Deltaic systems and their contribution to an understanding of basin-fill successions

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SUMMARY: Deltaic systems are prominent features of many clastic basin-fill successions throughout the geological record and are also important as sites of fossil fuel reserves. The process-based classification of deltaic systems into fluvial-, wave- and tide-dominated types adopted in recent years remains valid, but requires additional information on, for example, the sediment load of the system, its position in the basin and the extent of synsedimentary deformation in order to be a meaningful characterization of a delta. The range of delta types is further extended by research into ancient deltaic systems which can result in the definition of a non-actualistic delta which differs from modern systems. This is an important trend which should develop in the future as well-constrained ancient systems are characterized to their full extent. A further avenue of future research lies in examining the nature of links of deltaic systems to shelf, slope and submarine-fan systems, with particular reference to depositional analysis of seismic stratigraphic information.

Deltaic systems are important elements of many clastic basin-fill successions; they are important in their own right and have significant links with alluvial, shelf, slope and deep-sea fan systems. Interpretations of sediment dispersal and deposition in clastic basins are often greatly enhanced if the position, character and behaviour of basin-margin delta systems are constrained. Deltaic successions are also important economically; organic-rich shales and coals can be important as hydrocarbon source rocks, sandstone bodies serve as reservoirs in numerous hydrocarbon provinces and significant coal reserves are hosted in deltaic successions. Modern and ancient deltaic systems have been extensively researched for many decades, with many of the basic principles of sedimentation such as cyclicity, facies and sequence analysis being developed and tested in these successions. However, despite the longevity and high quality of this research, important problems still remain. The aim of this paper is to review recent progress in deltaic studies and to identify outstanding problems which are currently attracting attention or might do so in the near future. The paper commences by considering various aspects of deltas as discrete depositional systems and continues by discussing the links between deltas and other depositional systems in clastic basin-fill successions.

Present status of deltaic models

The notion that deltas are highly variable depositional systems which cannot be summarized in terms of a single facies model is now well established. The variability of modern deltas has, for some time, been reviewed by means of a ternary diagram with fluvial-, wave- and tide-dominated end-members (Galloway 1975). This process-based scheme is directly applicable to ancient deltaic successions and has been readily adopted in numerous studies. Once the subenvironments of an ancient delta have been recognized on general facies criteria, it is possible to examine the nature of the physical processes which operated in various subenvironments in more detail and hence to reconstruct the character of the ancient delta. The nature of the delta-front sequence and, more particularly, the river-mouth part of the delta front is critical in this regard since it is here that the interaction between the sediment-laden river waters and those of the receiving basin takes place. The identification and thorough examination of this subenvironment at an early stage in an investigation can yield significant insights into the nature of the delta system by providing a reliable first-order interpretation of the type of delta. Fluvial- and wave-dominated deltaic systems have become increasingly well understood in both modern and ancient settings in recent years, but progress in understanding tide-dominated deltas is, by comparison, limited. The addition of the tide-dominated Mahakam Delta in Indonesia to our suite of well-documented modern deltas is a significant development in this respect (Allen *et al.* 1979), but further developments are required to advance our understanding of modern and ancient tide-dominated deltaic systems. What is the medium- to long-term behaviour of distributary channels in tide-dominated deltas? Do tide-dominated deltas develop lobes or lobe complexes, or is this tendency suppressed by the confined gulf-like basin settings in which these deltas often form? How are tide-dominated deltas

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modified during abandonment and how efficient are the reworking processes? These and other questions are central to an understanding of tide-dominated deltaic systems, particularly in terms of predictive facies modelling in hydrocarbon-bearing successions.

Despite the success of the process-based classification of delta systems it is clear that depositional systems as complex as deltas cannot be adequately summarized in terms of a single parameter, no matter how central to the formation of the delta this parameter is in our view. In any comprehensive assessment of a modern or ancient delta a number of other factors should be included in the characterization of the system. For example, the amount and calibre of the sediment load directly influences the nature of the delta and the resultant facies pattern. Variations in sediment load caused by climatic or tectonic events in the hinterland may induce a change in the nature of the delta which, to a degree, is independent of the basin regime. With regard to modern deltas, information on present sediment loads and recent fluctuations in supply is extremely limited. As a result our understanding of this important parameter is rather vague.

The basin type and the position of the delta in the basin are both important in determining factors such as the salinity of the basin waters, the water depth into which the delta is prograding, the nature of the basinal processes which are operative and the prevailing subsidence rate. The extent of synsedimentary deformation processes such as slumping, diapirism and growth faulting is also important. In many deltaic systems features related to synsedimentary deformation appear scarce, but in others they are abundant and the correct identification and interpretation of the various styles of deformation are essential to a full understanding of the facies and sand-body characteristics of the system (see below). Viewing the modern Mississippi Delta in this regard, it is undeniably a fluvial-dominated delta, but it is also an extremely fine-grained highly unstable delta system located in a relatively deep-water setting within 30 km of the present shelf edge. Key features of the modern delta such as the fixing of distributary channel courses due to their incision into previously deposited cohesive muds and the distinctive bar-finger sand-body pattern stem from the fine-grained nature of the system rather than its fluvial-dominated character. The logical conclusion of emphasizing a wide range of factors may be to render each delta unique, which is probably the truth of the matter. The way forward seems to be to use information on all the major factors controlling the delta system within a process-based framework.

River-mouth processes in deltaic systems

Rather surprisingly one of the key problems which often faces sedimentologists concerned with interpreting ancient deltaic successions is the manner in which fluvial currents decelerate and deposit sediment in the vicinity of the river mouth. Despite the pioneering work of Bates (1953) and more recent research it remains difficult to generalize on precisely what happens to fluvial currents as they leave the river mouth and enter the basin. In the case of deltas forming in low energy marine basins the density difference between freshwater and saline water gives rise to a buoyantly supported plume of sediment which is dispersed into the basin as the plume mixes with the basin water (Wright & Coleman 1974; Wright 1977). During low river stage saline basin waters can enter the lower reaches of the channel (the salt wedge) and cause the fluvial currents to detach from the channel floor. As river stage rises during flood periods, the salt wedge is flushed out of the channel and the fluvial currents transport bed-load sediment over the floor of the channel and the shallow crestal regions of the mouth bar. But how far and to what depth do these fluvial currents extend into the basin? Information on this point is surprisingly sparse and this creates problems in the interpretation of fluvial-dominated delta-front sequences in ancient sequences. The middle to upper parts of these sequences are often characterized by numerous thin erosive-based beds of sandstone deposited by basinward-directed waning currents. These currents are considered to have issued directly from the river mouth, but to judge from their position in the delta-front sequence the lowest examples of these beds must have been deposited in moderate water depths beyond the immediate river mouth. Evidence from modern delta systems is insufficient to determine whether this is feasible. In the case of relatively small delta-filled cratonic basins which prevailed, for example, during the Upper Carboniferous in northern Europe it is often debated whether fully marine salinities were maintained permanently in the basin. The lowering of basin salinity, coupled with high concentrations of suspended load, could reduce the density difference between the fluvial and basin waters and may have permitted traction currents to extend down the delta front for greater distances. This notion has been extended in some cases to include the idea that density-driven currents may be initiated at the river mouth, in a similar manner to sediment-laden fluvial waters entering a freshwater lake (*eg* the Rhone river entering Lake Geneva).

Support for the notion of density-driven underflows operating on delta fronts in marine basins has come from the Yellow River Delta in China (Wright *et al.* 1988). The sediment load of this system is predominantly loess silt which is supplied in high suspended-load concentrations during flood periods. The flows are dispersed as underflows 1–4 m deep which decelerate rapidly across the delta front, depositing most of their sediment load between the 5 and 10 m isobaths, 1–5 km from the river mouth. The origin of these flows lies mainly in the exceptionally high concentrations of suspended load during flood period. Traction transport does not appear to be associated with these underflows, although this may be a function of the fine-grained nature of the sediment supply.

Shelf deltas versus shelf-margin deltas

The distinction drawn by early researchers in the Gulf of Mexico between pre-modern shoal-water deltas and the modern deep-water Mississippi Delta has been revived in subsurface studies of Tertiary and Pleistocene deltas in the region (Edwards 1981; Winker 1982; Winker & Edwards 1983). These workers use the terms shelf deltas and shelf-margin deltas to discriminate between deltas which prograded across a shallow water shelf and those which were relatively fixed in position in the vicinity of the shelf–slope break. Shelf deltas are characterized by laterally extensive delta-front sands, large progradation distances and a lack of growth faulting. In contrast, deeper-water shelf-margin deltas are characterized by short progradation distances and are extensively growth faulted. The stratigraphical successions of shelf-margin deltas are thick and localized within major growth fault structures. The successions are characterized by repeated vertical stacking of delta-front sequences, pronounced basinward increases in sediment thickness and rapid basinward facies changes. In view of the large displacements associated with the growth faults in these systems correlation of stratigraphic units is difficult and there are marked deviations in dip from the regional. Seismic facies mapping in Pleistocene shelf-edge deltas reveals steep basinward clinoform stratification and, in some cases, chaotic patterns of seismic reflectors which are considered to reflect synsedimentary sliding and slumping (Winker & Edwards 1983). In plan view the deltas appear lobate rather than elongate as in the case of the modern shelf-margin Mississippi Delta. In the Tertiary Wilcox Group Edwards (1981) considers that this is due to a relatively high sand load which prevailed at the time and was being partially reworked along-shore by basin-wave processes. However, in Pleistocene shelf-margin deltas Winker & Edwards (1983) interpret the strike-oriented nature of the sediment body as a response to the geometry of the growth fault structure which defined the depocentre of the delta rather than the process regime of the delta.

Synsedimentary deformation in modern and ancient deltas

It has been appreciated for some time that certain delta systems are characterized by synsedimentary deformational processes such as slumping, mud diapirism and growth faulting which operate during delta progradation. However, the full range and scale of these processes has only really been appreciated in recent years following a major research programme in the Mississippi Delta, initiated after the failure of offshore petroleum platforms sited on the delta-front regions of the delta (Coleman *et al.* 1974; Coleman 1981). New maps of distributary mouth bars of the Mississippi Delta reveal a high diversity and density of synsedimentary deformational features which are active during deposition. Mud diapirs, rotational slides and slump sheets, collapse depressions, mudflow gullies and lobes, and normal faults proliferate on the surface of the mouth bars. It is estimated that 50% of sediment deposited in distributary mouth bars of the Mississippi Delta is involved in down-slope mass movements which translate upper mouth-bar facies into the deeper parts of the basin, often beyond the limits of the delta itself. The recurrence interval of slumps is high and mouth-bar progradation is therefore erratic with the slopes acting as transfer or bypass routes for sediment for much of the time (Lindsay *et al.* 1984). Slumping is initiated aseismically by a combination of processes including high pore-water and methane pressures in the sediment, wave-induced cyclic loading or pounding of the sediments during storms and hurricanes and oversteepening of the bar front due to differential sedimentation rates on the bar front during flood periods and jacking-up of the bar-front slope by mud diapir activity beneath the mouth bar. Recent research in the Gulf of Mexico has also demonstrated that major canyons in the outer shelf/continental slope in front of the Mississippi Delta were formed by very-large-scale slope failures which removed a substantial amount of sediment (12 000 km^3) from the upper part of the slope (Shepard 1981;

Coleman *et al.* 1983). The slump material is estimated to account for 15% of the deposits of the Mississippi fan. The slump scar formed a subbasin on the slope which was infilled mainly by the distal parts of shelf-edge delta lobes.

In view of the range, density and frequency of operation of these synsedimentary deformational processes it is necessary critically to re-evaluate our view of the facies pattern which is likely to be finally preserved. At present our view is still dominated by our understanding of the depositional processes active on the delta front, with only a limited role for deformational processes having been recognized. The work of Fisk and the early work of Coleman and co-workers in describing the facies patterns of the Mississippi Delta includes very few features attributable to synsedimentary deformation and is now in conflict with the new information from the delta. The deformational features referred to above are by no means confined to the Mississippi Delta; research programmes as intensive as that recently undertaken in the Mississippi Delta may reveal the same range and density of deformational features in other deltas.

In recent years a number of studies of ancient deltaic successions have recognized features which reflect synsedimentary deformation processes analogous to those of modern delta systems (Edwards 1976; Chisholm 1977; Rider 1978; Elliott & Ladipo 1981; Nemec *et al.* 1988; Pulham, this volume). Slump sheets, collapse structures and growth faults are the most widely described features. The examples of growth faults clearly demonstrate the role of these structures in defining localized sandstone-dominated depositional centres and suggest that delta systems characterized by extensive growth faulting should be regarded as a distinct category as the facies patterns may be determined principally by the history of growth faulting (as in Tertiary successions of the Niger Delta; Weber 1971; Evamy *et al.* 1978). Growth faults recognized in exposed ancient deltaic successions are directly analogous to structures identified in subsurface studies in all aspects except scale. All examples of growth faults described to date from surface exposures are substantially smaller than subsurface equivalents (tens of metres scale as opposed to kilometres scale). Large-scale growth faults have still to be recognized, or inferred, in exposed terrains and, conversely, smaller-scale growth faults beyond the resolution of seismic data await discovery in subsurface investigations. Further research in well-exposed deltaic successions and greater refinement in subsurface interpretation techniques may address the range of scales of growth faults in the near future.

Non-actualistic deltaic models

One consequence of stressing the wide range of controls which influence deltas is, as noted above, the tendency for each delta to be regarded as unique. It follows from this that ancient delta systems might differ substantially from the known range of modern deltas, giving rise to the notion of non-actualistic delta models. In the early stages of an investigation or where the available data are strictly limited it is perhaps inevitable that comparisons with modern deltas will be made and that the system may be interpreted with reference to a modern system (*eg* as Rhone-like or Niger-like). However, in the latter stages of study of a well-exposed or extensively cored delta system it should be possible to produce a model which honours all the available data and thereby produces a distinctive delta type which may differ in several important respects from modern deltas. To date, there are very few examples of this kind of interpretation. The Carboniferous Kinderscout Delta system provides an example of this point (Collinson 1969; McCabe 1978). Large high-discharge river systems characterized by coarse-grained bedforms several tens of metres in height supplied copious amounts of sediment to the Central Pennine Basin. The basin was a small confined intracratonic basin in which the basin salinity was appreciably diluted by the large amounts of freshwater discharge entering the basin. As a result, most of the sand-grade sediment bypassed the shoreline and was transported to the deeper parts of the basin via turbidity currents. Delta-front slumping may also have assisted in the transfer of sand-grade sediment to the deeper part of the basin (McCabe 1978). This delta system is characterized by major sand-rich fluvial distributary channels, a fine-dominated delta front with incised delta-front channels and a sand-rich submarine fan at the foot of the delta front. It is quite unlike any modern delta system.

In a less striking although still significant way, the oil-bearing Brent Delta system of the northern North Sea may provide another example of a non-actualistic delta system which can be interpreted from the large data base which is now available. There is a widespread consensus that the Brent Delta system was wave dominated in view of the predominance of storm-deposited facies in the coarsening-upward delta-front sequence and the laterally extensive sheet-like nature of the sandstone unit at the top of this sequence (the Rannoch Formation; Bowen 1975; Brown *et al.* 1987). The most detailed published account of the system makes a comparison with the Nile Delta system, in terms of both delta type and scale of the system (Johnson & Stewart 1985). In keeping with other modern wave-dominated delta systems the Nile Delta has few active distributary channels (two, in fact), with the result that the channel sandstones form relatively narrow bodies which are locally incised into the more widespread sheet sandstone of the upper delta front. In contrast, channel sandstones are extremely common in the lower part of the Etive Formation which directly overlies the delta-front sequence of the Rannoch Formation, seeming to form an extensive multistorey multilateral channel-belt sandstone body. This may suggest that the channels were more numerous and/or more laterally unstable than in modern wave-dominated deltas. An important control on this distinctive feature of the Brent Delta system was that the delta was supplied with a high sediment load which included a very significant proportion of sand-grade material. The high sediment load enabled the delta to prograde at a rapid rate despite a concurrent rise in sea level, and the abundance of sand may have caused the delta plain to resemble a braid plain of highly mobile shallow sand-dominated channels which coalesced vertically and laterally to produce the extensive channel-belt sandstone body found in the underlying Etive Formation. Once again, this view of the delta system renders it different from modern delta systems.

Delta–shelf interactions

The supply of sand-grade sediment to continental shelves often results from interactions between deltaic systems and the adjacent shelf. An understanding of sandstone-dominated shelf successions in the geological record is therefore aided by considering the nature, position and history of coeval deltaic systems along the inner margin of the shelf in view of their importance as a source of sediment. This may occur in response to low stands in sea level when deltas and their fluvial trunk streams deposit sand-grade sediment which is reworked during the ensuing transgression and by the physical regime of the shelf established by the transgression (*eg* the E coast, USA). However, this mechanism will produce only relatively thin shelf sandstone units (a few tens of metres thick?). Thicker sand-dominated shelf successions require either a more direct link between the delta and the adjacent shelf which operates during delta progradation or a repeated history of shoreline progradation and transgression.

The transfer of sand-grade sediment to the shelf requires a set of processes which are capable of transporting sand beyond the nearshore wave-induced 'littoral fence' which tends to retain sand in the nearshore area. Storm-driven processes and tidal currents are capable of transporting substantial volumes of sand from the delta front and transporting it to the adjacent shelf. These processes can be effective during delta progradation and may be enhanced by abandonment of the delta. Aerial photograph or map views of modern wave-dominated deltas are characterized by parallel beach ridges which are broadly aligned with the trend of the delta front (Psuty 1967; Curray *et al.* 1969). The ridges record the incremental growth of the delta during progradation; in effect, they are the growth rings of the delta. Often the ridges occur in groups or clusters separated by erosional discontinuities which truncate the earlier formed ridges and establish the trend for a new cluster of parallel ridges. The discontinuities reflect temporary abandonment phases in the history of the delta which are generally caused either by the avulsion of a distributary channel or by the waning of discharge in a channel. With a reduction in clastic input to part of the delta wave processes rework that part of the delta front and create a discontinuity surface whilst at the same time progradation continues elsewhere (as in the present-day Rhone Delta). Wave reworking is most significant during storm periods and therefore a large proportion of the sand eroded from the upper delta front during the temporary abandonment phases may be redeposited on the adjacent shelf by geostrophic currents.

Tidal currents can provide continuity of process between the delta front and the shelf and can override the retaining ability of the wave-induced littoral fence. In view of the persistent nature of tidal sand transport as opposed to the intermittent nature of storm-induced sand transport it is likely that tide-influenced deltas provide the most efficient means of transferring sand-grade sediment to the shelf. This mechanism has been used to explain thick sand-rich shelf successions in the geological record which lack evidence for substantial fluctuations in sea level. For example, the late Precambrian of northern Norway includes a 1500 m succession of mature cross-bedded sandstones which are interpreted as tide-dominated shallow-marine deposits (Levell 1980). The sand-grade sediment is considered to have been supplied to the shelf during the transgressive abandonment phase reworking of a series of tide-dominated deltas located at the basin margin.

Thus, both storm-driven and tidal current processes can be effective in transporting sand from deltas to the adjacent shelf during delta progradation and, more particularly, during delta abandonment. Cases where storm-driven processes enhance tidal current transport may provide the greatest potential in this respect. Consideration of the nature, position and history of deltaic systems along the inner margin of a shelf is crucial to understanding the genesis of sandstone-dominated shelf successions.

Delta–slope–submarine-fan links

Numerous modern and ancient delta systems are associated with submarine-fan systems in the deeper parts of basins. A key point in these systems is the extent to which the delta, slope and submarine fan are a linked set of coeval systems or conversely whether they are somewhat independent, with sediment transfer between the systems occurring primarily when there is a reduction in sea level (see below). The geological record provides several examples of deltas and submarine fans which are considered to be linked coeval systems and this has led to the view that delta-related submarine fans should be considered separately from other submarine fans (Galloway & Brown 1973; Heller & Dickinson 1985; Collinson 1986). Distinctive features of delta-related submarine fans include (i) the lack of a shelf separating the delta and submarine-fan systems, and commonly a small-scale slope system by comparison with continental slopes on passive margins, (ii) the presence of numerous channels incised into the basin slope rather than a single major-canyon feeder route and (iii) a comparative lack of organization in the fan deposits arising from the numerous slope feeder channels and the fact that the avulsion of distributary channels in the delta system can cause appreciable fluctuations in the locus of sediment supply to the fan. As with selected shelf systems, a comprehensive understanding of certain submarine-fan systems will require information on the nature and behaviour of the adjacent delta system. Discussions on the spectrum of delta-related submarine fans, the precise nature of links between the delta and the fan, and the facies patterns of the fan deposits are at an early stage and are likely to be a topical research area in the future.

Deltaic systems and seismic stratigraphy

Deltaic systems are often a prominent component of passive margin settings, forming preferentially during the post-rift phase during which regional thermally induced subsidence prevails. The depositional histories of passive margins have been exhaustively studied in recent years using the seismic stratigraphic approach and it is therefore appropriate in this review to consider the significance of deltaic systems in this approach.

In terms of seismic sequence and depositional systems tracts analysis, deltas are regarded as prominent features of high-stand periods. At times of high sea level wide shelves prevail and deltas prograde and aggrade on the shelf, producing a regressive facies sequence across the shelf. Shelf deltas or shoal-water deltas should therefore form extensively during these periods. In contrast, during periods of lowered sea level the shelf may be partially or entirely exposed, giving rise to type 1 and type 2 unconformities respectively. During these periods former high-stand deltas are eroded and active deltaic systems are confined to the outer part of the shelf where they form either after type 2 unconformities which exposed the inner part of the shelf or during the early stages of onlap which follow type 1 unconformities. In the latter case, deltas form at the shelf–slope break when sea level is beginning to rise and the heads of submarine canyons cut into the upper slope during the low stand in sea level are being filled rather than acting as transfer routes to the deeper parts of the basin.

Following this reasoning there is a tendency to equate widely developed shelf deltas with periods of high stand in sea level and more localized shelf-margin deltas with periods of low stand in sea level. However, consideration of the Gulf of Mexico region in this regard suggests that a degree of caution is required. In this region the development of shelf-margin deltas during the Tertiary and through to the present day has been controlled by sediment supply rather than eustatic sea-level fluctuations (Edwards 1981; Winker & Edwards 1983). The distribution of shelf-margin deltas is related to variations in sediment supply which are not basin-wide and are controlled by events in the hinterland source area. In the Gulf of Mexico, the main cause seems to be tectonic events in the Rocky Mountains and consequent changes in the continental drainage basin. Large and highly organized drainage basins are an essential feature of any major long-lived deltaic system and tectonic events which influence the drainage basin will directly influence the delta system, irrespective of how remote the tectonics are from the depositional site. Periods of shelf-margin progradation involving delta systems in the Gulf of Mexico deltaic province correspond with changes in the sand-to-shale ratio and sand provenance which can be related to discrete phases in the tectonic evolution of the Rocky Mountains (Winker 1982).

In terms of seismic facies analysis, Mitchum *et al.* (1977) interpret certain basinward-dipping clinoforms as successive phases in the progradation of a delta system, with the production of clinoforms presumably relating to lobe or delta switching events. Berg (1982) argues that fluvial- and wave-dominated deltas can be distinguished using details of the seismic reflector patterns. Fluvial-dominated deltas are often characterized by oblique tangential reflectors which are terminated up-dip. This pattern is considered to represent the deposits of deltas which accumulated under low subsidence rates and are dominated by delta-front facies. Alternatively, fluvial-dominated deltas can exhibit complex sigmoid-oblique reflectors which include an interval of flat reflectors at the top of the package. These are considered to have accumulated under conditions of higher subsidence and therefore include an interval of aggradational delta-plain facies. Wave-dominated deltas are considered to be characterized by relatively simple, shingled and oblique (parallel) reflectors, although the problem of discriminating between deltaic and non-deltaic prograding shorelines is not addressed by Berg (1982).

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