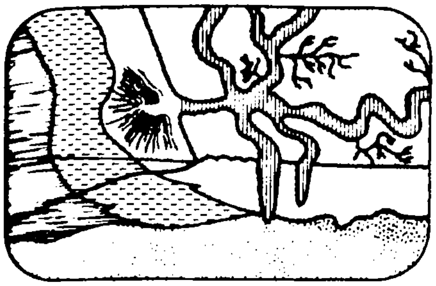

Deltas

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INTRODUCTION

Deltaic depositional models differ from most others in that their construction has not depended on a distillation of observations on ancient rocks but has arisen largely from a study of depositional processes on modern deltas. There are at least three distinct delta models or "norms" to consider in interpreting ancient rocks, but these are end members of a broad specturm of delta types, and many modern and ancient deltas combine features of all three.

DEFINITION

The concept of the delta is one of the oldest in geology, dating back to about 400 B.C. when Herodotus observed that the alluvial plain at the mouth of the Nile was similar in shape to the Greek letter Δ. The term has been used for similar geographic features ever since.

We now define a delta, geologically, as "a deposit, partly subaerial, built by a river into or against a permanent body of water" (Barrell, 1912). The result is an irregular progradation of the shoreline directly contolled by the river. The sediments are formed under subaerial and shallow marine or lacustrine environments and typically show a gradation into finer-grained offshore facies. A crucial part of the definition is that the influence of a river or rivers as the main sediment source should be recognized. In the ancient record this is best accomplished by mapping lithofacies distributions, which should show the presence of a significant thickening of the clastic succession close to presumed locations of riverine sediment input into the sedimentary basin. However, in many deltas the fluvial influence is masked strongly by waves, ocean currents, tidal currents or winds. Ancient deltaic deposits of this type may be hard to recognize, and it seems likely that many have been interpreted, in the past, in terms of these modifying processes as wave-formed beach complexes or tidal flat deposits.

A SHORT HISTORY OF DELTA STUDIES

Modern work in the English-speaking world commenced with the classic studies of Gilbert on the deltas in Lake Bonneville. Gilbert was the first to attempt a hydrodynamic explanation of delta formation, and his ideas dominated thinking on the subject for many years. A classic paper by Barrell (1912) on the ancient Catskill delta also had a far-ranging influence.

Since the 1920s interest in deltas has been stimulated by the fact that the sediments of many ancient deltas contain extremely large deposits of coal, oil and gas. Nowhere is this more true than in the hydrocarbon-rich Gulf Coast of Texas and Louisiana, and research into deltaic sedimentation during the last forty years has been overwhelmingly dominated by studies of Holocene Gulf Coast deltas and their Quaternary and Tertiary antecedents. Most attention became focused on the Mississippi, which rapidly replaced the Lake Bonneville deltas of Gilbert as the standard model delta in geology textbooks.

Sedimentological research into the Mississippi commenced with the monumental work of Fisk, who established the depositional framework of the modern delta with the aid of many thousands of shallow boreholes. Subsequently the American Petroleum Institute funded a major research effort (Project 51), the objective of which was the study of modern sediments along the northwest margin of the Gulf of Mexico. The publication which summarizes this work (Shepard *et al.*, 1960) contains landmark papers on depositional processes in the Mississippi by Shepard and by Scruton. Further publications on the depositional environments and cyclic sedimentation in the Mississippi were provided by Kolb and Van Lopik (1966), by Frazier (1967) and by Coleman and Gagliano (1964, 1965).

The other deltas that were studied extensively at this time were those of the Niger (Allen, 1970; Oomkens, 1974), the Orinoco (Van Andel, 1967) and the Rhône (Oomkens, 1970).

Useful compilations of papers on ancient and modern deltas include those of Morgan (1970), Broussard (1975) and Le Blanc (1976a, 1976b). The basis of the modern three-fold classification of deltas (Fig. 1) was established

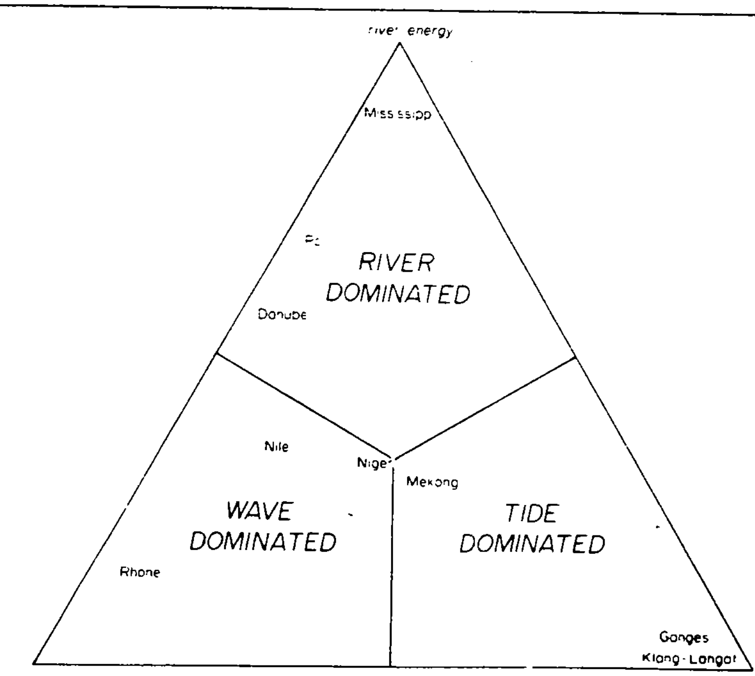

Figure 1
A classification of deltas based on variations in transportation patterns on the delta (after Galloway, 1975).

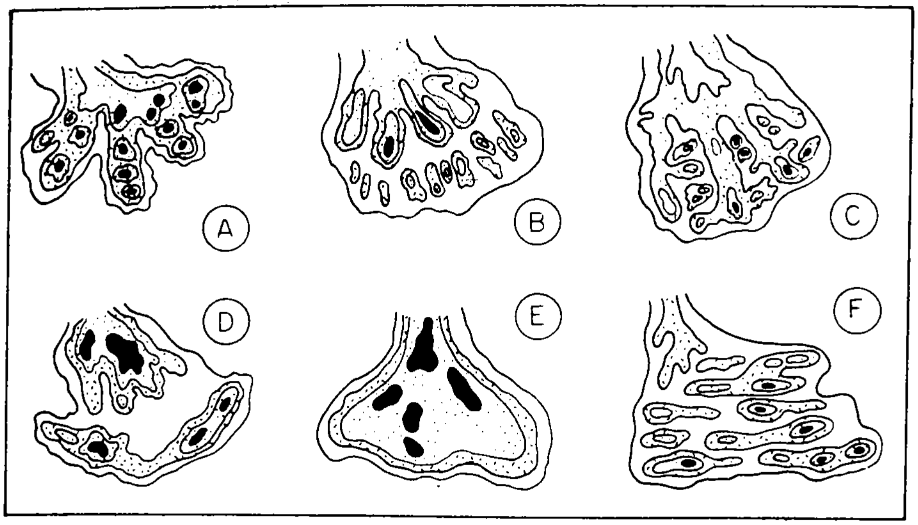

Figure 2
Delta models of Coleman and Wright (1975). A) River-dominated with low wave and tide energy, low littoral drift; B) River-dominated with low wave energy, high tide range, low littoral drift; C) Intermediate wave energy, high tide, low littoral drift; D) Intermediate wave energy, low tide range; E) High wave energy, low littoral drift; F) high wave energy, strong littoral drift.

by Fisher *et al.*, (1969; see also Galloway, 1975), who proposed a subdivision into river-, wave- and tide-dominated types (these are the three end members or "norms" referred to above). Wright *et al.*, (1974) elaborated this classicification, showing that various combinations of the three main processes could form six principal delta types (Fig. 2). Useful summaries of this work are provided by Coleman (1981) and Coleman and Wright (1975), and it is discussed later in this paper. An excellent general summary of deltaic sedimentation is given by Elliot (1978).

The only major development in delta studies during the last ten years has been the increasing recognition of the importance of syndepositional deformation on delta front surfaces, particularly in river-dominated deltas. Slumps, slides and growth faults are pervasive in many modern and ancient deltas, and have a major effect on subsurface stratigraphy and lithofacies distributions (Coleman *et al.*, 1983; Winker and Edwards, 1983).

Most of the major developments in the understanding of deltas are attributed to Gulf Coast geologists, particularly the staff of the Coastal Studies Institute at Louisiana State University and the Bureau of Economic Geology at the University of Texas. The pre-eminence of this group is remarkable, and is mainly a reflection of the profound importance of modern and ancient Gulf Coast deltas to the economy of that region (petroleum, coal and uranium production, environmental geology). However, it has tended to bias geologists everywhere towards interpretations based on Gulf Coast models, particularly that of the Mississippi delta, although these are not everywhere appropriate and, to some extent, may even be unique.

Delta facies models seem now to have reached a mature phase of development, in contrast to those for other environments, particularly models of continental margin sedimentation and shelf sedimentation (Walker, "Shelf and Shallow Marine Sands", this volume), which are still undergoing rapid evolution. However, considerable work is needed to test the models by careful documentation of the ancient record. This is especially necessary for wave- and tide-influenced deltas, of which few well-described ancient examples exist.

DELTA FORMATION AND CLASSIFICATION

The distribution, orientation and internal geometry of deltaic deposits is controlled by a variety of factors, including climate, water discharge, sediment load, river-mouth processes, waves, tides, currents, winds, shelf width and slope, and the tectonics and geometry of the receiving basin (Wright *et al.*, 1974). In a brief paper such as this it is impossible to describe fully the inter-relationships between all these variables, but several generalizations are possible, such as those on which the principal classification of deltas are based (Figs. 1 and 2; discussed below).

Variations in Sediment Input

Climate, water discharge (rate and variability) and sediment load (quantity and grain-size) are to some extent inter-related. In humid, tropical regions precipitation normally is high relative to evapotranspiration; runoff tends to be high and steady. The predominance of chemical over mechanical weathering leads to high dissolved-load sediment yields. These factors give rise to relatively stable, meandering channel patterns.

In arctic or arid conditions precipitation is erratic, vegetation is sparse, and braided channel patterns with large bedloads tend to occur (Coleman, 1981, and Coleman and Wright, 1975 provide a more complete discussion of this topic).

These distinctions are most easily recognized in the fluvial delta plain deposits by the geometry and grain size of the distributary channel fill units (see "Coarse Alluvial Deposits", and "Sandy Fluvial Systems", this volume). However, where the delta is not significantly modified by processes there will be differences in the structure of the delta as a whole, as discussed below.

Variations in River-Mouth Flow Behaviour

When a sediment-laden river enters a body of standing water one of three types of flow dispersal may occur, depending on the density differences between the river water and that of the lake or sea into which it flows. Variations in temperature, salinity and sediment load can cause such differences in density.

A) Inflow More Dense. This is a common occurrence where sediment-laden streams enter fresh-water lakes (e.g., glacier-fed streams in Alpine regions). A narrow, arcuate zone of active deltaic progradation containing the coarse bedload may occur along the shore.
The delta which forms contains the distinct, steeply-dipping forests of the classical Gilbertian delta. The finer sediment fraction may be dispersed offshore as density interflows or underflows, forming repeated graded units.

B) Inflow Equally Dense. This is also a common occurrence in fresh-water deltas, and may also develop at the mouths of rivers entering brackish back-barrier lagoons. Sediment is dispersed radially and competency is lost rapidly. The bulk of the sediment is deposited on a Gilbertian delta.

C) Inflow Less Dense. Most marine deltas are formed under these conditions because freshwater is less dense than seawater, unless it is unusually cold or sediment laden. Lacustrine deltas formed at the mouths of suspended-load rivers are also of this type. The river effluent tends to form a discrete plume floating on the surface of the sea. The suspended sediment load is widely dispersed, resulting in a large active delta-front area, typically dipping at 1° or less, and contrasting with the 10 to 20° dip of typical Gilbertian deltas.

Marine waters beneath the effluent jet form a "salt-wedge", which may extend for tens of kilometres upstream, particularly during high tide. Marine faunas can thus be found well inland – a possible source of confusion in the study of ancient deltaic deposits.

These patterns can be radically modified by tide or current activity, as described below.

Variations in Transport Pattern on the Delta

The type of energy conditions that exist in the sea at the river mouth are of fundamental importance in controlling depositional environments and the geometry of the resulting sediments. In fact the most useful classification of delta types is one based on the relative strengths of fluvial and marine processes (Fig. 1), as shown by Fisher *et al.* (1969), Coleman (1981), Galloway (1975) and Coleman and Wright (1975). Interrelationships between these processes form the main basis for recognizing three deltaic "norms".

A) River-Dominated Deltas. If waves, tidal currents and longshore currents are weak, rapid seaward progradation takes place, and a variety of characteristic, fluvially dominated depositional environments develops. At the mouth of each distributary subaqueous levees may form where the competence of the effluent jet is reduced by friction with the static sea water at the margins of the flow (Fig. 3). The main sediment load is deposited in a distributary mouth bar, which becomes finer grained toward the sea. The proximal mouth bar region is characterized by scour channels and by temporary bars and islands with abundant crossbedding, resulting from variations in flow conditions (changes in river discharge, tidal effects).

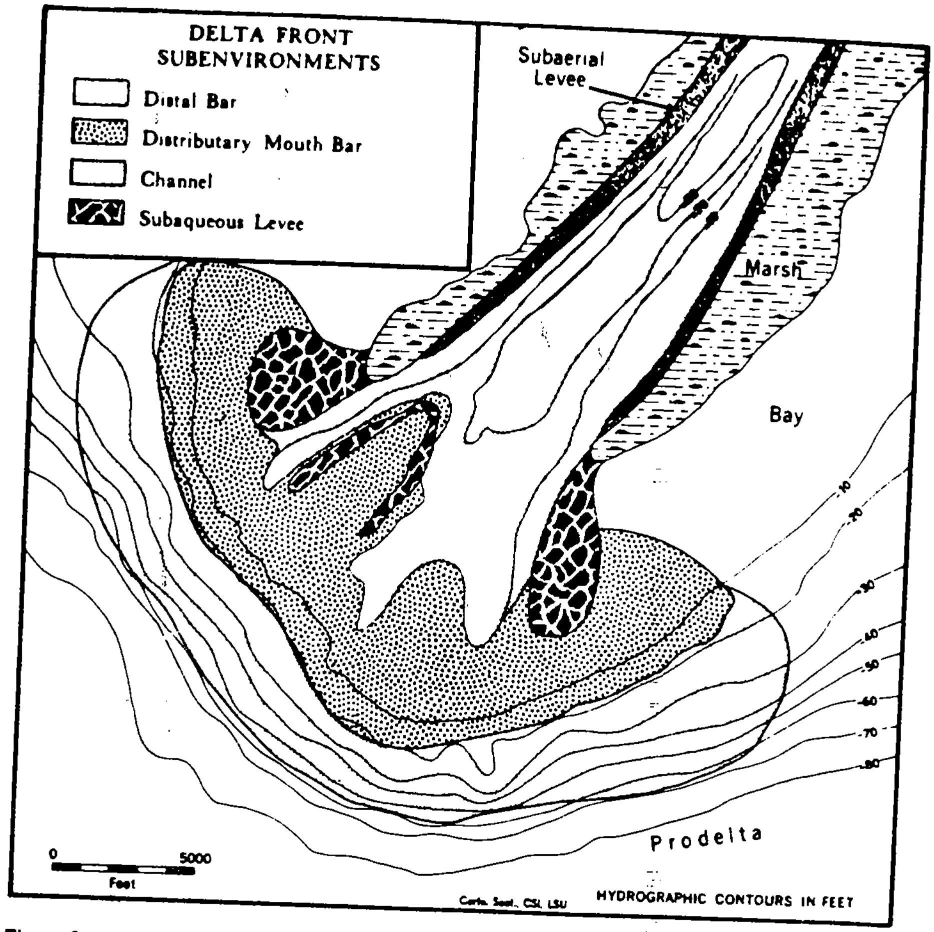

Figure 3
Subenvironments at a distributary mouth in a river-dominated, birdsfoot-type delta, South Pass, Mississippi delta. Progradation seaward leads to the development of elongate sand bodies called "bar-finger" or "shoestring" sands (Coleman and Gagliano, 1965).

In the case of mixed- or suspended-load distributary channels, which are relatively stable in position, and in the absence of significant wave- or tide-induced scour, sedimentation gradually extends the mouths seaward. The resulting lithofacies assemblage, of which the mouth bar sand is the most important, tends to be oriented at a high angle to the coastline (basin margin), as in Figure 2A, a fact that can be of considerable importance in the understanding of an ancient deltaic deposit. "Bar-finger" or "shoestring" sands are a typical component of such a deltaic assemblage. The modern Mississippi delta is the best modern example of this pattern, showing the distinctive "birdsfoot" shape in plan view (Figs. 3 and 4).

Between the distributaries are interdistributary bays, which commonly are areas of low energy, muddy sedimentation and abundant organic activity. Shell beds and bioturbation are common. These bays eventually fill with sediment and become marshes. One of the most important ways in which this occurs is by the development of crevasse splays, which occurs in the following manner.

As progradation proceeds the river slope is flattened and flow becomes less competent. At this stage a breach in the subaerial levee may occur upstream during a period of high discharge. Such a breach is termed a crevasse. The shorter route it offers to the sea via an interdistributary bay generally is the cause of a major flow diversion, and a subdelta (crevasse-splay) deposit may develop rapidly. Eventually the crevasse may become a major distributary and the process is repeated.

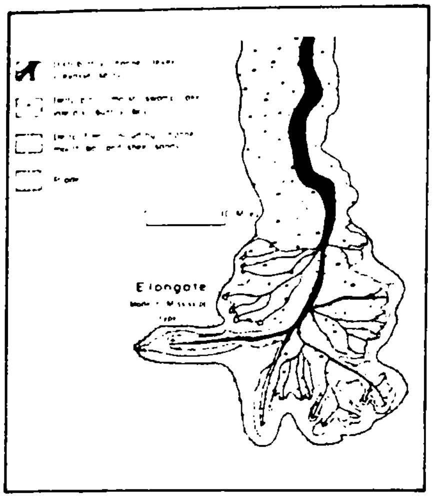

Figure 4
A birdsfoot-type river-dominated delta; the modern Mississippi delta (Fisher et al., *1969).*

Where delta distributaries are of the unstable, low sinuosity (braided) type, with shifting courses and numerous bars and islands, a different type of delta may develop. The outline tends to be lobate, and mouth bars merge laterally into a sheet sand. Crevasse splays may be absent, but sediment is distributed throughout the delta by distributary switching (avulsion), a process analogous to that of crevassing. The radiating pattern of distributaries is similar to that of alluvial fans, and the term fan-delta is commonly used to describe them (Fig. 5). Pebbly sands and gravels are common to dominant components of the delta plain and delta front environment. Good descriptions of modern fan delta sedimentation have been given by McGowen (1970), Galloway (1976), and Wescott and Ethridge (1980).

At present, fan deltas tend to occur in arctic or arid environments, where the abundance of coarse bedload and the variable river discharge favour unstable braided distributary networks. Fan deltas were probably the dominant type of river-dominated delta in pre-Devonian time because, until the advent of land vegetation, which tends to store rainfall and regulate runoff, braided channel networks were probably the main fluvial style.

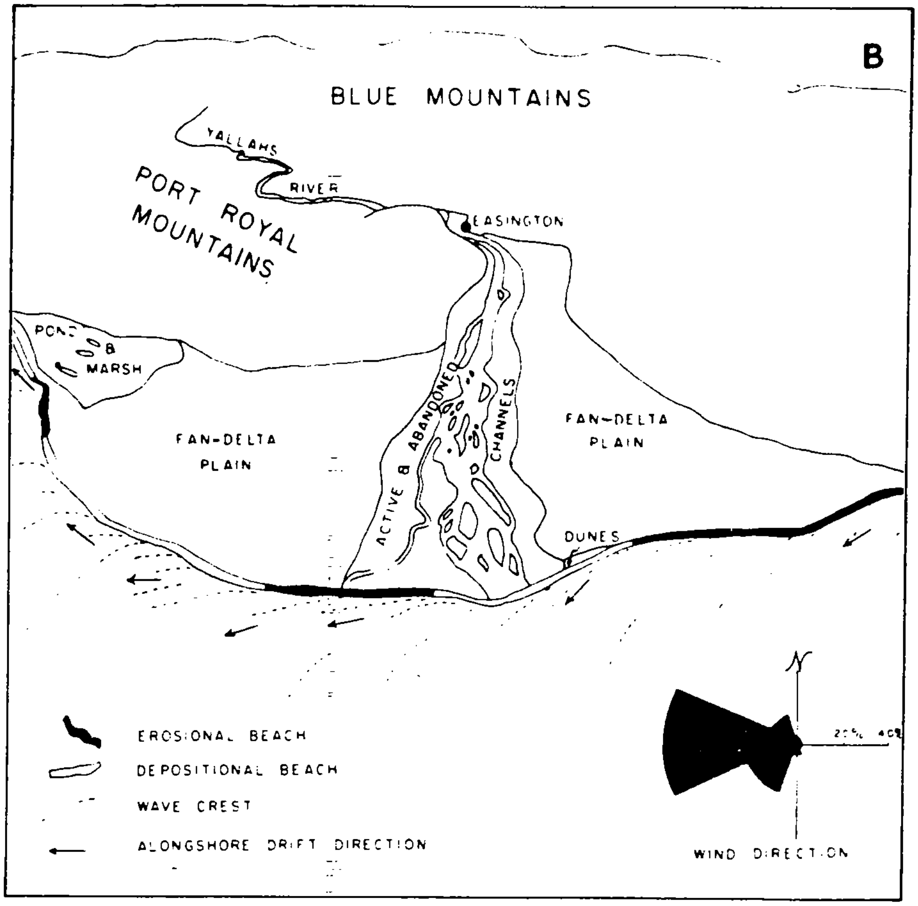

Figure 5
Interpretive sketch map of the modern Yallahs fan delta, Jamaica, drawn from an oblique air photo (Wescott and Ethridge, 1980).

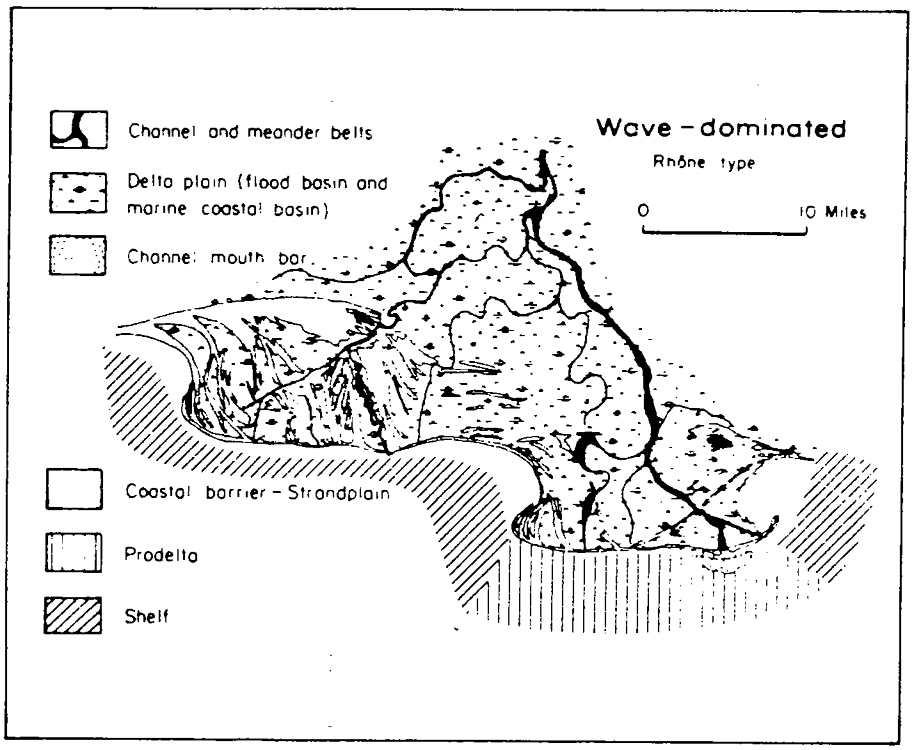

Figure 6
A wave-dominated delta; the modern Rhône delta (Fisher et al., *1969).*

B) Wave-Dominated Deltas. On most coastlines waves rework shoreline sediments and account for local distinctive facies. However, the contrasts between the minor wave activity in areas such as the Gulf Coast, and the wave-dominated coastlines of much of the Atlantic and Pacific oceans, are dramatic. Coleman and Wright (1975) suggested that it takes a whole year of wave activity on the Mississippi delta to equal ten hours of wave energy expenditure on the São Francisco delta, Brazil.

In a wave-influenced delta (e.g., Figs. 2C, 2D, 6), mouth bar deposits are continually reworked into a series of curved beach ridges. If the winds are predominantly onshore, they may redistribute much of the beach sand as an eolian dune field capping the delta plain.

The geometry of the delta front beach complex depends largely on the nature of shoreline circulation patterns. An oblique angle of wave attack may develop a powerful longshore drift current, in which case the entire delta may become asymmetrical and skewed downcurrent (Fig. 2F). Beaches grow laterally and fill interdistributary bays by the develoment of curved spits, as in the modern Rhône delta (Fig. 6). Whether or not this longshore drift occurs, individual sand bodies tend to be oriented more or less parallel to the coastline in marked distinction to that of other delta types. The facies characteristics and mature petrography of these shoreline sand bodies are distinctive, as discussed elsewhere in this volume.

C) Tide-Dominated Deltas. Where the tidal range is high the reversing flow that occurs in the distributary channels during flood and ebb may become the principal source of sediment dispersal energy. Within and seaward of the distributary mouths the sediment may be reworked into a series of parallel, linear or digitate ridges parallel to the direction of tidal currents and separated from each other by linear scour channels (Fig. 7). The ridge-and-channel morphology, with a trend perpendicular to shoreline, is one of the most characteristic features of the tide-dominated delta, and may be readily detected by careful lithofacies mapping (Figs. 2B and 2C). The subaerial part of the delta consists largely of tidal flats comprising mainly fine-grained deposits. Distributaries may contain well sorted sands deposited under conditions of reversing flow, and large quantities of clay and silt will tend to be flushed into the delta marsh by overbank flooding during high tides.

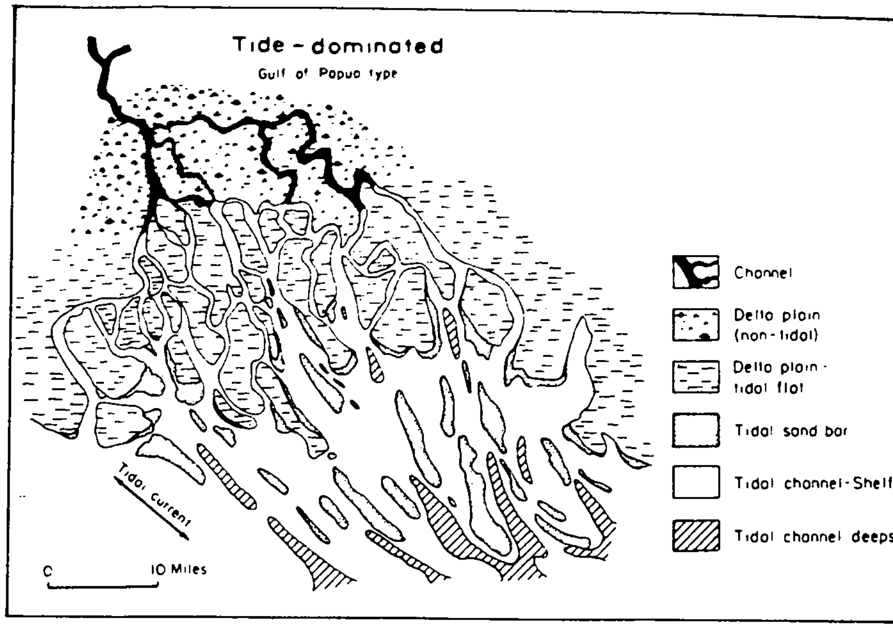

Figure 7
A tide-dominated delta: the modern Ganges-Brahmaputra delta (Fisher et al., *1969).*

As in the case of wave-dominated deltas, tidal currents may completely rework the deposits and redistribute them away from the river mouth. In such a case it may be difficult to recognize the deposits as deltaic. Many ancient beach or shallow marine deposits, with evidence of wave or tidal reworking, may have been misidentified as a result. The large volume of the deposit, or the presence of a landward facies change into a thick fluvial sequence, may be the only clues to a deltaic interpretation.

Syndepositional Deformation

Rapid sedimentation on deltas leads to gravitational instabilities and the generation of a variety of small to medium scale structures as a result of loading or slope failure (Fig. 8; see Coleman *et al.*, 1983). Such structures are likely to be more common on river-dominated deltas, where the rate of seaward growth tends to be more rapid. The most important of these structures are growth faults, formed by sediment loading and episodic failure on the seaward side of the fault plane. Sedimentary units

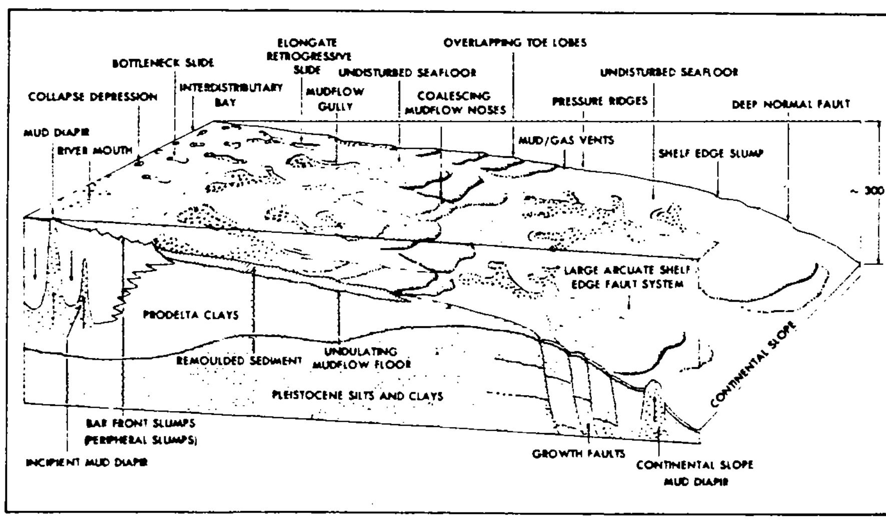

Figure 8
Schematic block diagram showing the various types of delta front to prodelta sediment instabilities off the modern Mississippi delta (Coleman et al., *1983).*

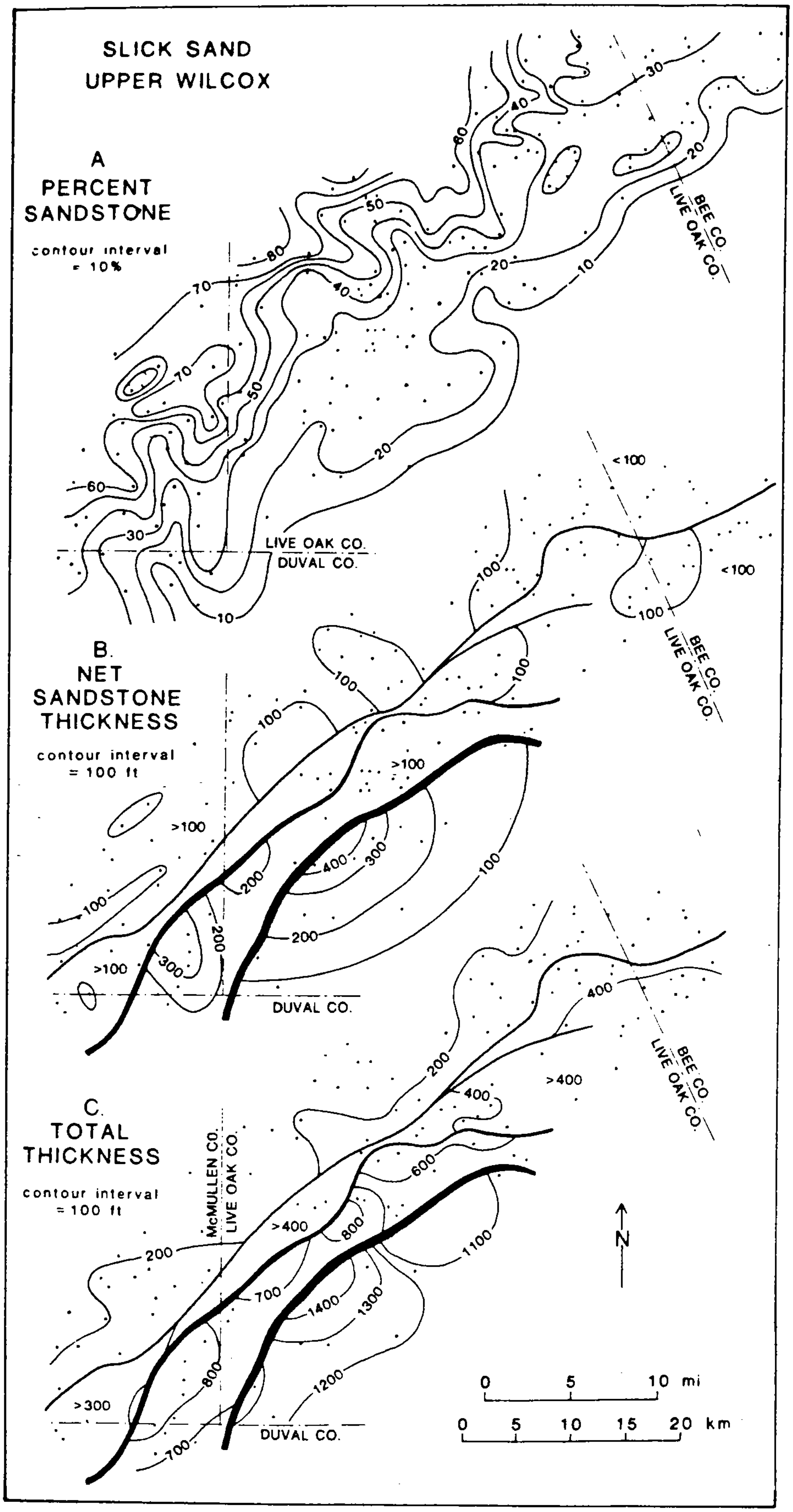

Figure 9
Lithofacies maps of an interval in the Wilcox Sand (Eocene), Gulf Coast. See text for discussion (Winker and Edwards, 1983).

thicken across the fault as a result of syndepositional movement. This occurs commonly particularly during deposition of denser sediment such as sand. and can result in the development of significantly thickened strike-parallel wedges of sandstone in the section (Fig. 9). These wedges could be misinterpreted as wave-modified sand bodies similar to those in Figures 2C and 2D, unless independent evidence or structure (e.g., seismic data) was available (Winker and Edwards, 1983).

The delta-front surface may be unstable because of sedimentary oversteepening and under-compaction. Slumps and slides commonly are the result, generating slide scars, large slide blocks, slump structures and convolute bedding. Diapiric intrusion of prodeltaic mud (or evaporite) into overlying deltaic facies is caused by rapid sediment loading. Growth of the diapirs tends to be long-lived, and they frequently rise to the surface to form sea-floor mounds, or even islands.

DELTAIC CYCLES

Scruton (1960) was one of the first to point out that the growth of a delta is cyclic. The process has now been described many times (e.g., Fisher *et al.*, 1969; Coleman and Wright, 1975; Elliot, 1978). There are two phases.

A) Progradational Phase. Active seaward progradation causes prodelta muds to be overlain by delta front silts and sands, and these in turn by distributary mouth deposits, mainly sands (and gravels, if present), and finally by topset delta marsh sediments, including fluvial facies and peats, mud, or eolian dunes, depending on local climate and sediment supply (Fig. 10).

B) Abandonment Phase. A delta lobe is eventually abandoned if crevassing generates a shorter route to the sea. The topmost beds are then attacked by wave and current activity and may be completely reworked. Compaction and/or subsidence may allow a local marine transgression to occur. The result typically is a thin to moderately thick unit of sands or clays containing a marine fauna, abundant bioturbation and possibly, glauconite. There may be abundant evidence of wave and tide reworking in the form of distinctive assemblages of sedimentary structures.

Lobe switching is probably more common in river-dominated deltas, resulting in a more frequent initiation of new progradational cycles. The overall mechanism probably is similar to wave-dominated deltas (e.g., the Rhône), but may not occur on tide-dominated deltas. Large-scale alternation between the two phases may reflect regional regression-transgression cycles caused by tectonism or eustatic sea level changes. An example is discussed below.

The complete delta cycle (sometimes termed a megacycle) may be about 50 to 150 m (or more) in thickness, but it may contain or pass laterally into numerous smaller cycles representing the progradation of individual distributaries or crevasse splays. As shown by Coleman and Gagliano (1964) and Elliott (1974) these can range from approximately 2 to 14 m in thickness. As in the case of the larger scale cycles they tend to coarsen upward, as described below.

The manner in which cyclic deltaic sequences are superimposed upon each other depends on the relative rates of sedimentation, subsidence (including compaction) and lobe switching. If the rates of sedimentation and subsidence are in approximate balance a delta will

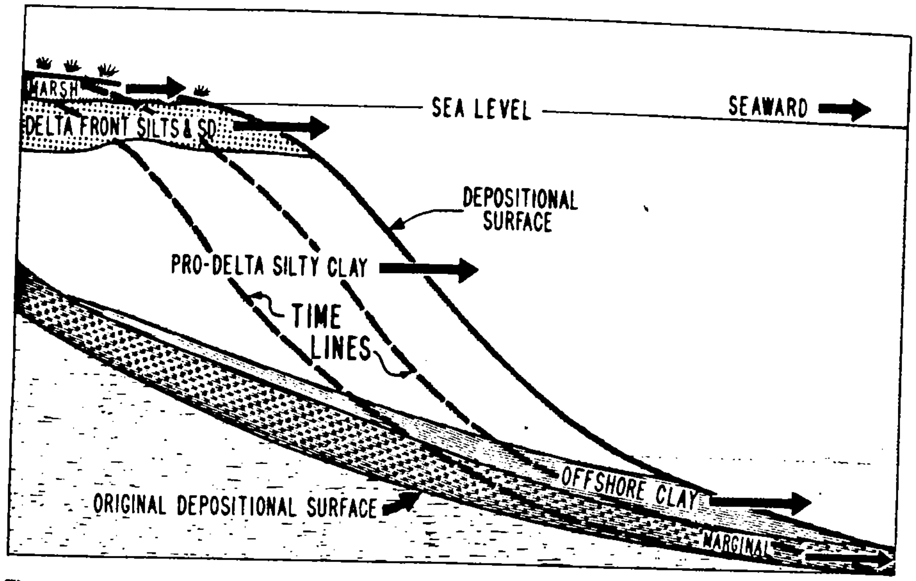

Figure 10
Development of the "clinoform"; depositional surface of the delta front and prodelta: the progradational phase of delta growth (Scruton, 1960).

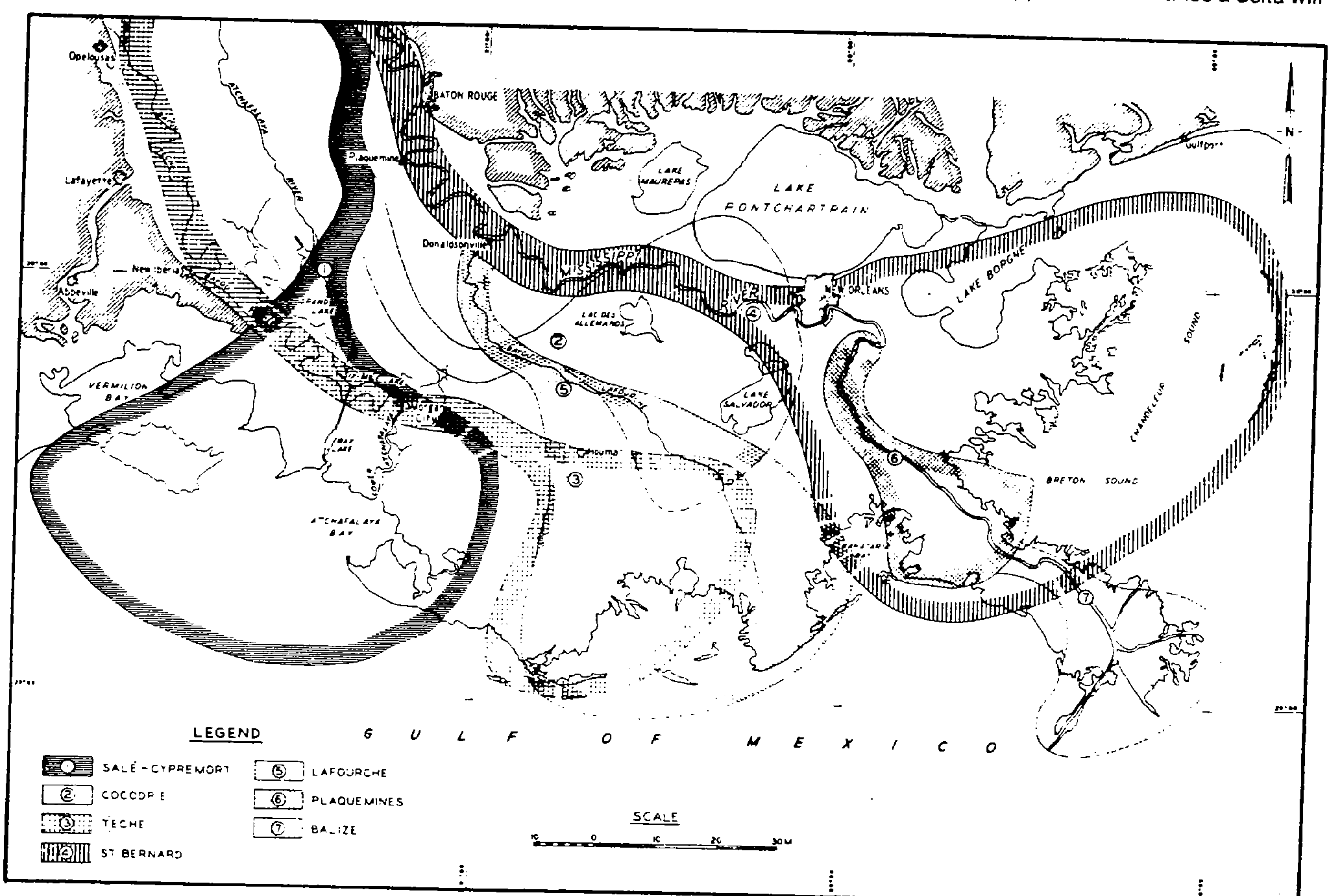

Figure 11
The seven partially overlapping lobes of the Mississippi delta which have developed during the last 5000 years (Kolb and Van Lopik, 1966). Sedimentation is now active again in the area of lobe 1 (Roberts et al., 1980) as well as on the main modern lobe (#7).

tend to build vertically; if subsidence is slower the delta will prograde seaward. As each part of the depositional basin becomes filled, successive progradational events will move laterally (Curtis, 1970, p. 293-297). This is demonstrated dramatically by the Mississippi delta. Here both subsidence and sedimentation have been rapid since the Pleistocene, but the enormous sediment supply has resulted in the development of a suite of seven separate but partially overlapping lobes at the mouth of the Mississippi during the last 5000 years (Fig. 11). The most recent lobe is itself in the process of forming several subdeltas, by similar processes of crevasse splay and distributary switching.

Given a broad shelf or a generally shallow basin a delta may continue to prograde basinward for many kilometres. The depositional surfaces representing each time horizon (Fig. 10) define gently-dipping, wedge-shaped stratigraphic units termed clinoforms. These are very distinctive on regional seismic cross-sections (Fig. 12, Brazos Delta; see Brown and Fisher, 1977; Winker and Edwards, 1983). In strike sections these same units show a large scale mounded or hummocky pattern, recording the lateral switching or offsetting of individual delta lobes.

RECOGNIZING ANCIENT DELTAS

Deltas contain no single distinctive lithofacies but consist of assemblages of lithofacies, each of which can occur in a variety of other environments. It is, necessary, therefore, to identify ancient deltas by a series of steps, eliminating other possibilities and using distinguishing characteristics of facies type, bed geometry and type of cyclic succession to focus in gradually on the correct delta model. This process is complicated by the existence of three end-member "norms", and by the fact that most natural modern and ancient deltas probably are combinations of all three, with added local complications of basin geometry and basin tectonics to be unravelled. In addition, very few good examples of ancient wave- and tide-dominated deltas are available for use as analogues.

The most useful overall indicator of a major deltaic deposit is the presence of a thick wedge or lobe of nonmarine to shallow marine lacustrine sediment, passing basinward into finer grained, deeper water facies, and landward into an entirely nonmarine (usually fluvial) facies (although the latter may have been removed by uplift and erosion of the basin margin). To detect such a deposit requires careful stratigraphic correlation and the application of lithofacies mapping techniques.

Attempts to correlate deltaic units must be carried out with care because the presence of numerous lateral facies changes can be the cause of many mistakes. Cant ("Subsurface Facies Analysis", this volume) describes the methods of subsurface correlation using geophysical logs, and Figure 12 (Southwest Pass) is an example of correlation of a Recent sand unit in the Mississippi delta. Note the typical coarsening-upward profile, and the interpretation of a locally thickened sand wedge in terms of growth fault. Figure 12 (Brazos Delta) is an example of the clinoform seismic facies so commonly recorded from deltaic deposits. This example is of a modern delta, in which the relationship of the dipping depositional surface to the clinoform stratigraphy is quite obvious (see Fig. 10). A word of caution is required, however, because clinoform reflections can be generated in other environments (alluvial fans, submarine fans, continental slopes, reef talus wedges) and so are not always reliable as a primary facies indicator of a deltaic environment.

If a network of well correlated surface or subsurface sections can be developed, the deltas can be delineated

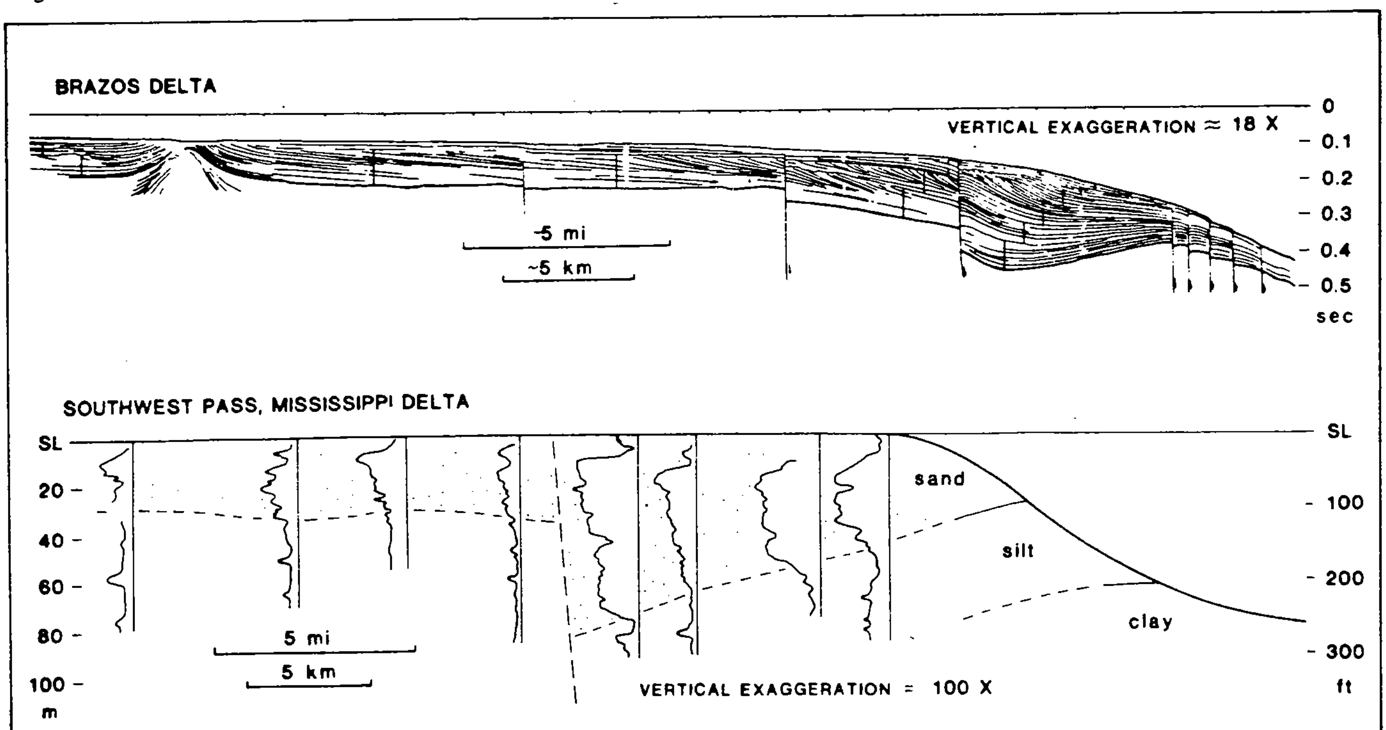

Figure 12
Seismic facies of the modern Brazos River delta (Winker and Edwards, 1983); and subsurface correlation of a deltaic sand-silt unit, in Southwest Pass, Mississippi delta, showing characteristic geophysical log profile of coarsening-upward cycles, and recognition of a growth fault.

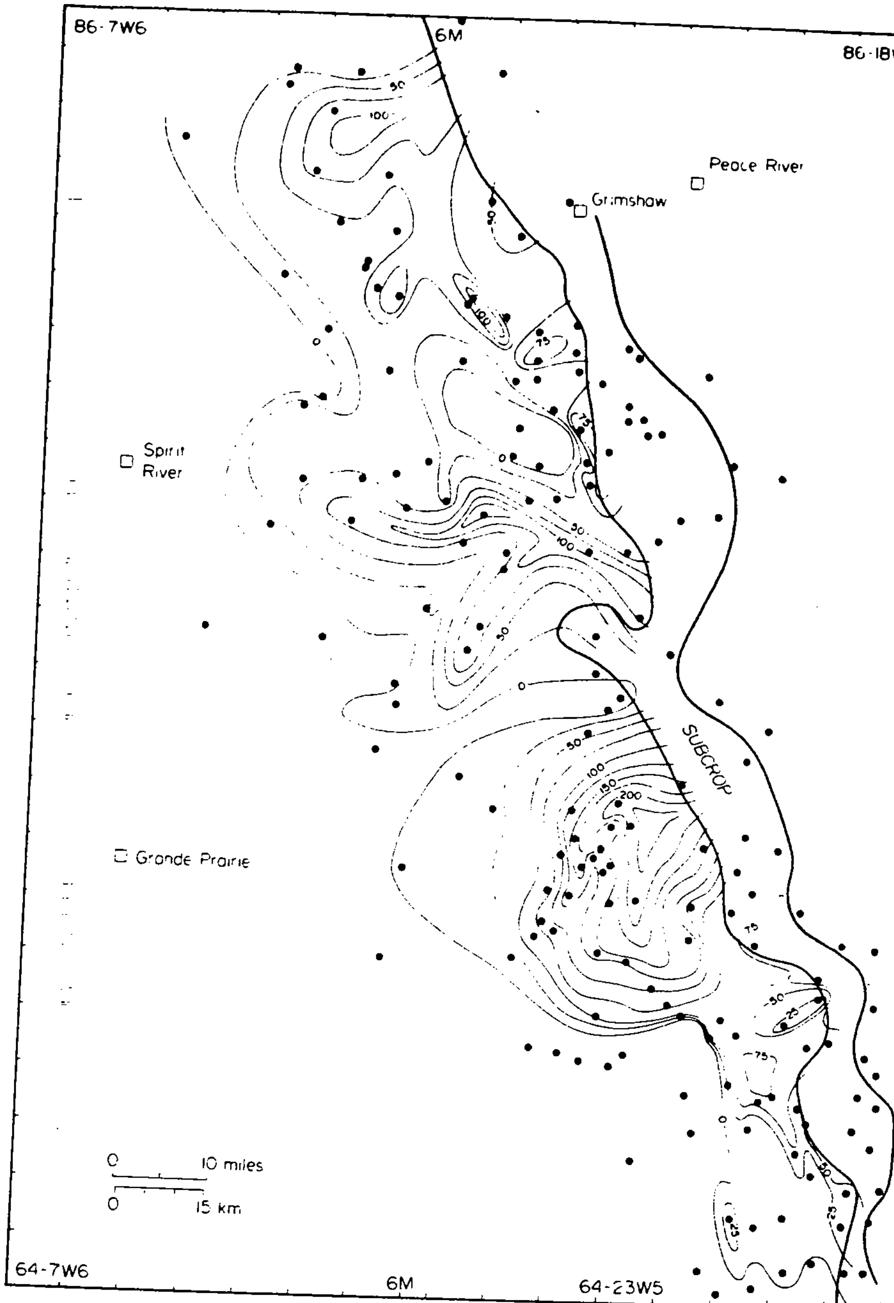

Figure 13
Lobate and birdsfoot deltas in a member of the Triassic Toad-Grayling Formation. northwest Alberta. Contours show the distribution of net porous section, in feet (Miall, 1976a).

using lithofacies mapping techniques. Various parameters may be used, including sand/shale ratio, total sand thickness, or sand thickness expressed as a per cent of a total section. The results may show important differences. For example, the same interval of Eocene sand on the Gulf Coast is mapped in three ways in Figure 9. Map A shows the characteristic lobate pattern of river-dominated deltas, with sand content diminishing distally toward the southeast. Maps B and C show a very different pattern. Lobes of thick sand are present, oriented parallel to strike, but are interpreted here in terms of locally increased subsidence and sedimentation rates along growth faults. The strike-parallel pattern of sand bodies could be confused with that of a wave-influenced delta (see Fig. 2C) if the researcher was not aware of the growth faults. Because the entire thickness of section increases across growth faults, maps of sand percentage (Fig. 9A) may not reveal the effects of syndepositional faulting. However, if allowance is made for these possibilities the outline of local deltaic depocentres revealed by lithofacies mapping techniques may yield useful clues about delta type. For example, Figure 13 shows a map of total porous section (mainly sandstone) in a member of the Toad Grayling Formation (Triassic) of northwest Alberta (Miall, 1976a). The shapes of the lobes and fingers of thick sandstone can be compared to idealized diagrams such as Figure 2. The subcrop of the Toad Grayling beneath the Jurassic is known to be approximately parallel to regional shoreline. The sandstone trends are more or less perpendicular to this shoreline, and have the shape of birdsfoot and lobate river-dominated deltas. Other excellent examples of such maps have been published by Busch (1971) and Wermund and Jenkins (1970).

Interpretations can be refined by detailed examination of vertical sections, using the characteristics of the three end-member delta types as "norms" and as guides for interpretation. For example, they may show the repeated coarsening-upward cycles characteristic of wave- and river-dominated deltas (Fig. 12, Southwest Pass). Cores and outcrops may reveal distinctive assemblages of lithofacies and sedimentary structures, and paleocurrent analysis may be employed (if suitable outcrops are available) in order to map dispersal patterns. Using these data the effects of fluvial and marine currents can be assessed and suitable comparisons with the appropriate deltaic norms (Figs. 1 and 2) can be suggested, and compared with the results of lithofacies mapping.

Figure 14 illustrates two outcrop profiles through the Bokkeveld Group (Early Devonian) of Cape Province, South Africa (Tankard and Barwis, 1982). The generalized section on the left illustrates repeated coarsening upward megacycles, while the detailed, interpreted section shows some of the subenvironments that can be recognized within individual megacycles. Smaller scale cycles up to 20 m thick record the progradation of mouth bars and some of the barrier and tidal sands produced by marine reworking. The lower 105 m of the detailed section is a typical product of river-dominated delta progradation, with a coarsening-

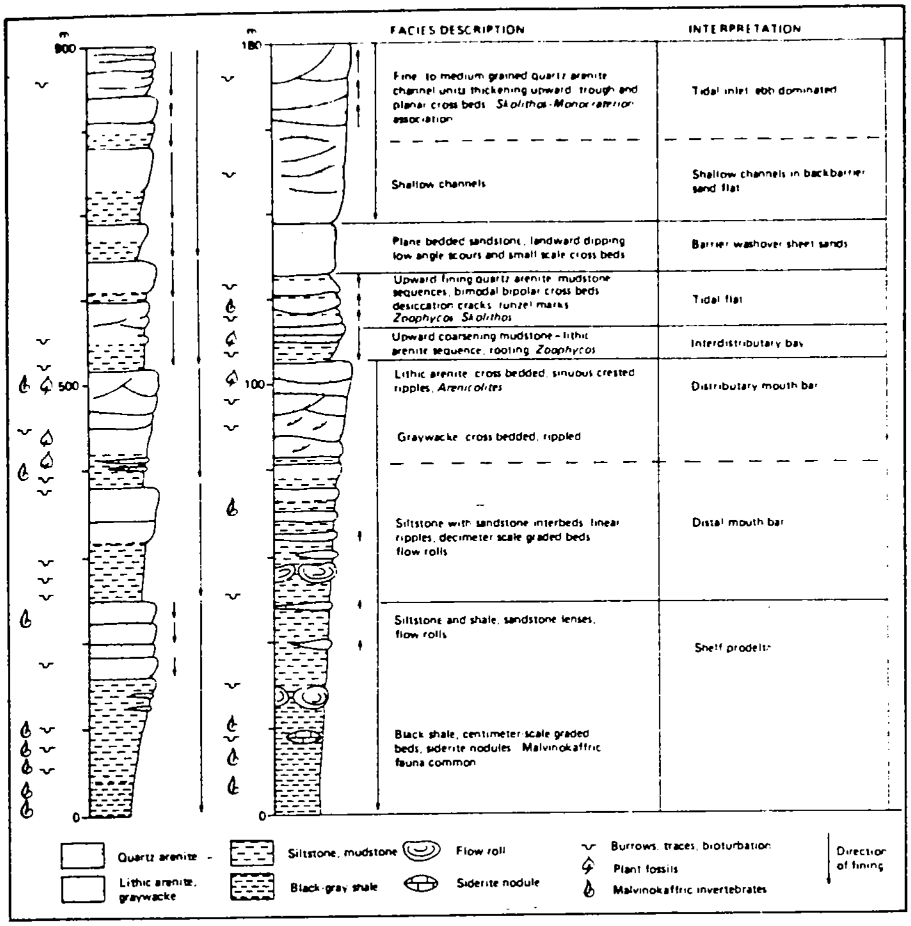

Figure 14
Stratigraphic section through the Bokkeveld Group, Cape Province, South Africa (left) and detailed lithofacies and interpretation of an idealized cyclic sequence (Tankard and Barwis, 1982).

upward succession of shales, siltstones and thin sands representing the build up of the prodelta to distal mouth bar sediments. The sequence is capped by scoured and crossbedded lithic arenites of the proximal mouth bar.

The progradational facies are overlain here by quartz arenites up to 70 m thick showing evidence of wave and tide reworking of the Bokkeveld deltas. Facies and structures are similar to those occurring in other wave- and tide-influenced coastlines (see "Barrier Island and Associated Strand Plain Systems", this volume) but their thickness and associations here suggest a deltaic origin. Barriers and washover sheets are indicated by flat to gently dipping planar sand sheets with a seaward oriented foreshore dip or with the landward dip of washover fans. Tidal inlet and associated delta deposits show polymodal, but commonly ebb-dominated paleocurrent patterns in medium scale crossbedding. Each facies contains a distinct ichnofacies (see "Trace Fossil Facies Models", this volume). The Bokkeveld deltas are interpreted as "wave-influenced" deltas, the lower part of each megacycle shows a predominant fluvial influence, while the reworked marine facies indicate strong wave activity and a moderate tidal influence. This alternation is probably the result of subsidence or sea level change periodically altering the subtle balance between fluvial and marine influences. Another similar example was described by Vos (1981b).

Examples of ancient tidally-influenced deltas have been described by Clemmensen (1976), Eriksson (1979), Verdier *et al.*, (1980) and Rahmani (1982). For example, Eriksson (1979) documented the presence of flood-dominated elongate sand shoals oriented perpendicular to the shoreline, and proposed a model of a non-barred estuary for part of the Archean Moodies Group of South Africa. Figure 15 illustrates a local facies model developed for the modern Niger River by Allen (1970). This river shows elements of all three deltaic end members or "norms", including well-developed beach ridges and active tidal channels undergoing vigorous reversing flow. The lithofacies characteristics shown in the circles around the block diagram illustrate the characteristic coarsening upward nature of the deposit, with distinctive beach-accretion sets and herringbone cross-bedding attesting to the strong marine influence.

Numerous examples of ancient river-dominated deltas have been described. Selected examples are listed in the bibliography. The presence of lobate or finer-shaped deltaic trends, radial paleocurrent patterns, and the characteristic lithofacies assemblages of shoe string sands, interdistributary bays, crevasse splays and mouth bars, are the main criteria for recognizing this type of delta. A Tertiary example is shown in Figure 16 exhibiting, in this case, most of the characteristic features of the river-dominated deltaic "norm".

Increasing attention is being paid to the fan-delta model, particularly by sedimentologists studying pre-Devonian (pre-vegetation) deltas. Another common paleogeographic environment in which fan deltas are found is at the mouths of short, steep rivers carrying abundant bedload. Fan deltas typically lack interdistributary bays and crevasse splays. They show a highly scoured and channelized transition between the coarse, commonly conglomeratic, delta plain and delta front deposits and the finer grained prodelta facies. Selected examples are listed in the bibliography.

CONCLUSIONS

The delta of the Mississippi is still pre-eminent in the minds of many geologists, for the historical and economic reasons described at the beginning of this paper. However, analyses of ancient deltas are becoming increasingly sophisticated, and the Mississippi is no longer the model automatically used in interpretations of the ancient record.

The next development in the interpretation of ancient deltas may be to interpret the alternations of progradational and abandonment phases in terms of regional changes in relative sea level, and to relate dispersal patterns to

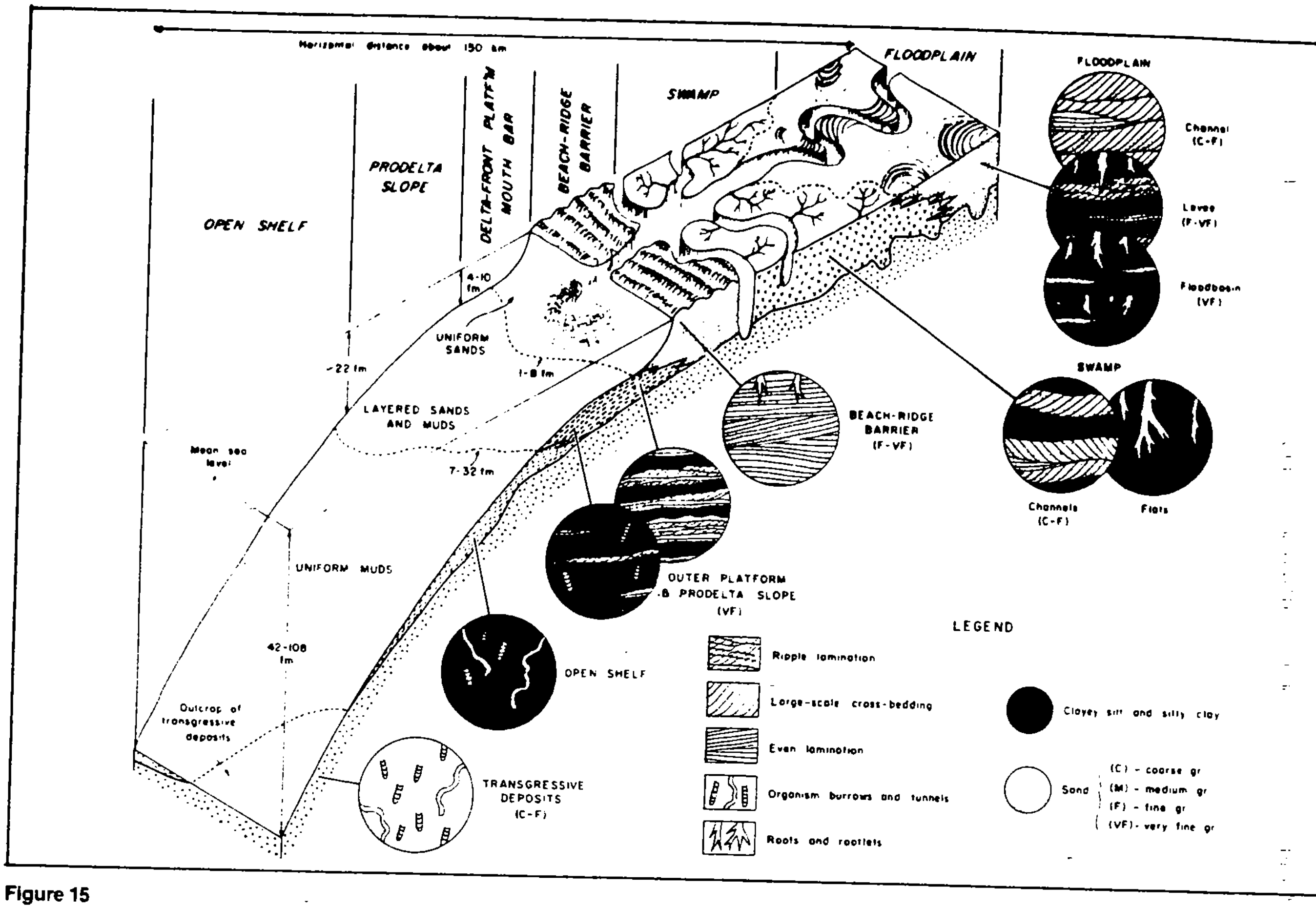

Figure 15
Block diagram model of the modern Niger delta (Allen, 1970).

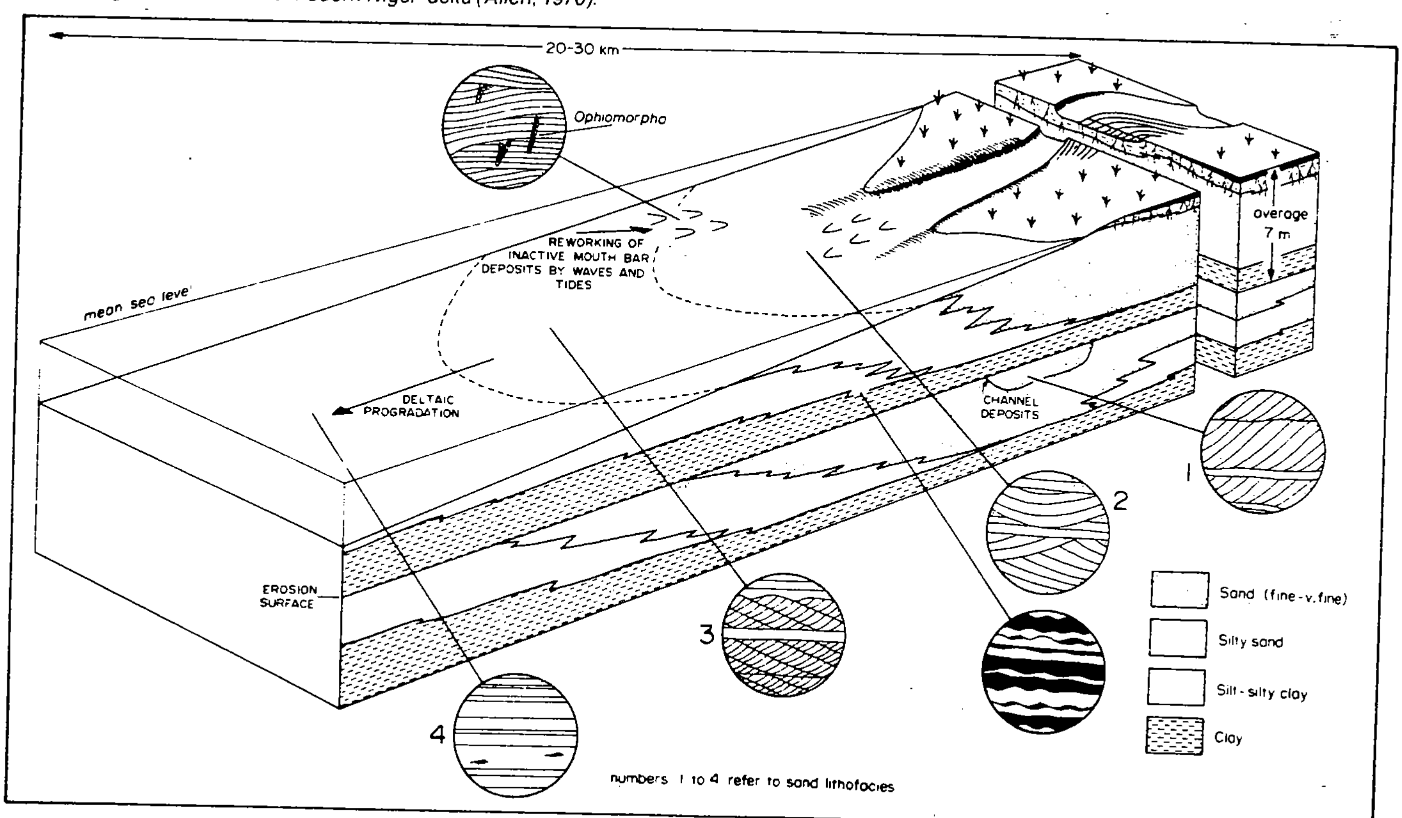

Figure 16
Block diagram model of the Eureka Sound Formation (Tertiary), Banks Island, Arctic Canada, showing interpretation of coarsening upward cycles in terms of distributary mouth bar sands (Miall, 1976b).

tectonic setting and structural grain. As suggested by Miall (1981) some useful information about local plate tectonic history may emerge from this type of analysis.

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