D

DELTAS AND ESTUARIES

Definition of a delta

A delta is a discrete bulge of the shoreline formed at the point where a river enters an ocean, sea, lake, lagoon or other standing body of water (Figures D4 and D5). The bulge is formed because sediment is supplied more rapidly than it can be redistributed by basinal processes, such as waves and tides. Deltas are thus fundamentally regressive in nature, which means that their deposits record a seaward migration or progradation of the shoreline. The term delta has also been used to describe any regressive deposit built by any terrestrial feeder system into any standing body of water (Nemec, 1990 in Colela and Prior, 1990). In this scheme, terrestrial feeder systems can be alluvial (rivers, alluvial fans, braidplains, scree-cones) or non-alluvial (volcanic lavas or pyroclastic flows). The terms ebb- and flood-tidal delta have also been generally applied to sediment accumulations that form around tidal inlet channels in barrier-lagoon depositional systems (see *Tidal Inlets and Deltas*), but these do not fit the above definition of a delta because they are not linked to a river or terrestrial feeder. This entry focuses on river deltas as a discrete depositional system in which both environments and their deposits will be described.

Definition of an estuary

Sedimentologists define an estuary (Figure D5) as the seaward portion of a drowned river valley which receives sediment from both fluvial and marine sources (modified after Dalrymple *et al*., 1992). An estuary may be affected by tide, wave, and river processes and is defined as extending from the landward limit of tidal influence to the seaward limit of coastal influence.

The term estuary is also defined on an oceanographic basis as a semi-enclosed body of marine water that is measurably diluted by land-derived fresh water (Pritchard, 1967; Nichols and Biggs, 1985). Sedimentologists tend to reject this usage as being too broad since it includes all brackish water environments including lagoons and many marine-influenced delta fronts which are not generally thought of as estuarine by sedimentologists. The etymology of the word estuary also means tides, so by definition all estuaries are formed adjacent to a marine body of water. There are no entirely fresh-water estuaries because measurable tides do not occur in lakes. Consequently, drowned river valleys filled during rising lake levels are not generally considered as estuarine.

In an estuary, the seaward portion of the valley is filled with marine sediments and estuaries are fundamentally transgressive in nature, unlike deltas, which are regressive. Deltas and estuaries are not mutually exclusive, however, because regressive bayhead delta deposits can readily form within the up-valley reaches of an estuary (Figure D5). In this case, the delta deposits would form a minor component of a larger, overally transgressive estuarine valley-fill. If fluvial discharge became high enough to "flush out the valley" and begin to form a broadly regressive deposit then the estuary would evolve into a delta.

Estuaries form by the interaction of waves, tides and fluvial processes. Two end members have been described (Figure D5). In tide-dominated estuaries (such as the Bay of Fundy in Nova Scotia, Canada) the mouth of the estuary is kept open by strong tidal currents. The center of the estuary tends to be dominated by sandy bedforms and tidal bars whereas the margins tend to be muddy tidal flats. In Wave-dominated estuaries, the mouth of the estuary is partly closed by a wave-formed barrier island. A brackish lagoon or bay lies behind the barrier and is commonly filled with fine-grained mud. At the head of the bay, fluvial or tide-influenced bayhead delta deposits form, which may be sandy or muddy. Mud accumulates primarily in the so-called "central basin" bounded by the barrier and bay head delta.

Distinguishing deltas, barriers, estuaries, and strandplains

Most of the sediment in a delta is derived directly from the river that feeds it; in contrast with estuaries in which much of the sediment is derived from the marine realm and in which deposits are fundamentally transgressive. In barrier-island

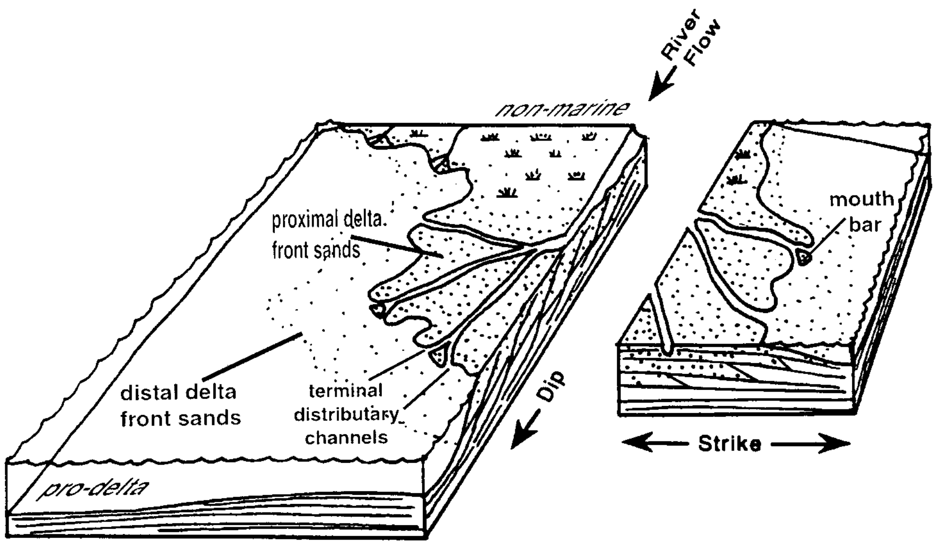

Figure D4 Block diagram of a lobate, river-dominated delta showing numerous channel bifurcations. Terminal distributary channels fed triangular-shaped mouth bar deposits. Seaward progradation forms a series of offlapping inclined strata in dip-view. The strike view shows a lens-shaped sediment body with beds dipping away from the depositional axis of the delta lobe.

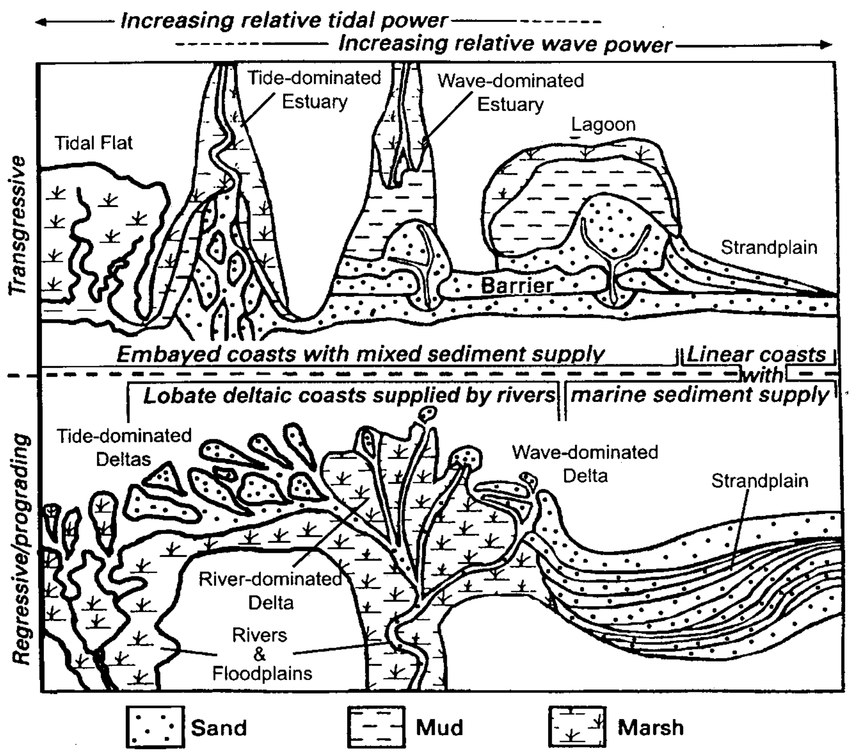

Figure D5 Comparison of regressive versus transgressive coastal depositional systems. Deltas form lobate sediment bodies. The character and distribution of sediment in a delta is highly sensitive to the relative proportion of wave, tide, and fluvial processes. Differences in these processes result in different shapes sand bodies. Also, note river-dominated delta at the head of the wave-influenced estuary. Deltas can thus form smaller components of other types of coastal depositional systems. Changes in sediment supply and sea level change can cause one type of depositional system to evolve into another type (modified from Reading and Collinson, 1996 based on Heward, 1981, and Boyd, Dalrymple, and Zaitlin, 1992).

systems (Figure D5), sediment is supplied by alongshore transport. Alongshore transport occurs because waves approaching the shoreline are deflected and migrate parallel to the shoreline causing longshore drift. The longshore drift system may carry sand and gravel, which can be deposited as linear shoreface deposits, or they may carry large quantities of fluidized mud that can be deposited to form muddy coastlines. In mud-dominated coastlines, silt, sand, or shelly material may be winnowed out in the intertidal zone, forming thin and narrow beach deposits termed **cheniers**. Barrier-islands may also form components of wave-influenced deltas. Rivers can act as a baffle or groin, that causes sediment carried in the longshore drift system to be deposited on the updrift side of the distributary channel (see wave-dominated delta in Figure D5).

Where basinal processes redistribute sediment to the point that the fluvial source and delta morphology can no longer be recognized, more general terms such as paralic, strandplain or coastal plain may be preferable.

Scale and importance of deltas

Deltas occur at a wide variety of scales ranging from basin-scale depositional systems, such as the modern Mississippi delta with an area of about 28,500 km^2, to smaller components of other depositional systems such as bayhead deltas within estuarine or lagoonal systems. Many large deltas, such as the Danube in Romania and the Mississippi in the Gulf of Mexico, contain several scales of delta lobes associated with the fact that as a channel splits into several smaller channels, each new channel can feed its own lobe.

A large number of the earth's peoples live on or near deltaic coastlines and they are thus important from an environmental perspective. Ancient deltas are also economically important because they are commonly associated with major coal, oil and gas reserves. As a consequence, much has been written about deltas, although there is still much interest in new delta research. There has recently been an increase in documented examples of delta types that have been historically lacking, such as tide-influenced systems (e.g., Maguregui and Tyler, 1991; Reading and Collinson, 1996; Willis *et al*., 1999). Readers are referred to several summaries for general information on deltas (Reading and Collinson, 1996; Bhattacharya and Walker, 1992; Colella and Prior, 1990; Whateley and Pickering, 1989; Coleman and Prior, 1982; Broussard, 1975) and estuaries (Nichols and Biggs, 1985; Dalrymple *et al*., 1992; Dalrymple *et al*., 1994).

History of delta research

Historical overviews of delta research are provided by Bhattacharya and Walker (1992) and Reading and Collinson (1996) and summarized here. The concept of a delta dates back to the time of Herodotus (*c*. 400 BC) who recognized that the alluvial plain at the mouth of the Nile had the form of the Greek letter Δ. The first study of ancient deltas was that of Gilbert, 1885 (see Bhattacharya and Walker, 1995), who described Pleistocene fresh-water gravelly deltas in Lake Bonneville, Utah. Gilbert recognized a threefold cross-sectional division of a delta into topset, foreset and bottomset deposits (note sigmoidal stratal geometry in Figures D4 and D7). Barrell (1912 *ibid*.) extended these subdivisions to the much larger scale of the Devonian Catskill wedge in the Appalachians, and also provided the first explicit definition of the essential features of an ancient delta deposit. Barrell considered the recognition of overlying non-marine facies crucial in recognizing ancient deltas, although recent research demonstrates that in a significant number of deltas, non-marine topset facies may not be preserved (e.g., Bhattacharya and Willis, 2001). Barrell actually wrote his 1912 paper in order to address what he perceived as an over-application of an estuarine interpretation to many ancient sedimentary successions that contained a marine to non-marine transition and that he believed should be better interpreted as deltas.

The Mississippi river and its deltas have long been a focus for understanding continental-scale delta systems (see summary of early papers by LeBlanc, 1975). Scruton (1960, see LeBlanc, 1975) recognized that deltas are cyclic in nature and consist of a progradational constructive phase usually followed by a thinner retrogradational destructive phase coinciding with delta abandonment. He also illustrated a vertical facies succession of coarsening- and sandier-upward facies related to the progradation of bottomset, foreset and topset strata (Figure D6). Kolb and Van Lopik (1966, see LeBlanc, 1975) summarized much of the work that described the way in which the Mississippi river constructed its delta plain over the past 9000 years, suggesting that the development was autocyclic. This work was critical in establishing the idea that apparently cyclic vertical successions of sedimentary strata can result from the intrinsic way in which river channels naturally avulse and cause switching of delta lobes.

Coleman and Wright (in Broussard, 1975) compiled data on 34 modern deltas and developed a six-fold classification based on sand distribution patterns. One of the most widely used classification schemes still used today is that of Galloway (in Broussard, 1975), who subdivided deltas according to the dominant processes controlling their morphology; rivers, waves and tides (Figure D5). This scheme has since been expanded to include grain calibre (Orton and Reading, 1993; Reading and Collinson, 1996). This scheme has also been extended to show how deltas, estuaries and barrier-lagoons may evolve into one another in the context of changing sea-level and sediment supply (Dalrymple *et al*., 1992).

Improvements in sea floor-imaging and seismic data acquisition led to the recognition of the abundance and importance of synsedimentary deformation in the subaqueous parts of modern deltas (Coleman, Prior and Lindsay, 1983; Winker and Edwards, 1983; Bhattacharya and Walker, 1992). Similar features have now been recognized in ancient deltas (e.g., Bhattacharya and Davies, 2001).

More recently the evolution of modern deltas has been interpreted in the context of sea level changes and plate tectonics, rather than just sediment supply (e.g., **Dominguez et al**., 1987; **Boyd, et al**., 1989; Bhattacharya and Walker, 1992; Hart and Long, 1996). This resulted in widespread abandonment of the idea that apparently cyclic sedimentary successions are autocyclic, but rather are controlled by allocyclic processes such as subsidence, sea level change, and climate change (see *Cyclic Sedimentation*). Integration of basin-scale seismic stratigraphic concepts with ideas about cyclic sea-level change were applied to many ancient deltas in the development of *sequence stratigraphy* (e.g., Galloway, 1989; Van Wagoner *et al*., 1990; Bhattacharya, 1993). More recent work is beginning to elucidate the nature of tide-influenced deltas that have heretofore been under-recognized in ancient sedimentary rocks because of lack of well-studied modern or

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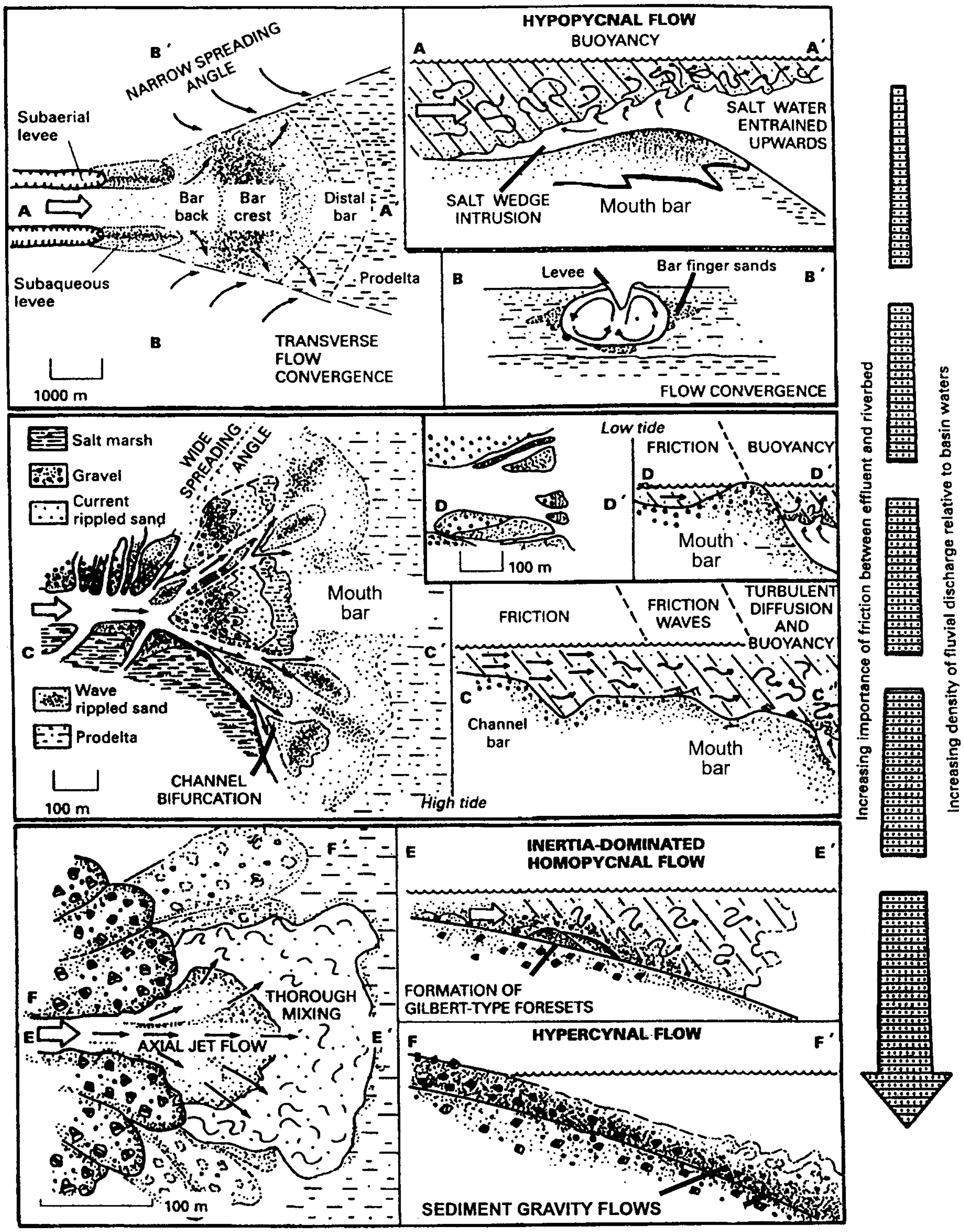

Figure D6 River Mouth processes and their deposits. Hypopycnal flow (top panel) is defined where inflowing water (typically fresh) is less dense than water in the receiving basin (typically saline). This favors the formation of a salt wedge and elongate bar-finger type mouth bars. The less dense fresh water is buoyed-up by the denser sea-water and mud is carried far offshore. These delta fronts are typically referred to as buoyancy dominated. As the sediment becomes coarser-grained (middle panel), more friction is generated. This is common where the density of inflowing and receiving waters are the same (homopycnal) such as in many lacustrine deltas and in rivers with high sediment loads. These delta fronts are sometimes referred to as friction-dominated and favor development of triangular (radial) mouth bars. In rivers with exceptionally high sediment concentrations (lower panel), especially small muddy rivers, hyperpycnal conditions may result. In these cases, sediment-laden water is more dense than water in the receiving basin. The inflowing mixture of water and sediment may have enough inertia to continue flowing down the sea bed as a sediment gravity flow. These types of delta fronts are said to be inertia-dominated. These types of deltas may be linked to deep water depositional systems and provide a means of supplying sediment to submarine fan deposits. These mouth bar types are not mutually exclusive. Rivers can change from hypopycnal to hyperpycnal as discharge increases during exceptional flooding events and the degree of buoyant, frictional and inertial forces can vary across a bar (middle and lower panel). Modified after Reading and Collinson, 1996, based on Orton and Reading, 1993.

ancient examples (e.g., **Maguregui and Tyler**, 1991; Reading and Collinson, 1996; Jenette and Jones, 1995; Willis *et al*., 1999).

River mouth processes

A delta forms when a river of sediment-laden freshwater enters a standing body of water, loses its competence to carry sediment, and deposits it. Much of the active sand deposition occurs in distinctive *distributary mouth bars*, formed directly at the mouth of the channel (Figure D7). The mouth bars form naturally as a consequence of the decrease in discharge and bed shear stresses associated with the loss of flow competence, although very little work has been done that quantifies the mechanics of how mouth bars scale to the flow behavior at the river mouth. River mouths may be deflected downdrift by waves and can be scoured and modified by tidal currents (Figure D5).

The general form of the deltaic deposit depends upon (1) whether the river outflow is more dense (*hyperpycnal flow*), equally dense (*homopycnal*) or less dense (*hypopycnal*) than the standing body of water (Figure D7), and (2) the extent to which the deposits are reworked by wave and tidal processes, although tidal processes are insignificant in lakes. At any given river mouth, inertial, frictional and buoyant forces may be operative in varying proportions (Figure D7). In hyperpycnal deltas that have exceedingly high sediment concentrations at the river mouth, the slurry-like mixture of sediment and water just keeps on moving downslope as a sediment gravity flow (see sediment gravity flow). These sediments can end up being deposited in deepwater systems. Hyperpycnal rivers tend to be small and/or "dirty" such as the modern Sepik River, in Papua New Guinea, the Eel River in Northern California, and the rather larger Yellow River (Yangste) in China (Mulder and Syvitsky, 1995). In hypopycnal settings buoyant, less dense fresh water rides over a marine salt-wedge and carries suspended mud far offshore. Sand tends to be segregated and deposited at the mouth of the channel as a distinct sandy mouth bar with muddier sediments deposited farther offshore in the prodelta area (Figure D7). In homopycnal deltas a great degree of mixing occurs and frictional forces cause rapid deposition of all of the mud, sand, and/or gravel carried by the river (Figure D7). This results in deposition of a large poorly sorted "Gilbert-delta"-type mouth bar commonly with angle-of-repose foresets (Figure D6).

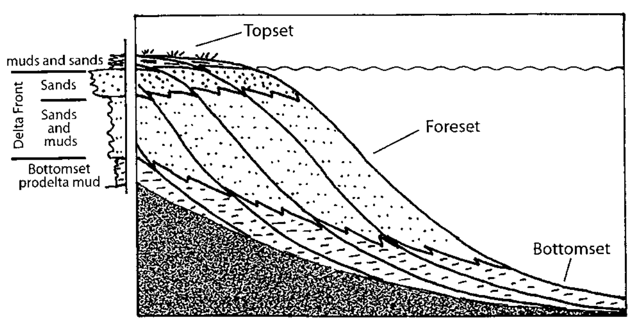

Figure D7 Seaward migration (termed progradation or regression) of a delta builds an upward coarsening facies succession, that shows a transition from marine into non-marine topset deposits (modified after Scruton, 1960). Topset facies may be eroded by waves as the sea floods back over the land during transgression.

Rapid sedimentation in all delta types can cause sediment instability at the river mouth (see *Synsedimentary Structures and Growth Faults*). Slumping commonly occurs after the mouth bar builds up to a slope that exceeds the failure threshold. Mouth bars are especially susceptible to failure because of the high amount of water trapped within the sediment that causes high pore pressure. Slumped sediment at the river mouth can evolve into various types of sediment gravity flows and are an important way of providing sediment to the deep oceans.

Many rivers will experience dramatic changes in discharge as a function of seasonal climate change or as a result of major storms. Sediment discharge and sediment caliber of the river plays an important role in determining the sediment concentration discharged at the river mouth (Figure D7). These changes in sediment concentration can cause a river to change from hypopycnal to hyperpycnal, even in fully marine settings (Mulder and Syvitsky, 1995). Recent work has attempted to distinguish the relative importance of these processes in classifying ancient river mouth sediments (e.g., **Martinsen, 1990;** Reading and Collinson, 1996).

River mouth processes can also be important in the autocyclic process of river avulsion that results in delta lobe switching. In this process, the river builds a large deltaic edifice that creates enormous form friction at the mouth of the river. This friction causes a loss of discharge at the river mouth. In addition, the river extends seaward, which decreases the effective slope. The loss of discharge and decreasing slope propagates upstream and eventually causes the river to avulse.

At a more local scale, friction at the river mouth may cause upstream deposition of sand. In a study of Cretaceous-age growth faulted deltaic strata in Utah, growth faults initiate both upstream and downstream as the loci of rapidly deposited sands shift (Bhattacharya and Davies, 2001).

Delta environments

No one environment is characteristic of a delta. In plan view, deltas comprise three main environments: the delta plain (where river processes dominate), the delta front (where river and basinal processes are both important) and the prodelta (where basinal processes dominate). In cross-sectional views, these three environments roughly coincide with the topset, foreset and bottomset strata of early workers (Figure D7).

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Delta plains usually contain distributary channels and a wide variety of nonmarine to brackish, paralic environments including swamps, marshes, tidal flats, and interdistributary bays (Figure D4). The line that demarcates the landward limit of tidal incursion of seawater is referred to as the bay line and marks the boundary between the upper and lower delta plain. In ancient settings, the bay line may be indicated by the landward limit of marine or brackish- tolerant fossils or trace fossils. Lacustrine deltas have no bayline as such, since there are no significant tides in lakes.

Many deltas contain distributary channels that show different sizes and shapes in different positions on the delta. There is therefore no such thing as "a distributary channel" in many deltas. Typically, a trunk fluvial system will first avulse at the point where the river becomes unconfined forming a nodal avulsion point (Mackey and Bridge, 1995). Delta plain channels tend to be few in number and are separated by wide areas of interdistributary bays, swamps, marshes, or lakes in the upper delta plain, although these interdistributary areas can be replaced with channel deposits depending on the avulsion frequency (Mackey and Bridge, 1995). Upper delta plain channels may be exceedingly difficult to distinguish from fluvial channels, especially in lacustrine deltas. In fact, these types of distributaries are, strictly speaking, non-marine in nature and have been described in the context of fluvial depositional systems (Mackey and Bridge, 1995). Distributaries can show several orders of branching. The smallest scale channels are referred to as terminal distributary channels and are associated with the proximal delta front. Commonly these are only a few meters deep and will tend to lie on top of associated distal delta front deposits.

In many ancient examples, thick channelized deposits overlying marine prodelta shales have been interpreted as distributary channels (e.g., Rasmussen *et al*., 1985) eroding into their associated delta fronts. Some of these sandstones are over 30 m thick and cut into delta front sandstones that are only 10 m or so thick. Terminal distributaries should actually be difficult to recognize in subsurface because they tend to be shallow and completely contained within the sandy delta front facies. Some of these deeply incised channels are now interpreted to be fluvially-incised valleys (e.g., Dalrymple *et al*., 1994; Willis, 1997).

The delta front is the site of much of the active deposition, particularly at the mouths of distributary channels, where the coarsest sediment is deposited in distinct bars. Much of the deposition occurs in distributary mouth bars (also referred to as stream mouth or middle-ground bars) separated by shallow "terminal" distributary channels (Figures D4 and D7). Mouth bars can be on the order of several hundred meters wide and several kilometers long, such as in the Atchafalaya delta in the Gulf of Mexico (e.g., **Van Heerden and Roberts**, 1988; Bhattacharya and Walker, 1992). These mouth bars typically coalesce to form broader depositional lobes. **Sediments deposited in mouth bars can also be profoundly reworked by waves, to form shore-parallel beach and strandplain deposits, or they can be reworked by tides to form shore-normal tidal bars (Figure D5).**

Some distributary channels are fixed in the same position for long time periods, especially in deep-water mud-dominated deltas that build into relatively quiet marine basins (low tidal range, low wave action, Figure D6). The seaward building forms elongate bar fingers, as in the modern Mississippi "birdfoot" delta and in many bayhead lagoonal deltas. By contrast in siltier or sandier systems, deposited in shallower water, distributary channels switch more rapidly and coalesce to form more lobate sediment bodies, as in the Lafourche and Atchafalaya deltas in the Gulf of Mexico. Some researchers have used the term "braid" delta or "braidplain" delta to refer to a sandy or gravelly delta front fed by a braided river and characterized by a fringe of active mouth bars such as in the Canterbury Plains of New Zealand or in many glacial outwash plains (e.g., McPherson, Shanmugam and Moiola, 1987; Reading and Collinson, 1996).

The seaward-dipping slope associated with distributary mouth bars is referred to as the distal delta front and can form a relatively continuous sandy fringe in front of the active mouth bar (Figure D4).

The prodelta is the area where fine material settles out of suspension. It may be burrowed or largely unburrowed, depending on sedimentation rates. Prodelta muds tend to merge seaward with fine-grained sediment of the basin floor. The preservation of silty or sandy lamination is commonly taken to mark the influence of the river, as opposed to total bioturbation of the basin floor sediments in areas away from the active river. Where the sediments are rhythmically laminated, there may be a tidal influence. Also, because of the abundant suspended sediment, certain types of vertical filter feeders and other organisms that produce open vertical burrows of the *Skolithos* ichnofacies tend to be suppressed (e.g., Gingras *et al*., 1998). Because the delta front and prodelta areas are characterized by high levels of suspended sediment and the mixing of fresh and marine water, they tend to form very stressful environments for organisms resulting in low biological diversity (see *Bioturbation and Trace Fossils*). In New Orleans oyster bars, the best oysters (filter feeders) come from areas away from active river mouths whereas deposit-feeding crawfish favor more muddy prodelta and brackish lake environments.

Vertical facies successions

Progradation of a delta lobe will tend to produce a single, relatively thick coarsening-upward facies succession (Figure D6) showing a transition from muddier facies of the prodelta into the sandier facies of the delta front and mouth bar environments (see numerous examples in Bhattacharya and Walker, 1992; and Reading and Collinson, 1996). Thicknesses may range from a few meters to a hundred meters depending on the scale of the delta and the water depth. Continued progradation may result in delta plain facies overlying the delta front sands in a continuous succession. However, delta front sands may be partially eroded by progradation of distributary channels or fluvial channels over its own mouth bar. Commonly, progradational delta lobe successions are truncated by thin transgressive abandonment facies.

In deltas deposited at the edge of the continental shelf, thick coarsening-upward delta front successions are commonly completely preserved within thicker deposits of the hanging wall of growth faults (e.g., Winker and Edwards, 1983; Bhattacharya and Walker, 1992).

The specific nature of the facies in prograding prodelta and delta front successions will depend on the processes influencing sediment transport, deposition, and reworking. In addition, coarsening-upward facies successions can be produced by the progradation of other types of shoreline depositional systems.

Facies successions through distributary channels are erosionally based and typically fine upwards. Filling commonly takes place after channel switching and lobe abandonment. At this time, the distributary channel may develop into an estuary, and the fill may be transgressive. The facies succession will tend to fine upward, with some preserved fluvially derived facies at the base, and a greater proportion of marine facies in the upper part of the channel fill. The extent of marine facies development will depend on the degree of fluvial dominance. Numerous examples of these different types are presented in Bhattacharya and Walker (1992) and Reading and Collinson (1996).

The overall proportion of distributary channel facies is a function of the type of delta. In general, the more wave-dominated the delta, the greater will be the proportion of lobe sediment with more limited amounts of interlobe and distributary channel facies

Interdistributary and interlobe areas tend to be less sandy, and commonly contain a series of relatively thin, stacked coarsening- and fining-upward facies successions. These are usually less than ten meters thick, and much more irregular than the successions found in prograding deltaic lobes (see examples in Reading and Collinson, 1996). The proportion of lobe versus interlobe successions will depend on the nature and type of delta system and will tend to be greater in more river- or tide-influenced systems and less in wave-dominated deltas, although wave-influenced systems, like the Danube Delta in the Black Sea, can contain significant lagoonal and bay mudstones in regions downdrift of the river mouth (Bhattacharya and Giosan, *submitted*).

Lateral facies variability

The lateral facies variability of many depositional systems requires a detailed understanding of bedding geometry. Bedding geometry and lateral facies variability can be addressed by the use of seismic data, Ground Penetrating Radar, continuous outcrop data (e.g., Willis *et al*., 1999), and interpolation of well data. Analysis of lateral facies variability by tracing facies and bedding is termed *Facies Architectural Analysis*, in which discrete sediment bodies are analyzed on the basis of bounding surfaces and bedding geometry (Miall, 1985). Facies variations associated with bounding surfaces can have significant impact on fluid flow in subsurface reservoirs. Considerable research in the petroleum industry has thus been dedicated to investigating the importance of bounding surfaces at a variety of scales. Much of this research emphasis has been on fluvial systems (see examples in Miall and Tyler, 1991; Flint and Bryant, 1993) but more recent studies of deltaic systems are becoming available (e.g., Ainsworth *et al*., 1999; Willis *et al*., 1999; Tye *et al*., 1999).

Dip-variability

In cross-sectional view, deltas show the distinct topset, foreset and bottomset geometry, with strata typically organized into an offlapping pattern, formed as the delta progrades (Figures D4 and D7). Strata associated with progradation of the entire continental shelf-slope and basins also form larger-scale "clinoforms". Delta-front foreset-dips range from a few degrees up to the angle of repose in coarse-grained Gilbert-type deltas. Prodelta bottomsets typically dip at less that 1° whereas non-marine topset facies are typically flat to undulating. The seaward migration of these geomorphic areas of deposition builds the vertical facies successions as shown above (Figure D7).

Berg (1982, see Bhattacharya and Walker, 1992) discussed typical seismic facies in deltaic depositional systems and suggested that sandy wave-dominated systems tend to be characterized by a more shingled pattern. The muddier river-dominated delta types tend to show more of an oblique-sigmoidal pattern. The steeply dipping, sigmoid- shaped portions are probably characteristic of the mud-dominated prodelta facies whereas the more flat-lying upper reflectors represent the sandier delta front and delta plain facies. Frazier (1974, see Bhattacharya and Walker, 1992) showed a similar geometry based on geological studies of the Mississippi delta plain. Offlapping clinoform geometries have also been recognized in the Late Quaternary wave-dominated sediments of the Rhone shelf (Tesson *et al*., 1990; Bhattacharya and Walker, 1992) and in many other studies (e.g., Hart and Long, 1996).

Strike variability

Along strike, facies relationships may be less predictable and depositional surfaces may dip in different directions (Figure D4). This is particularly so in more river- dominated deltas where along-strike reworking is not significant and abrupt facies transitions may occur between distributaries and interdistributary areas. Overlapping delta lobes result in lens-shaped stratigraphic units that exhibit a mounded appearance on seismic lines (Figure D4). 3D bedding geometries have been simulated in computer-based models developed by Tetzlaff and Harbaugh (1989).

Conclusions

A good case can be made for regarding deltas as the single most important clastic sedimentary environment (Leeder, 1999, p. 383) but because of their complexity deltas cannot be classified according to any one simplistic model. Parameters now considered to be essential in understanding facies distribution in deltas include: feeder type, river discharge, sediment caliber, water depth, basin physiography, storms, waves and tides, sea level, physical position in the basin, and degree of soft-sediment deformation. Clearly, combination of these parameters results in a nearly infinite number of possible delta types reflecting a chaotic, non-linear, dynamic sedimentary continuum.

Many depositional systems (e.g., barrier-islands, deltas, estuaries) are not mutually exclusive and components of one can be found in another. Also, because of changes in parameters through time, one type of depositional environment can evolve into another. There are now too many end-member delta models. Future facies models must take a more quantitative, dynamic, predictive, parametric approach, such as used by Tetzlaff and Harbaugh (1989) in simulating deltaic deposition. These approaches will necessarily focus on the mechanics of delta formation and resulting facies distribution, informed by focused field studies, rather than merely classifying the type of delta observed in an outcrop or core.

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Cross-references

Angle of Repose
Barrier Islands
Biogenic Sedimentary Structures
Coastal and Shallow Wave-Dominated Environments
Cyclic Sedimentation
Lacustrine Sediments
Ripple, Ripple Mark, and Ripple Structure
Rivers and Alluvial Fans
Sediment Gravity Flows
Sediment Transport by Tides
Sediment Transport by Waves
Synsedimentary Structures and Growth Faults
Tidal Inlets and Deltas
Tidal Flat