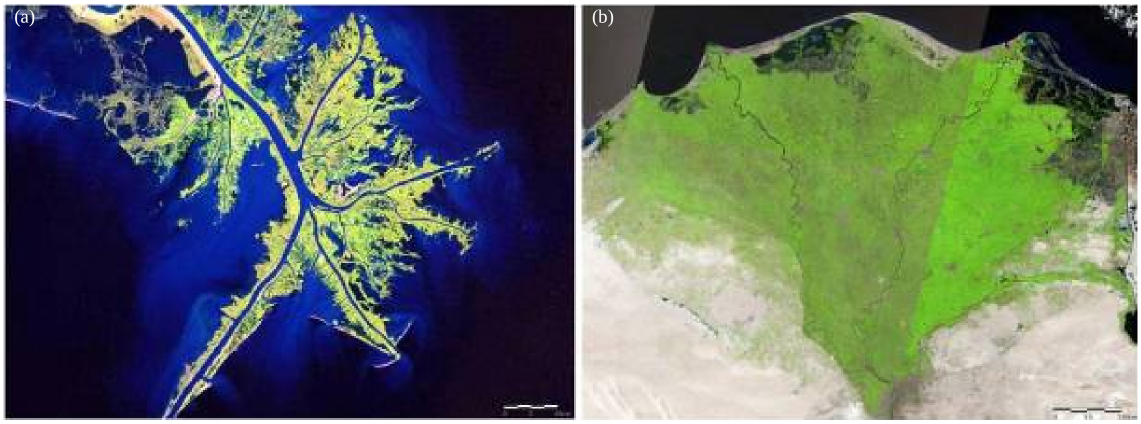


Fig. 3(a-b): Google and satellite images of (a) Mississippi delta and (b) Nile delta, an example of river dominated deltas, shows the distribution of single channel into distributary lobes

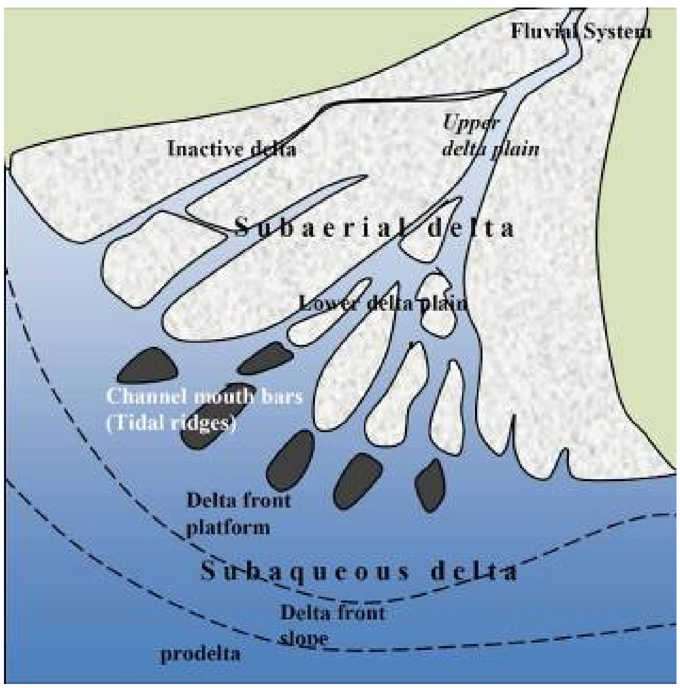


Fig. 4: Three main forms of delta; the delta plain (where river process dominate), the delta front (where river and basinal processes are both important) and the prodelta (where basinal processes dominated)[53]

on either side of the bar. Two small mouth-bars are then deposited in the mouths of these channels and the channel continues to split until become too small to carry sediments (Fig. 5). After this, the system becomes chocked and avulsion or lobe switching occurs[35], the good example is Mississippi delta system.

The formation of shallow-marine deltaic basins is typically exhibit a lobe shape with multi-scale coeval terminal distributary channels[35]. The relationship of terminal distributary channels and coeval mouth-bars has been described by Olariu and Bhattacharya[35], Van Heerden[55] and DuMars[56]. Recent studies[28,35,54,57] showed that both modern and ancient delta-front have a complicated morphology, consisting of multiple terminal distributary channels, subaqueous levee deposits and mouth-bars. Few studies have been dedicated to delta-front deposits, despite the key importance of delta sub-environment to understanding delta growth and facies architecture[35]. Hence, distributary channels are described from delta plain and from when the main channel reaches an area with low variability of lateral gradient

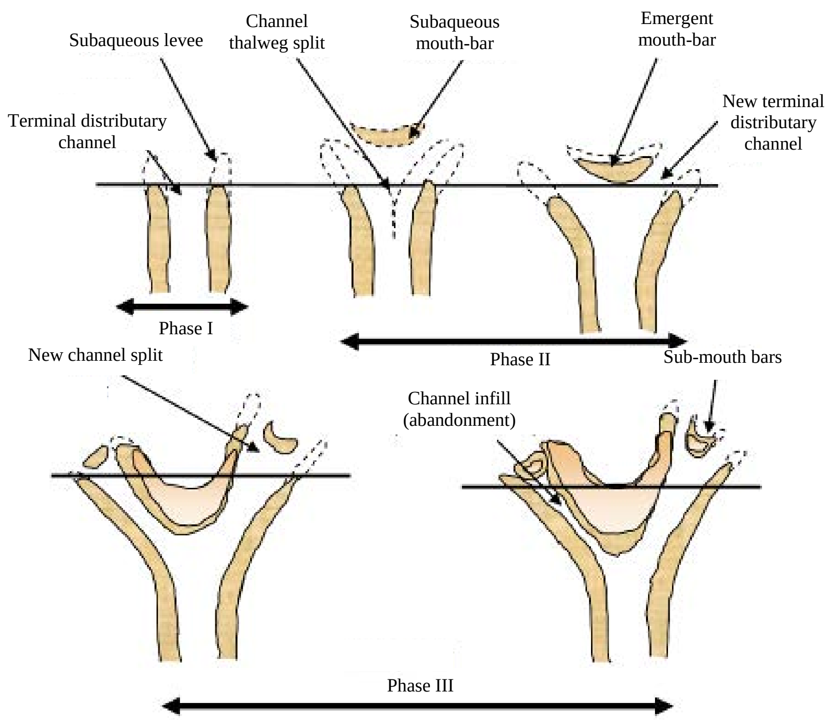


Fig. 5: Conceptional formation and evolution of a terminal distributary channel mouth-bar system[54]

Three main phases of evolution have been distinguished, (i) Formation of new terminal distributary channels and mouth-bars, (ii) Migration of mouth-bars and extension of terminal distributary channels and (iii) Abandonment of terminal distributary channels. Dotted lines represent subaqueous features

into shallow-water environment. Because the delta plain gradient are small and sedimentary rates are higher, the direction of distributary channels can be change easily by aggradation of different facies architecture or differential subsidence and compaction, such that the gradient will be steeper in other direction and might capture part of the flow, creating a new distributary channels.

As a consequence of this successive splitting, the distributary channels become smaller in the downstream direction. Olariu and Bhattacharya[35] indicated that with each bifurcation or avulsion of channel width and depth changes as $B_{k+1} = 0.7B_k$ and $h_{k+1} = 0.8h_k$, respectively. Where, 'B' is channel width, 'h' is channel depth and 'k' is channel order. For a large delta system (Volga delta, Lena delta), distributaries can rejoin, forming a delta pattern similar to braided or anastomosed rivers[35]. This results in smoothing of the platform (or map-view) shape of the delta as the channels move across its surface and deposit sediment. Because, the sediment is laid down in this fashion, the shape of these deltas approximates a fan. In case of wave delta system where waves redistribute the sand supplied to the beach by the rivers, the delta shape changes, known as wave-dominated delta. The sediment is carried off down the longshore drift direction and mouth-bars of distributary channels are unstable and easily reworked by waves, which form a beach-ridges barriers complex that is approximately parallel to shoreline. The modern example is the Nile delta in Egypt[19], the Sao Francisco in Brazil, Baram in Borneo and Ebro in Spain.

Whereas, if the delta is influenced by the tidal energy, the geomorphology of the delta changes to tide-dominated delta, with features a landward tapering funnel-shaped valley (Fig. 1) and river is connected to the sea via distributary channels[58,59].

Stratigraphy: The deltas are characterized by multiple laterally discontinuous sand bodies arranged in complex spatial patterns. This complexity reflects the hierarchical staking of lobate depositional bodies that form by deceleration of effluent water at the mouth of deltaic distributary channels debouching into a standing body of water[60]. Such depositional bodies have been documented at four distinct orders of a stratigraphic hierarchy in deltas: (1) Distributary mouth-bars, which correspond to the individual mouth-bar in river delta and associated delta front

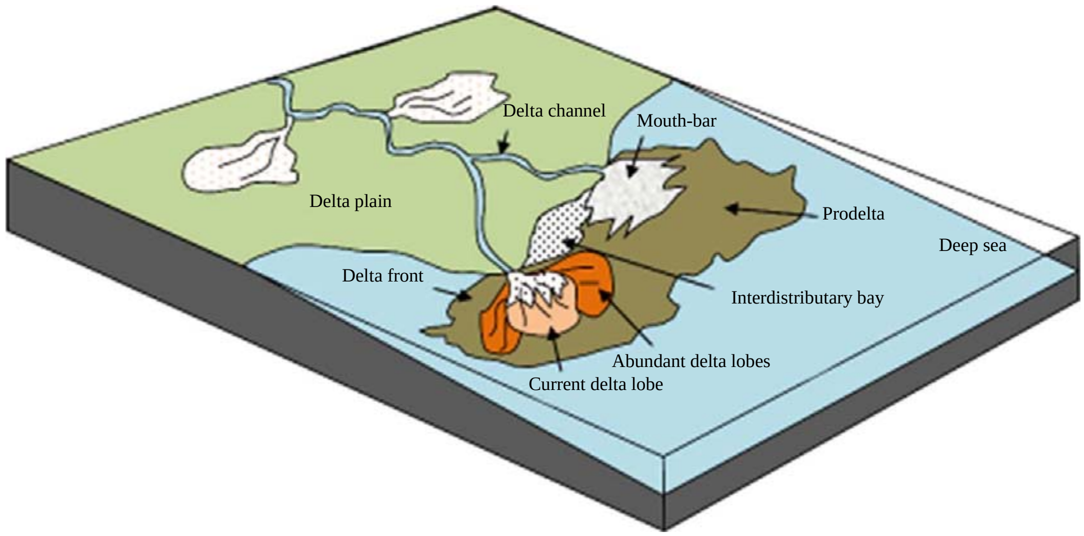


Fig. 6: Arrangement stratigraphic elements in delta distribution and its control of variety of autogenic and allogenic processes resulting in complex stratigraphic architecture[74]

and prodelta deposits fed via terminal distributary channels[49], (2) Mouth-bars assemblages, which comprise multiple coalesced mouth-bar deposits that is fed via the same shallow downstream-bifurcating distributary channel network with parallel mouth-bars (in wave-influence processes) to shoreline or perpendicular mouth-bar (in tidal-influence processes) to shoreline, (3) Delta lobes, each of which have bed feed via single major trunk distributary channel[35] and corresponds to a delta front clinoform set[59] and (4) Delta complex, which comprise multiple delta lobe that formed via switching because a nodal avulsion of major trunk distributary and which correspond to laterally offset and compensationally stacked clinoform sets[61].

It has been studied that, the deposits of an abandoned lobe will gradually compact as water deposited with the fine-grained sediment escapes from the pore spaces and the bulk density increases. This compaction occurs without any additional load and results in the abandoned lobe subsiding below sea level. The beds that mark the end of sedimentation on a delta lobe are known as the abandonment facies[41]. In the upper part of the delta plain there will be peats or paleosols, which represents a low elastic supply to this part of the plain, after this, that active lobe progradation have been moved elsewhere on the delta. These fringes of the delta lobe will be areas of slow, fine-grained deposition of shallow water. Abandonment facies may show intense bioturbation because of the slow sedimentation rate. The arrangement of these stratigraphic elements was controlled by a variety of autogenic and allogenic processes resulting in a fundamentally complex stratigraphic architecture[49] (Fig. 6).

Facies characteristics: A common feature of deltas is channel instability due to very low gradient of the delta plain, resulting in frequent avulsion of the major and minor channels called distributary channels, leaving the formal channel, its levees and overbank deposits abandoned. The deposition of deltas have well-developed delta top facies, consisting of channel and overbank sediments. The characteristics of these facies, the overbank areas of a delta top and plain may be sites of prolific growth of vegetation, leading to the formation of peat and eventually coal. The channels build out to form the 'toes' of the 'bird's foot', with upward thickening and coarsening delta front deposits have terminal-distributary channels facies interbedded with mouth-bar deposits (Fig. 7). In general, mouth-bar has different sedimentary structures compared to terminal distributary channels[35]. The mouth-bar having the interbedded upward-coarsening or thickening succession of burrowed, ripple cross-laminated, graded bedding, planar parallel, massive and trough cross-stratification sandstones contain disseminated organic matter and thin organic-rich mudstone (Fig. 7). Whereas, terminal distributary channels, usually having poorly sorted, medium to coarse-grained, unidirectional trough cross-stratification sandstone containing occasional mud clasts, flute casts and plant fragments. The preserved organic matter is commonly high in delta fronts[53].

In river-dominated deltas, prodelta mudstones and siltstones are typically massive to well-stratify and may show graded bedding. The graded bedding may results from (1) The setting of material carried out in suspension as a buoyant plume or (2) From density underflow generated at the river mouth during time of high discharge[50]. The amount

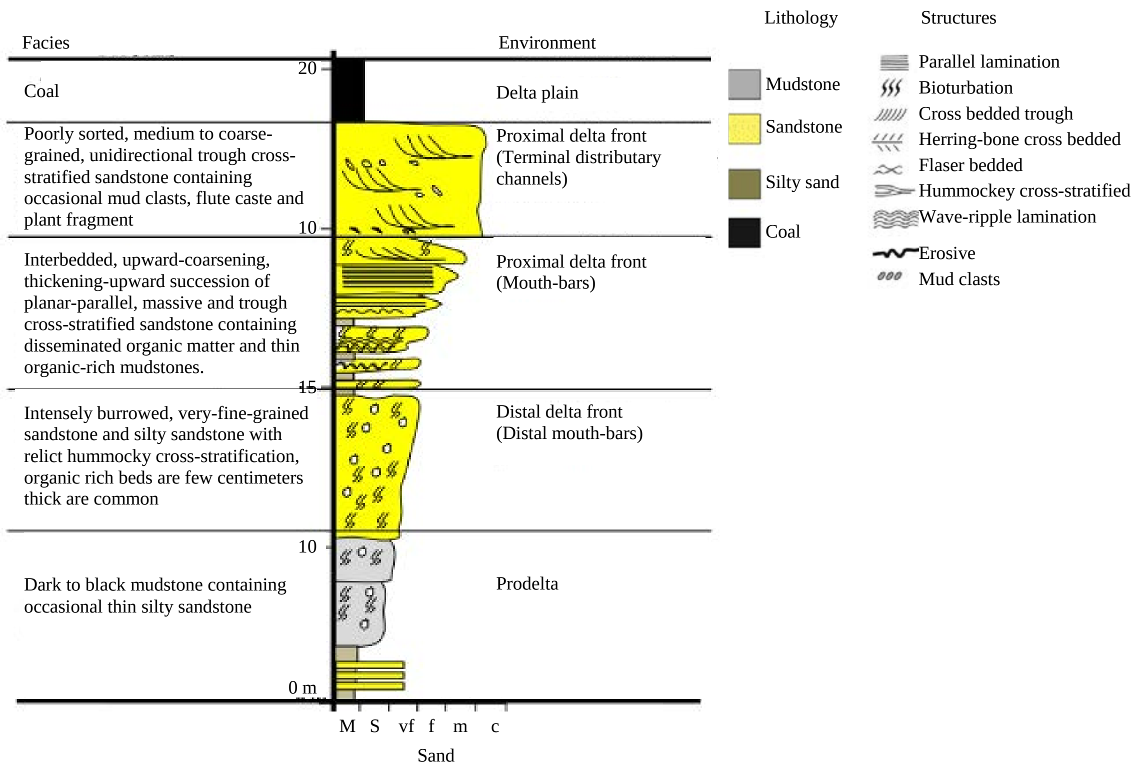


Fig. 7: Facie characteristics and stratigraphic distribution of delta depositional environment shows the different sets of parasequences and sedimentary structures from prodelta to delta plains

of bioturbation in variable, depending on rate of sediment supplied, wave-formed structure are common. Soft-sediment deformation features resulting from high sedimentation rates, are common in prodelta, or any be on a very large scale and involve large proportions of the delta front sediments, as in the Mississippi[62].

TIDE-DOMINATED ESTUARIES

An estuary is a partly enclosed coastal body of water with one or more rivers or streams flowing into it and with a free connection to the open sea[63-66]. The physical and biological processes in nearly all estuaries are influenced by tides. The degree of influence is governed by estuarine morphology, tidal range, water and sediment discharge, wind and shelf processes. Tide-dominated estuaries are those in which tidal currents play the dominated role in the opposition of river sediment supply[63]. There is appreciable upstream transport of bedload sediment as a result of deformation of tide during propagation.

Depositional environment and processes: Among tidally-influenced sedimentary environments, tidal estuaries are perhaps the most variable and difficult to characterize. This variability is due in part to the major role that fluvial system dominantly plays in defining estuary. A tidal estuary is a partially enclosed body of water formed where freshwater from river and streams flows into the ocean, mixing with the sea water under the influence of micro to mega tidal currents[64-67]. The tidal estuary are typically flanked by low-laying vegetated flood plains, tidal flats and swamps area because of appreciable tidal ranges and low incident wave power, results in coast parallel tidal bars with drainage channels (Fig. 8). Because of the dominance of tidal processes, the geomorphology of tide-dominated estuary features a landward tapering funnel-shaped valley and the river is connected to the sea via distributary channels, channels may be separated by a large expanses of low gradient vegetated swamps[59] (Fig. 8).

Most of the tidal estuaries today are located in tectonically active, low latitude region, including South Asia, East Asia and Oceania (Fig. 9). Many processes relevant to the development of tidal estuary system are common to these areas. First is amplification, in high tidal range, area is supported by broad, relatively shallow continental shelves and seas that are well connected to open ocean, e.g., Amazon estuary in Brazil, river Nith Estuary in South West Scotland and Exe Estuary in England are good examples. A second factor is common to

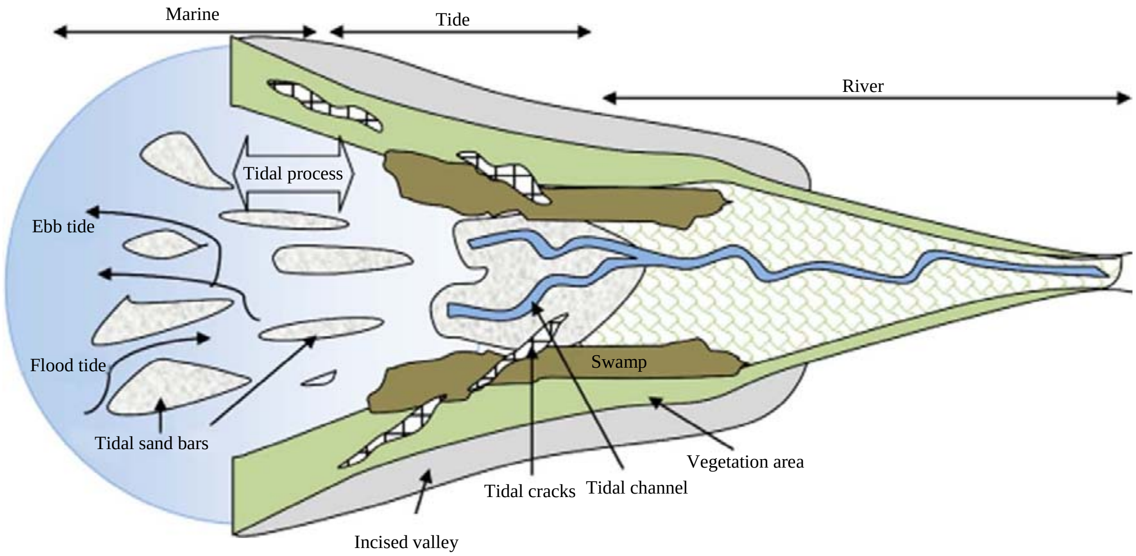


Fig. 8: Geomorphology of tide-dominated estuary features a landward tapering funnel-shaped valley
It shows a typically flanked by low-laying vegetated flood plains, tidal flats and swamps areas because of appreciable tidal ranges and low incident wave power, results in coast parallel tidal bars with drainage channels during flood and ebb tides

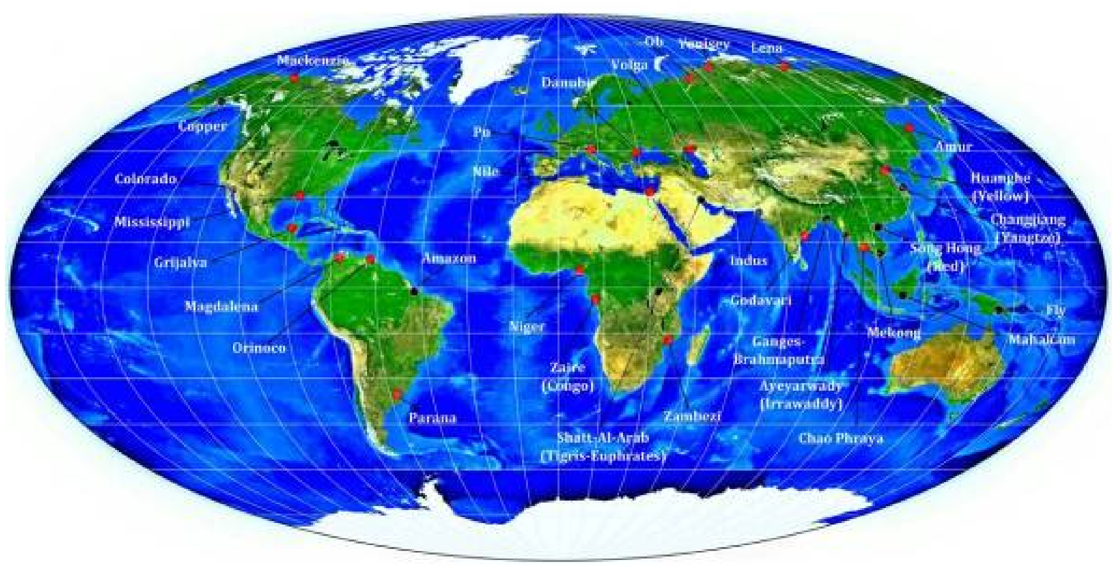


Fig. 9: Map of world's major river deltas system
With those forming tide-dominated deltas indicated in black circles are mostly located in tectonically active, low latitude region

most tidal estuaries and in many delta systems in general is that, they drain high-standing, tectonically active mountain[68]. Such active orogeny yield the abundant sediment required for estuary/delta to form in high-energy coastal basins. In particular the Himalayan-Tibetan uplift and Indonesia Archipelago Sustain among the world's highest sediment yield[68].

Stratigraphy: The tidal estuaries are initially formed at the beginning of transgression and migrate landward as transgression proceeds. As far as is known, relatively little morphological changes occurs during this process, as long as the external process variables remain constant and the facies zones simply translate landward[63]. Morphological changes which cause deviations from the end-member

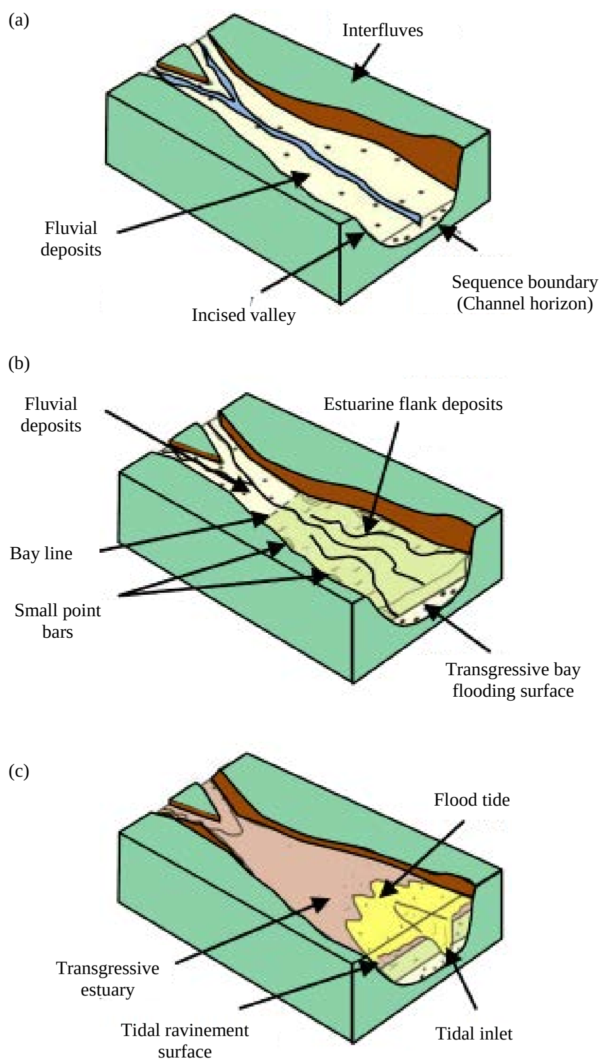


Fig. 10(a-c): Cyclical stratigraphic model of tidal estuary (a) Formation of incised valley with fluvial discharge which allows the deposition of channel sequence, (b) Tidal estuarine flank deposits over the channel sand with bay line transgressed towards the landward side and (c) Building of tidal inlet, bars and tidal ravinement surface

model begin to occur, however, once the rate of sediment supply exceeds the rate of relative sea-level rise and the estuary starts to fill.

With the advance of sequence stratigraphy in the late 1980s, several geologically models results that an incised-valley system with a basal sequence boundary is filled with transgressive deposits[42]. Here the cyclical stratigraphic model shows, estuaries valley fill is typically overlain directly by open marine shelf deposits with an intervening transitional phases[48,69,70]. The phase one (Fig. 10a) the fluvial discharge allow the deposition of channel sequence with formation of incised-valley. As the tidal-influence dominated over the river discharge, the tidal estuarine flank deposits over the channel sand with bay line transgressed towards the landward side (Fig. 10b). Finally, the tidal estuarine model builds with tidal inlet, bars and tidal ravinement surface (Fig. 10c). This is done, because of in tide-dominated estuaries, tidal current readily redistribute the sediment supplied by both river and marine sources[48]. As a result, there is rapid in filling of the deeper and wider parts and development of the classic funnel-shaped geometry and facies distribution. Once this situation exists, further sediment input should cause the stratigraphic zones to prograde seaward, with the relative distribution of facies remaining essentially constant. The stages in the growth of the tidal sand bars have been discussed by Harris[71], who showed that the bars become broader as the estuary fills.

Facies characteristics: The tide-dominated estuary facies are poorly known from the stratigraphic record and are notoriously complex, owing to the wide spectrum of facies encountered and their spatial/temporal variability[72]. As the total-tidal energy is not as pronounced as in wave-dominated estuaries, because tidal energy penetrates further headword than wave energy. Thus, the facies distribution is not as obvious and sands occur in the tidal channels that run along the length of the estuary[63]. The muddy sediments accumulate primarily in tidal flats swampy and marshes, deposited along the side of the estuary. Hence, tidal estuary fill deposits showing an upward fining succession with three basic deposition facies; subtidal flat, intertidal flat and supratidal flat (Fig. 11).

The estuary sequence is a complex of intertidal and shallow subtidal, mostly channel form intra-coastal facies dominated to some extent by tidal processes, exhibiting conspicuous variation in sedimentary texture, composition and provenance and in physical biological sedimentary structures[40,48]. The depositional environment comprising this complex of facies may encompass any number (or all) of the following: Tidal deltas, inlets, shoals, back-barrier, beaches, washover fans, swamps, point bars, tidal flat, marshes and channels. Thus, deposition of estuaries can be recognized as distinct entities but consisting of numerous component facies. Good example of vertical facies variability within a single system is shown in Fig. 11, which showed the characteristics bed forms include tidal bars, tidal flat, channel, swamps and flood plains, with characteristics sedimentary structures of cross bedding, flaser to lenticular bedding, swamp burrowed and bedding structures.

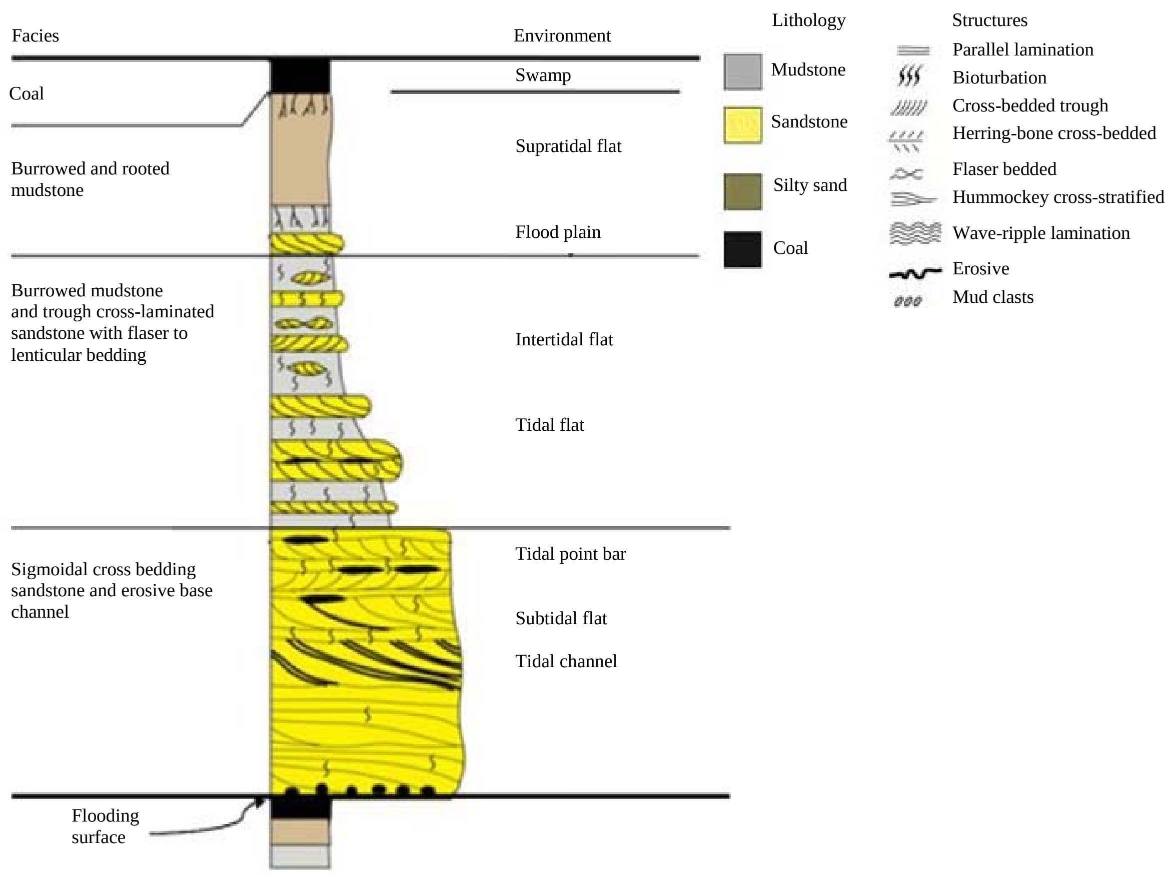


Fig. 11: Tidal estuary fill deposits showing an upward fining succession with three basic deposition facies and different sedimentary structures of subtidal flat, intertidal flat and supratidal flat[42]

Changjiang estuary is one of the good example of tidal estuary, located in Southern Jangsu province of Northern Zhejiang province of China. Estuary deposits show an upward fining succession were classified into five facies[73]: Tidal river, channel, muddy intertidal to subtidal facies, transgressive lag and tidal front. They consisted mainly of tide-influenced sediments such as very thinly interbedded to thinly laminated sand and mud (sand-mud couples), indicating that the estuary is a tide-dominated type. Moreover, most of the sediment for the estuarine fill would be supplied by the Paleo-Changjiang river, resulting in a significant difference in the morphological component with an idealized tide-dominated estuary illustrated by Dalrymple *et al.*[63], whose model cannot be applied to a large-river estuary, the Paleo-Changjiang[73].

WAVE-DOMINATED ESTUARY

In typical wave-dominated estuary, tidal influence is small and the mouth of the system experiences relatively high wave energy. The waves redistribute the sand supplied to the beach by the rivers. The sediment is carried off down the long shore drift direction and mouth-bars of distributary channels are unstable and easily reworked by waves, which forms a beach ridge barriers complex that is approximately parallel to the shoreline[19] (Fig. 12).

Depositional environment and processes: In wave-dominated estuaries, the main conduits of sediment input to the estuarine environment are the marine inlet channel and the bay head delta channel(s). Sediment brought into an estuary by the routes is subject to different transport processes based upon their particle size in relation to the current velocity. Generally, coarse sediment is transported as bedload, whereas, finer sediment is carried in suspension. Bedload is generally deposited on the marine tidal delta or fluvial delta complexes during either the ebb and flood flows of the tidal cycle (Fig. 12) or during periods of river flow, respectively[63]. Exceptions may occur during flooding events, when bed load sediment may be transported beyond the limit of the bay head deltas. Sediment in suspension is transported further than bedload and usually accumulates in the low-energy central basin of wave-dominated estuaries.

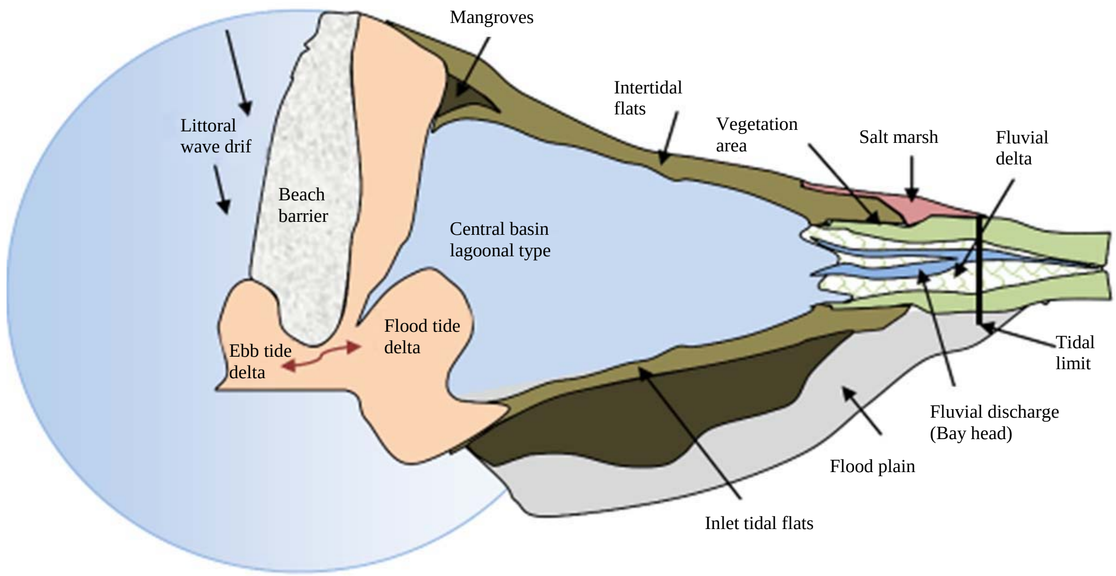


Fig. 12: Typical wave-dominated estuary and other geomorphic features
In this delta tidal influence is small and the mouth of the system experiences relatively high wave energy, which forms a beach ridge barriers complex that is approximately parallel to the shoreline. The bed loads is generally deposited on the marine tidal delta or fluvial delta complexes during either the ebb and flood flows of the tidal cycle

Suspended sediment usually undergoes repeated cycles of erosion, transport and deposited by ebb and flow tidal currents[74], before reaching this location (deposition occurring during the slack water period between ebb and flow tides).

In wave-dominated estuaries, coarser sediments have a tendency to become concentrated at the shore and fine sediments are shifted offshore[75]. The sediment which is concentrated at the shoreline of any estuary may be reworked (e.g., by winnowing) or re-suspended by wave action if it is present wind where prevalent, may introduced coastal sands into their shoreline deposits. Roy *et al.*[76] considered the marine tidal delta zone of wave-dominated estuaries to consist of high and low energy sub-environment with the former including deep tidal channels and shoaling bay beds and the latter including shallow subtidal and intertidal sand flats/shoals occurring along channel margins and the muddy slope-zone in the delta front (Fig. 12). The variability (spatial and temporal) of different flow types, leads to a complex distribution of estuarine sediments and therefore, sedimentary environments. Hence, a great range of such environments exist within estuaries due to variation to be found in these milieus[19].

Stratigraphy: A typical wave-dominated estuary composed as like tidal estuary. By Allen and Posamentier[69] a wave-dominated estuary is composed of following system tracts from bottom to top (Fig. 13): (1) Low-stand System Tract (LST), composed of fluvial sand and gravels, overlaying the Sequence Boundary (SB) formed during sea-level low stand by subaerial exposure and wave-erosion, (2) Transgressive System Tract (TST) separated from the LST by the transgressive surface and formed by estuarine sands and muds, where some or all of the barrier-bar complex is likely to be eroded during shoreface retreat and (3) High-stand System Tract (HST) constituted by a seaward prograding wedge composed of estuarine point bars, tidal bars and tidal flats down lapping onto a Maximum Flooding Surface (MFS) that overlies the estuary mouth sands and control basin muds. Whereas, the bay-head depositional facies system are likely to be common at the base of transgressive successions and can occur at the head of the progradational estuary, where they with exhibit an upward-coarsening succession.

Facies characteristics: Wave-dominated estuary deposits display well-developed mouth-bars and beaches sediments, occurring as elongated coarse sediment bodies approximately perpendicular to the orientation of the delta river channel. The estuary front facies is usually characterized by a relatively continuous coarsening upward facies succession, as in wave-dominated delta system. The proportion of

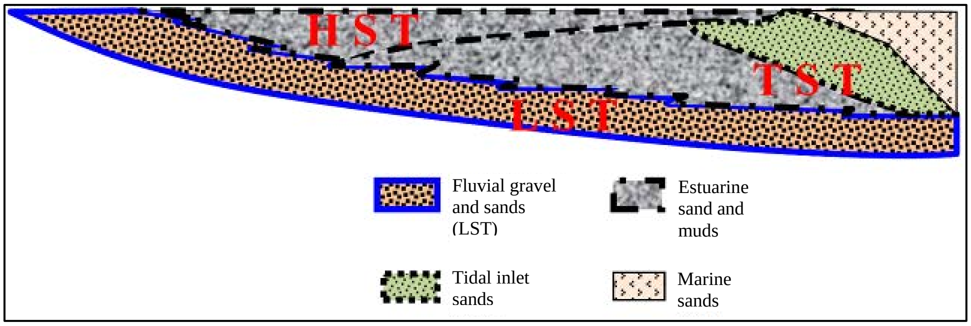


Fig. 13: Wave-dominated estuary and its composition of system tracts, High-strand System Tracts (HST) with mostly of sand and mudstone, Transgressive System Tracts (TST), with mudstone and Low-strand System Tract (LST) with mostly of sandstone

wave-produced structures (such as wave ripples) tends to be greater, whereas, indicators of high sedimentation rates and fresh water influence (e.g., soft sediment deformation, climbing current ripples, brackish fauna and syneresis cracks) tends to be fewer. The inter-distributary and inter-lobe areas tends to be less sandy and commonly contain a series of relatively thin succession, staked coarsening and fining-upward facies[28].

An estuary developed in an area with a small tidal ranges and strong wave energy has typically three division; the bay-head, the central basin (lagoon) and beach barrier. The bay-head facies deposited at the zone where fluvial processes are dominate or river flow enters the central lagoon. It form coarsening-up, progradational succession with channel and overbank facies building out over sands deposited at the channel mouth, which in turn overlies fine-grained deposits of central lagoon[63] (Fig. 14). In central lagoon, where wave energy is mainly concentrated at the barrier bar is the region of fine-grained deposition with organic rich marsh vegetation or mangroves. When central lagoon becomes filled with sediment, it becomes a region of salt-water marshed crossed by channels. In many estuaries, the central lagoon that receives influence of sand may be area where wave-ripples form washover of barrier island during high wave energy[28].

The outer part of wave-dominated estuary deposits the beach barrier which has the same characteristics as those found along clastic coasts, but it is elongated body which is parallel to shoreline and encloses fine-grained deposits of central lagoon. The good example of wave-dominated estuary is Danube estuary, formed by an alternate channel extension process[50]. The delta shows remarkable morphological variability as a result of variation in both riverine discharges among distributaries as well as wave energy along coast. During delta evolution, both river and wave-influenced lobes have been associated with different distributary[77]. Successive bifurcations of the terminal distributary channels via middle ground bar formation at the mouth, resulting in the development of a classical lobate river-dominated delta[28]. Minor wave reworking, periodically results in small barrier bars and splits at the mouths of secondary distributaries. The main sedimentary facies of the Danube estuary are channel, lagoonal complex located in the Southern most part of the delta and some secondary channels. Some marsh deposits mostly of organic origin are formed in depression areas with marsh vegetation[28].

BARRIERS ISLANDS AND LAGOONS

The barrier islands is the coastal landform and a type of barrier system that is relatively narrow strip of sand, parallel to the mainland coast. Whereas, main coasts forms a lagoon in a shallow body of water separated from large body of water by barrier islands. They usually occur in chains, consisting of anything from a few islands to more than a dozen, excepting the tidal inlets that separate the islands. A barrier chain may extend uninterrupted for over a 100 km, the longest and widest being Padre island in Mexico Gulf[78].

Depositional environment and processes

Barriers: Along some coastlines a barrier of sediment separates the open sea from a lagoon that lies between the barrier and the coastal plain (Fig. 15). They may be partially attached to land, that completely encloses a lagoon or can be isolated as a barrier island in front of a lagoon. The conditions required for a barrier to form are as followed by Boggs[79]: First, an abundant supply of sand or gravel-sized sediment is required and this must be sufficient to match or exceed any losses of sediment by erosion. The supply of the sediment is commonly by wave-driven long shore drift from the mouth of a river at some other point along the coast and there may also

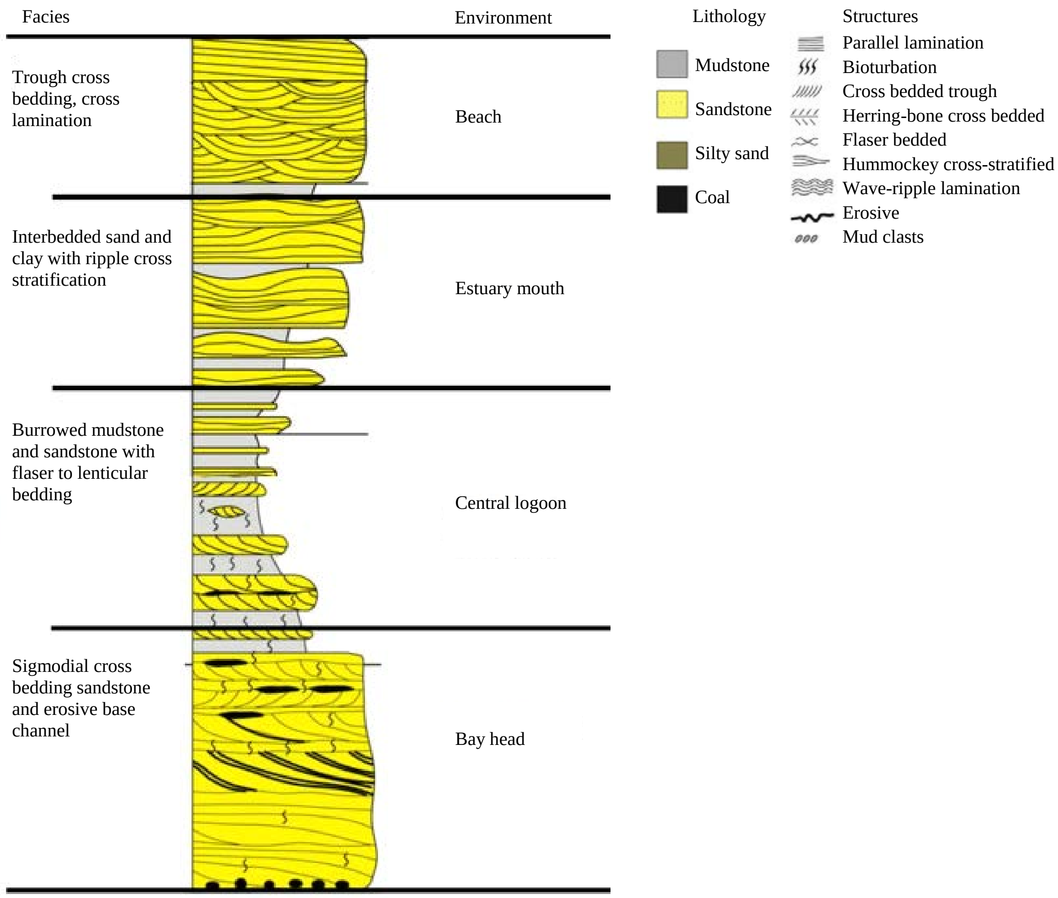


Fig. 14: Stratigraphic succession of wave-dominated estuary with progradational succession having channel and overbank facies building out over sands deposited at the channel mouth, which in turn overlies fine-grained deposits of central lagoon[42]

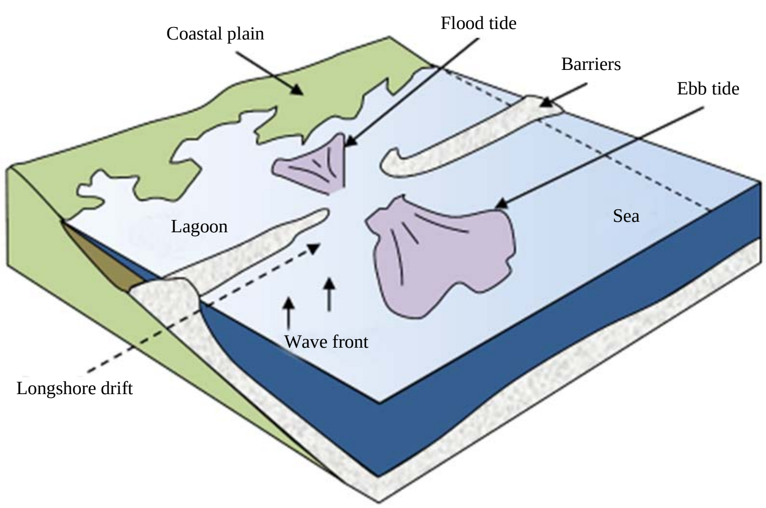


Fig. 15: Distribution of depositional setting of barrier and lagoon system

be some reworking of material from the sea bed further offshore[78]. Second, the tidal range must be small. In macro-tidal setting the exchange of water between a lagoon and the sea during each tidal cycle would prevent the formation of a barrier, because a restricted inlet would not be able to let the water pass through at a high enough rates[79]. Therefore, barrier island systems are best developed in micro-tidal and some extent to meso-tidal settings. The third process to form barrier is generally under condition of relative sea-level rise condition[75,80,81]. If there is a well developed beach ridge, the coastal plain behind it may be lower than the top of the ridge, hence with a small sea-level rise, the coastal plain can become partially flooded to form a lagoon and beach ridge will remain subaerial, forming a barrier.

Lagoons: Lagoons are coastal bodies of water that have very limited connection to open ocean. Sea water reaches a lagoon directly through a channel to the sea or via seepage through barrier, fresh water is supplied by rainfall or by surface run-off from the adjacent coastal plain[41]. Lagoons generally developed along coasts where there is a wave-formed barrier and are largely protected from power of open ocean wave. Tidal effects are generally small because the barrier lagoon morphology is only well developed along coasts with a small tidal range. The fine-grained clastic sediment is supplied to lagoons as suspended material in seawater entering past the barrier and in overland flow from the adjacent coastal plain[82]. Organic material may be abundant from vegetation which grows on the shores of the lagoon. Some coarse-grained may deposited in lagoon when storm wash the sediment over the barrier, which form thin layer of sand reworked by waves. Lagoonal process can be identified by fossil assemblage by marine influence and associated facies, i.e., lagoonal deposit occur above or below barrier sediments[82,83].

Stratigraphy: Barriers are developed in the part of the wave-dominated system where wave action reworks marine sediment. The stratigraphic facies characteristics of the barrier are the same as those found along clastic coast[84]. An inlet allows the exchange of water between the sea and the central lagoon and if there is any tidal current, a flood tidal delta of marine-derived sediment may progrades into central lagoon, which form under the barrier succession. As river flow rapidly decreases and the wave energy is mainly concentrated at the barrier bars, the lagoons are formed[75]. The lagoon is therefore form a fine-grained deposition succession, often rich in organic material. The relative thickness of each is depending on the balance between fluvial and marine supply of sediment during transgression and regression. The concept of regression and transgression refer to the overlapping of deeper water sediment over landward deposits in lagoon (transgression) or migration of shoreline oceanward to form barrier (regression).

Facies characteristics: The facies of barrier islands are mainly sand and gravel, whereas the lagoonal (back barrier) deposits consist of both mud and sand. The transition between lagoon deposits and barrier deposits occurs in the over lapping sub-environments of the back barrier tidal flats, marsh, washover fans and flood tidal deltas[81,84]. The barrier deposits dominate sedimentary structures of subhorizontal (planar) stratification and wave reworking with mostly sand and gravel (Fig. 15). Whereas, lagoon sequence consist of interbedded and inter-fingering sandstone, shale, siltstone and coal facies characteristics with number of overlapping sub-environment[74,85] (Fig. 15). Sediment accumulation rate and relative sea-level rise in lagoons. Sand facies includes washover sheet deposits and channel fill deposits of flood tidal delta origin. Fine-grained facies include those of the subaqueous lagoon and tidal flats, which are situated adjacent to the barrier or on landward side of the lagoon (Fig. 16). Organic deposits of coal and peat record marsh and swamp environments and usually are very thin, having formed on sand and mud flats succession of the lagoonal margin[84,86]. Whereas, subaqueous shale and siltstone facies in lagoon deposits are often characterized by brackish water. The good example of worldwide lagoon and barrier is the Fire island in New York, Texas barrier island.

STRAND PLAINS

A strand plain is a broad belt of sand along a shoreline with surface exhibiting well defined parallel or semi-parallel sand ridges separated by shallow swales. A strand plain differs from a barrier in that, it lacks either lagoons or tidal marsh that separate a barrier from the shoreline to which the strand plain is directly attached. Also the tidal channels and inlets, which cut through barrier islands are absent[84] (Fig. 16). Strand plains typically are created by the redistribution of waves and longshore currents sediment on either side of a river mouth. Thus, they are part of one type of wave-dominated delta[80].

Depositional environment and processes: The strand plains are marine-process-dominated depositional features welded into coastal mainland's (Fig. 16). According to Harris and Heap[58], strand plains form where wave-induced sediment transport (littoral drift) results in the formation of a series of coast-parallel depositional features. These strand plains are classed into two broad groups, beach ridges and cheniers

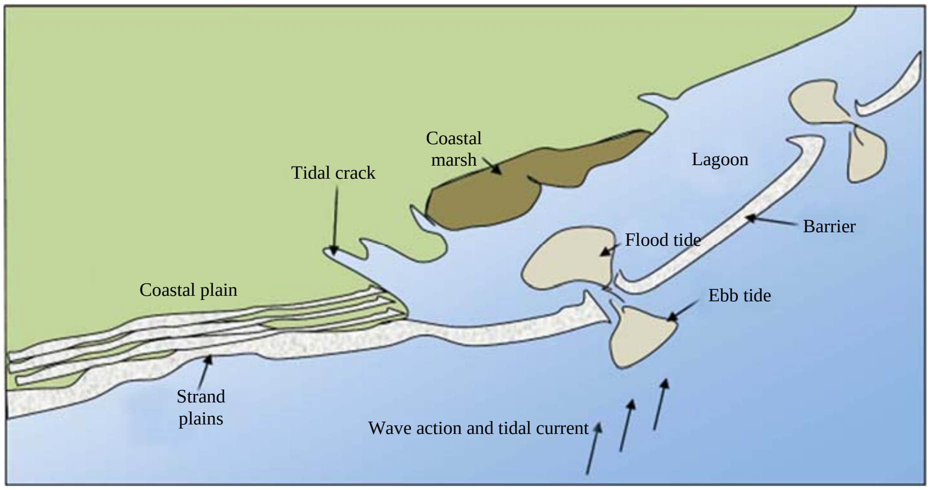


Fig. 16: Morphological features of a coastline influenced by wave processes and tidal currents, results in strand plains and barrier

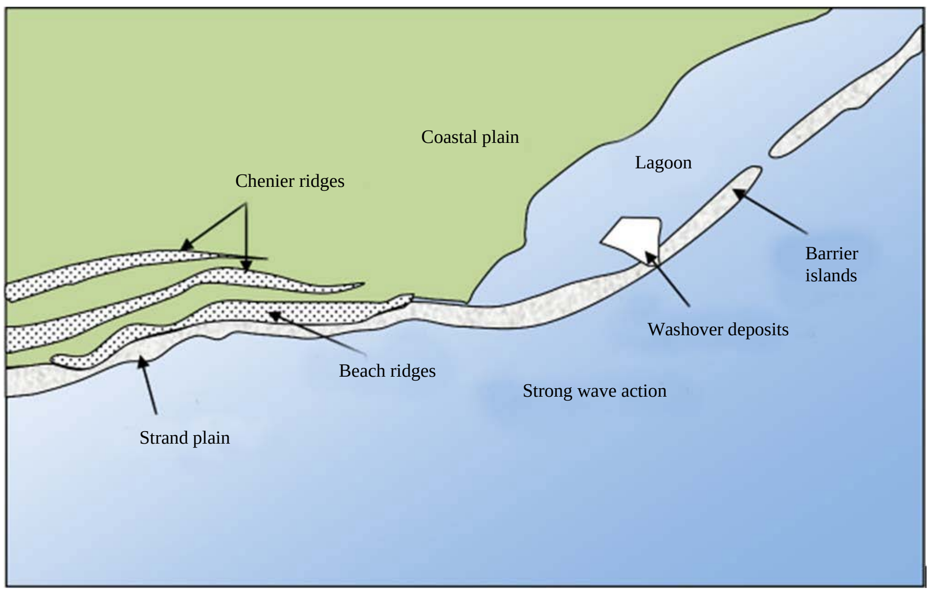


Fig. 17: Two subdivision group of strand plains due to strong wave action i.e., beach ridges and cheniers
Beach ridges complex is a strike-elongate, narrow shally bodies that compose the ridges separating mud flats on chenier plains

(Fig. 17). Beach ridge and chenier plains are dominantly progradational features, shaped by the relations among sediment texture and rate of supply, coastal physiography (including slope), wave and tidal energy[87].

An abundant supply of mud is required for the development of chenier plains. Beach ridges complex is a strike-elongate, narrow shally bodies that compose the ridge separating mud flats on chenier plains[53,87] (Fig. 17). Two processes account for their origin. During periods of low sediment supply, wave winnows the intertidal mud flats and concentrate the coarser clastic and shelly detritus into beach-ridges, forming Cheniers that rest on shoreface clays. Alternatively, storm-washover processes may build cheniers on marsh deposits[87].

Stratigraphy and facies characteristics: The two broad groups of strand plains (Beach ridges and chenier plains) are dominantly progradational feature[87]. Beach ridges are semi-continuous, generally mound of shelly sand and gravel, deposited above the high tide line[88]. A sandy beach is always present in front of the beach ridge, as marine-derived sediment accumulates along the coast, the sequence

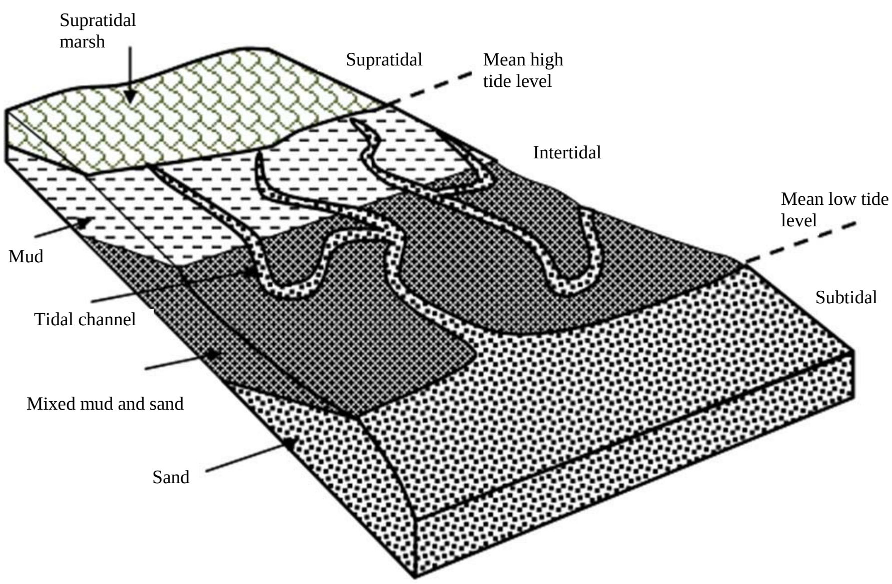


Fig. 18: Morphological features of tidal flats sediments from supratidal marsh (land) to subtidal (basin)

progrades seawards leaving the coarse-grained ridges "Stranded" within the fine-grained coastal plain[89]. Depression and between beach ridges may be connected and form a salt flat or shallow lagoon, joined to the sea by tidal inlets that punctuate the seaward ridges. The facies of beach ridges plains are: (1) A sandy beach ridge complex, which is the most widespread of the strand plain facies, (2) Crosscutting fluvial deltaic complexes, which consists of upward-fining channel sandstones. Dominate channel erode through the beach ridges and abandonment of the lesser channels commonly results in a mud plug[88] and (3) A sandy shoreface, lies seaward of and parallel to the beach plain which consists of finest of the coarse clastic and is transitional in position and in grain size between coarser beach, dune sands and lower shoreface to shelf mud.

The cheniers plains are comprised of coarse-grained sediment deposited as a narrow liner ridge above the level of high tide but separated from the shoreline by a marsh area comprised of fine-grained sediment[90,91] (Fig. 18). As cheniers form by reworking and erosion, the cyclical erosion and progradation of tidal flats (e.g., from succession storm events associated with varying rates of sediment supply) produces a series of parallel cheniers. Thus, grain size is a major factor differentiating cheniers from beach ridges. However, beach ridges with wide swales infilled by fine-grained sediment have been mistaken for cheniers and hence knowledge of the subsurface stratigraphy of the coastal sequence may be required for definitive classification in many cases[92]. Due to this constrain, cheniers have not been differentiated from beach ridges, in strain plain in the present studies.

The good recent examples of strain plains are Bahia province, caravelas strain plain in Brazil, West coast of Namibia, Afrikaan in Southern Africa, Eastern Texas and South-East and South-West coasts of Australia.

Tidal flats: Tidal flats level muddy surface bordering an estuary, alternately submerged and exposed to the air by changing tidal level[27,93]. The tidal water enters and leave a tidal flat through fairly straight major channels, with minor channels meander and migrate considerably over periods of several years[29,94,95]. This environment (tidal flats) is one of the most varying environments than in any other shallow-marine environment. This is due to alternating submergence and exposer, the varying influence of fresh river water and saline marine waters cause physical conditions (principally, temperature, salinity and acidity) to changes widely. The tidal flats are typically vegetated salt marsh area cut by tidal cracks that act as the conduits for water flow during the tidal cycle[66,96].

Depositional environment and processes: The tidal flats are modified by aeolian processes, when subaerially exposed at low tide and by wave and current processes when submerged at high tide[94]. Flood water is derived from the lagoon and driven onto the flats by strong and persistent winds during the

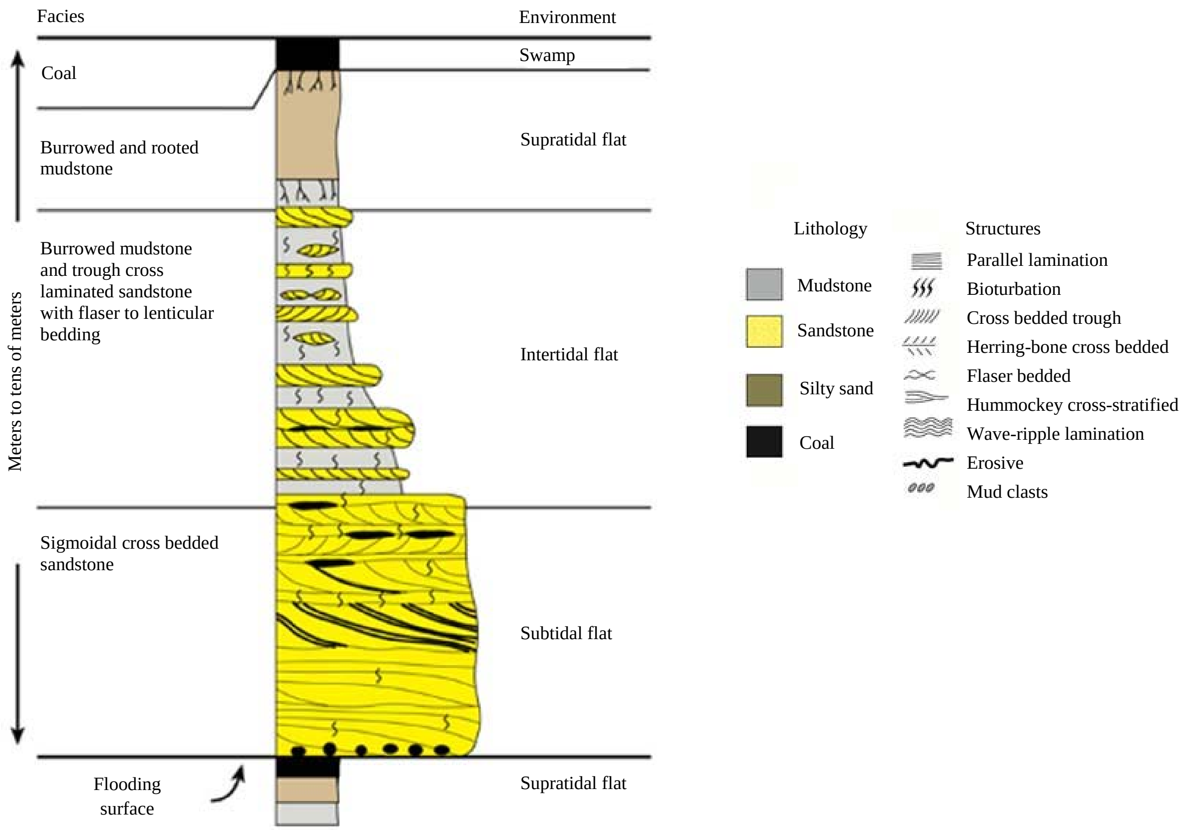


Fig. 19: Stratigraphic succession of tidal flat and its environment from supratidal flat to intertidal flat
Commonly encountered structures in the sands of the subtidal and lower intertidal zone includes mud-drapes forest, reactivation surface and local herring-bone cross bedding[42]

passage of cold fronts and tropical cyclones[85,93]. Low surface gradients of the flats prevent rapid drainage and promote seawater evaporation. The depositional products of these processes are interbedded and interlaminated sand, mud, marine shells and algal mats and evaporate[95]. The tidal flats have been divided into three basic environments i.e., subtidal, intertidal and supratidal (Fig. 19). The subtidal zone is below low tide and seldom exposed subaerially, the intertidal zone lies between normal low and high tides and is exposed once or twice daily, whereas, supratidal zone is above high tide and sediment deposited are exposed to subaerial conditions (most of the time with flooding) only during spring or storm tides. The supratidal is the highest part of the tidal flats may become vegetated to produced salt marshes, where the stratification is largely destroyed by rootlets. Salt water and freshwater peats can accumulate here. Desiccation cracks are most abundant in the upper intertidal and supratidal zones[27,96].

Tidal flats along exposed, open coasts exhibit the landward fining trend may be coarser-grained because of wave action and contain more wave-generated structure than tidal flat[96,97]. In tropical climates, sea grasses and mangroves commonly colonize large part of the tidal flats[98]. The muddy part of the tidal flats are dissected by a network of small-to medium-sized meandering tidal channels that increase in width and depth as the coalesce seaward (Fig. 20).

Stratigraphy and facies characteristics: The tidal flats sediments are common along prograding coasts, characterized by mean tidal ranges >≈4 m. They usually comprised of fine-grained marine sediment that has been transported towards the coast by strong currents associated with the larger tides. During the falling tide, drainage of seawater from the intertidal flats causes the development of tidal creeks[96,99]. Large tidal creeks often contain tidal sand banks and dunes. The mixed flats, in which mud layers become more abundant as the distance from the channel increases, lie shoreward of the sand flats. Mud flats consisting of laminated muds with relatively little sand lay still further landward (Fig. 18).

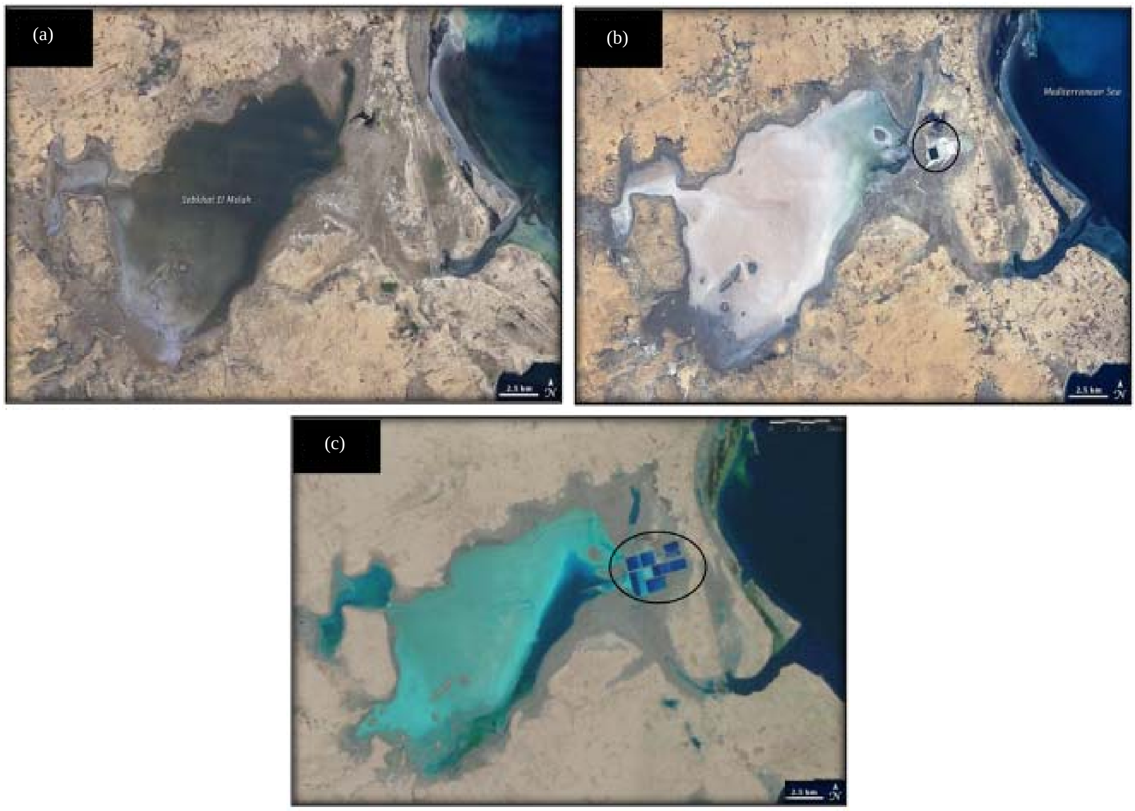


Fig. 20(a-c): An example of landsat images of Sebkha El Melah, Tunisia, (a) 1987, (b) 2001 and (c) 2011, with cyclic episodes of tidal flat deposits that are periodically inundated with evaporation process, leaving behind salt
1987: Landsat image of Sebkha El Melah, Tunisia was flooded, 2001: Landsat image of same area mostly dry, with salt deposition. Note rectangular industrial evaporite pans, for sea-salt production, upper right (circle) and 2011: Landsat image of same area highly flooded, industrial of evaporite pans, flooded, industrial of evaporite pans, for sea-salt production increases, upper right (circle)

The tidal builds a progradational succession. The progradation of tidal flat generates an upward-fining succession[67,72,93]. The succession typically begins with an erosional base that is scoured by tidal channels during a local transgression. Above this there is a gradual upward decrease in the grain size and thickness of sand beds and an increase in proportion of mud (Fig. 19). Commonly encountered structures in the sands of the subtidal and lower intertidal zone includes mud-drapes forest, reactivation surface and local herringbone cross bedding. The intertidal mud flats contain abundant flaser and lenticular bedding and erosional based tidal sediments. Rooted horizons and coals occur in the salt marsh. The bioturbation may ranges from very low to extensive. The good examples are known from the Wash, UK[99] and from San Sebastian Bay, Argentina[96]. They are usually comprised of fine-grained marine sediment that has been transported towards the coast by strong currents associated with the large tide[58]. Sabkhas are another good example that, although rare today is important to the geologic past of certain regions. Sabkhas can be thought of as tidal flats that are periodically inundated with water evaporated and leaving behind salt (Fig. 20).

CONCLUSION

This review has confirmed that key controls on morphology of shallow-marine clastic coastal depositional environments can easily be prophesied from the influence of wave, tide and river processes. The conceptual ternary diagram classifying the distribution of environments are operated by wave, tide and river power, resulting solely in 7 depositional processes which are main controls in facies style and architecture for erecting models. These processes are controlled by shoreline movements with sediment supply and accommodation space created.

Our review designates that deltas generally initiate along coasts having conditions of lower wave and tide influx, than coastlines where estuaries are predominant. This make probable results that higher wave and tide power results in estuaries, losing a greater percentage of sediment to the adjacent shelf and coastal areas. Thus inhibiting delta development with variation in the stratigraphic architecture of estuaries and creeks that drain intertidal flats and is naturally turbid and generally well amalgamated with unique sedimentary structures (e.g., herringbone cross bedded sandstone). In contrast, water contained in wave-dominated deltaic, wave-dominated estuaries and lagoons are naturally clear (low turbidity) and exhibits mainly clean stratified thick stratigraphic patterns in sedimentation with unique structures (e.g., hummocky cross-stratified sandstone). The same approach (using a database of coastal environments in this review) could be applied to any region on earth where clastic coastal depositional environments may be identified from stratigraphic characteristics.

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