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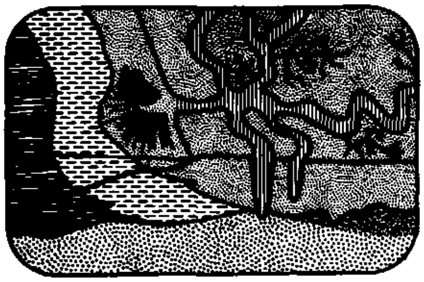

Facies Models 4. Deltas

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Introduction
Deltaic depositional models differ from those described in earlier papers in the facies models series in that their recognition has not depended on a distillation of observations on ancient rocks but has arisen largely from a study of depositional processes on modern delta systems. A second important difference is that there are at least three distinct delta models, or "norms", to choose from in interpreting ancient rocks; many deltas are combinations of all three.

Definition
The concept of the delta is one of the oldest in geology, dating back, in fact, to about 400 B.C. At that time Herodotus made the observation that the alluvial plain at the mouth of the Nile was similar in shape to the Greek letter Δ, and the term was born.

One of the earliest modern definitions of a delta was provided by Barrell (1912) who stated that is "a deposit, partly subaerial, built by a river into or against a permanent body of water". There is little reason even now to revise this definition. Common usage amongst present-day geologists studying ancient rocks is that the term deltaic deposit is restricted to those bodies of clastic sediment formed in subaerial and shallow water environments (marine or lacustrine) in which the influence of a river or rivers as the main sediment source can be recognized, and in which a gradation into an offshore, generally finer-grained facies, can be traced. As discussed below, there are many modern deltas where the depositional influence of the river is strongly masked by waves, ocean currents, tidal currents or winds, and the deposits of such deltas may be very hard to recognize in the ancient record.

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 nineteen twenties 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 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 named, succintly, 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 history, depositional environments and cyclic sedimentation in the Mississippi, were provided by Kolb and Van Lopik (*in* Shirley, 1966) and by Coleman and Gagliano (1964, 1965).

The other delta that was studied extensively at this time was that of the Niger (Allen, *in* Morgan, 1970a; Oomkens, 1974).

Recently, some very useful compilations of papers on ancient and modern deltas have appeared (Shirley, 1966; Morgan, 1970a; Broussard, 1975), and several series of short-course lecture notes have been published, all of which contain much of value both to the specialist and non-specialist (Fisher *et al.*, 1969; Curtis *et al.*, 1975).

Wright *et al.* (1974) studied some 400 parameters of 34 modern alluvial-deltaic systems using multivariate statistical techniques in order to determine what controls their geometry, orientation and composition. The unifying concepts which emerged from this study (summaries of which are provided by Coleman *in* Curtis *et al.*, 1975, and by Coleman and Wright *in* Broussard, 1975) are of fundamental importance to the geologist dealing with ancient rocks. They indicated that deltas can be divided into at least six types. However, for the purpose of the present paper it is sufficient to use the three main categories defined by Scott and Fisher (*in* Fisher *et al.*, 1969) and by Galloway (*in* Broussard, 1975) as shown in Figure 1. These are the three "norms" referred to in the introduction.

Most of the publications referred to above are dominated by Gulf Coast geologists. Several important papers by "outsiders" are included in the compilations, for example, descriptions of the Rhine delta in Lake Constance by Müller (*in* Shirley, 1966), of the Niger, by Allen (*in* Morgan, 1970a) and of the Rhône by Oomkens (*op. cit.*) but, nevertheless, the pre-eminence of Houston- and New Orleans-based oil companies and such organizations as the Coastal Studies Institute of Louisiana State University in delta research, is astonishing. Conversely, contributions by Canadians and about Canadian deltas, ancient and modern, are few and far between. None of the major advances in understanding of deltaic sedimentation were made in this country. Some of the earliest work on modern deltas was carried out by Johnson (1921, 1922) on the Fraser delta, although these publications appear to have had little influence on subsequent research in deltaic sedimentation.

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 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, and these enable a meaningful classification of delta types to be made, as shown in Figure 1:

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 *in* Curtis, 1975, and Coleman and Wright *in* Broussard, 1975 provide a more complete discussion of this topic).

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:* flow forms a planar jet along the bottom. The result commonly is a turbidity current. The deposits which form from such bottom currents are classified as submarine fans.

B) *Inflow equally dense:* this occurs where rivers enter freshwater lakes. Sediment is dispersed radially and competency is lost rapidly. The result is a narrow, arcuate zone of active deposition and the delta which forms contains distinct topsets, steeply-dipping foresets, and bottomsets. This is the classical 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. The type of sediment dispersal which takes place depends on the strength of waves, tides and longshore currents, as discussed below.

Variations in transportation patterns 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 Scott and Fisher (*in* Fisher *et al.*, 1969), Coleman (*in* Curtis, 1975), Galloway (*in* Broussard, 1975) and Coleman and Wright (*op. cit.*).

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 as the jet of river water enters the sea (Fig. 2). The main sediment load is deposited in a distributary mouth bar, which becomes finer grained seaward. 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.

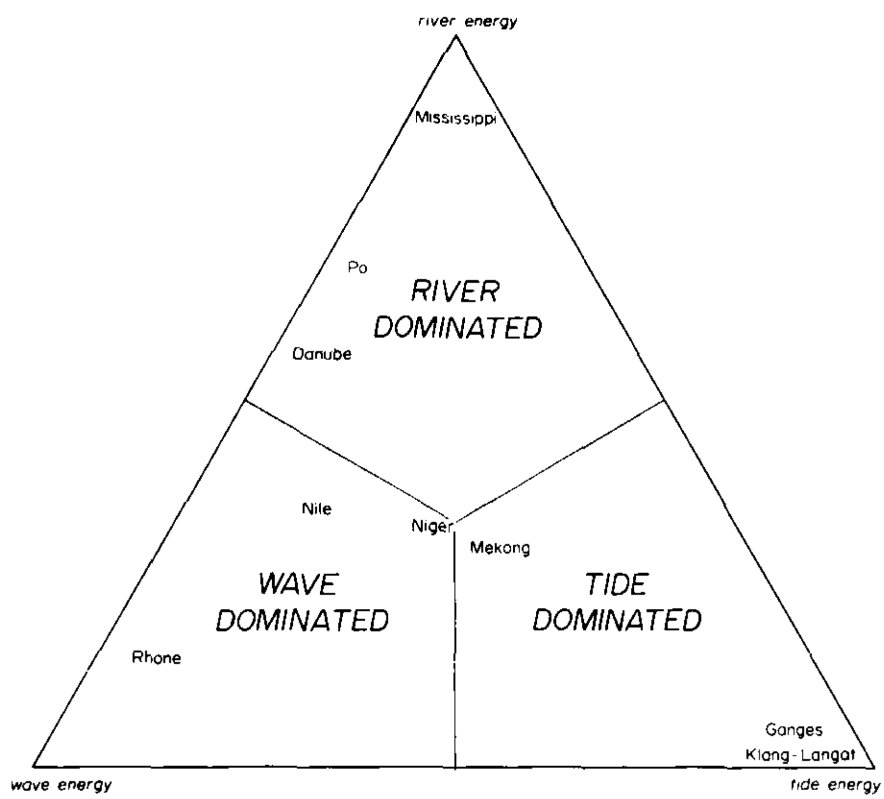

Figure 1
A classification of delta types, based on variations in transportation patterns on the delta (afer Galloway, Fig. 3, in Broussard, 1975).

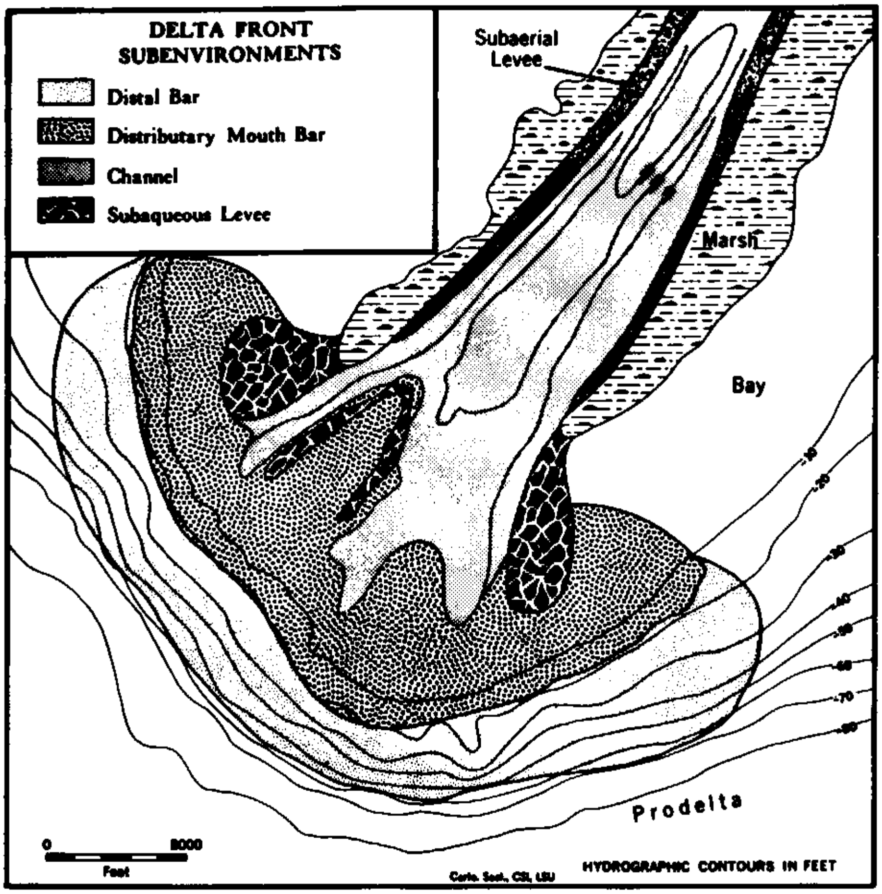

Figure 2
Subenvironments at a distributary mouth in a river-dominated delta, South Pass, Mississippi delta (from Coleman and Gagliano, 1965, Fig. 9).

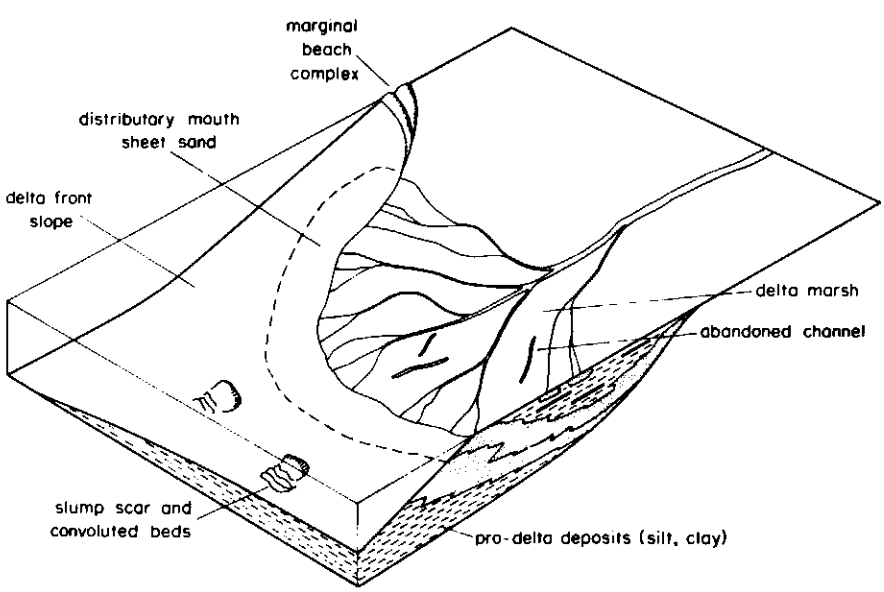

Figure 3
Block diagram of a lobate, river-dominated delta, showing the principal environments and sedimentary facies.

These are, in very brief outline, the principal mechanisms that occur in river-dominated deltas. The sediments, sedimentary structures and organic remains they contain will be described later.

There are two main subtypes in this delta category. It was stated earlier that the river discharge could be either steady, generally with a high suspension load, or fluctuating, with a typically higher proportion of bedload in the sediments. The first type tends to form birdsfoot deltas with few distributaries, shoestring sands and discrete mouth bar deposits (Figs. 2, 4). The second type normally is lobate in outline; there are a greater number of distributaries, each of which tends to be more ephemeral, and the sediments are coarser grained and the mouth bar deposits merge laterally into sheet sands (Fig. 3).

B) *Wave-dominated deltas:* in environments of strong wave activity mouth bar deposits are continually reworked into a series of superimposed coastal barriers. These may completely dominate the final sedimentary succession, and the internal geometry of the deposits will be quite distinctive. Sand bodies will tend to parallel the coastline, in contrast to those of river-dominated deltas, which are more nearly perpendicular to the coast (Fig. 5).

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 (Fig. 6).

In cases where powerful longshore currents exist the sediments will be reworked into a series of barrier deposits and offshore sand ridges parallel to the coastline. The area of principal sediment accumulation will be displaced downcurrent from the main distributary mouth(s) and, in extreme cases, the sediment may be completely dispersed along the shoreline with the development of no recognizable delta. Such deposits will be described in a subsequent paper on shoreline sand models.

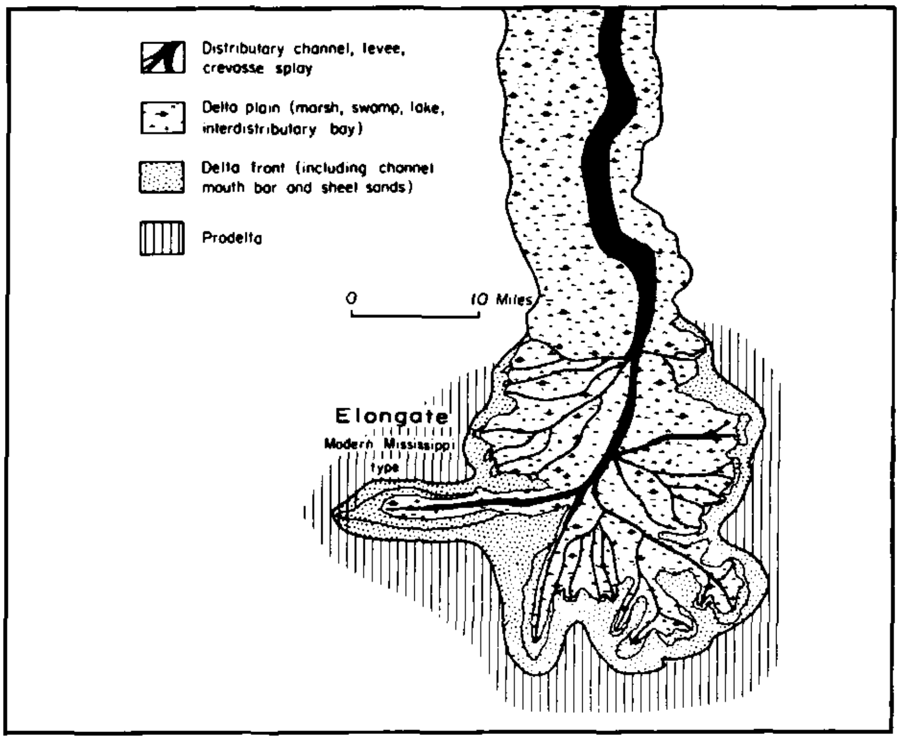

Figure 4
A birdsfoot-type river-dominated delta; the modern Mississippi delta (from Fisher et al., *1969, Fig. 39).*

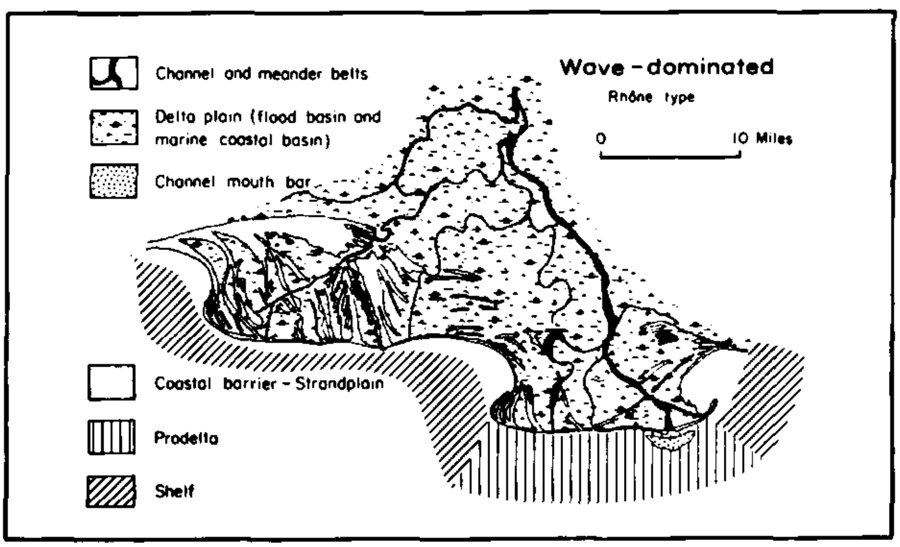

Figure 5
A wave-dominated delta; the modern Rhône delta (from Fisher et al., *1969, Fig. 37).*

Deltaic cycles
Scruton (*in* Shepard *et al.*, 1960) was one of the first to point out that the growth of a delta is cyclic. He divided the cycle into two phases:
A) *Constructional phase:* active seaward progradation causes prodelta muds to be overlain by delta-front silts and sands, these in turn by distributary-mouth deposits, mainly sands, and finally top-set delta marsh sediments, possibly including peat beds (Fig. 7).
B) *Destructional phase:* a delta lobe eventually is 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 may allow a local marine transgression to occur.

This description of the delta cycle is, of course, idealized. Firstly, it is most appropriate only for Mississippi-type deltas. Secondly, different parts of the same delta may be in different stages of development. The terminology is unfortunate; a major suite of superimposed barrier deposits caused by wave-reworking is as much a "constructive" deposit as is a distributary mouth sheet sand. Nevertheless, river- and wave-dominated deltas commonly are referred to as "*high-constructive*" and "high-destructive" deltas, respectively, in the literature (for example, Fisher *et al.*, 1969).

The complete delta cycle (sometimes termed a megacycle) may generate a stratigraphic succession between 50 and 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 two to 14 m in thickness. As in the case of the larger scale cycles they tend to coarsen upward (more complete descriptions later).

The manner in which cyclic deltaic sequences are superimposed upon each other depends on the relative rates of sedimentation and subsidence (including compaction). If the two rates are in approximate balance a delta will tend to build vertically; if subsidence is faster the delta will prograde seaward, and as each part of the depositional basin becomes filled successive progradational events will move laterally. The mechanisms are described by Curtis (*in* Morgan, 1970a, p. 293-297). Figure 8 shows how relatively slow subsidence rates have resulted in a suite of seven separate but partially overlapping lobes at the mouth of the Mississippi during the last 5000 years. The most recent lobe is itself in the process of forming several subdeltas, as shown in Figure 9.

Cyclic processes in other types of deltas are rather different. For example, in wave-dominated delta the sediments consist mainly of superimposed barrier sand deposits. However, far less subsurface information is available for modern wave- and tide-dominated deltas than for the Mississippi, and their internal geometry is, therefore, less well known.

Recognizing ancient deltas in the surface and subsurface

As shown in previous sections, numerous variables affect the nature of a deltaic deposit, and so it is impossible to describe a single delta model in a few brief sentences. In general terms: 1) deltaic deposits tend to be thick (several hundreds or even thousands of metres); 2) they contain considerable volumes of sand and/or silt; 3) coal beds commonly are present; 4) the faunal content of interbedded units may indicate marine, brackish and fresh water depositional environments; 5) sedimentary structures indicate shallow water deposition by traction- rather than turbidity-currents; 6) a gradation into finer-grained clastic deposits of offshore origin should be traceable (criteria 3 and 4 are, or course, of no use in the Precambrian).

Some more specific criteria for the recognition of the principal delta types are described in the following paragraphs.

River-dominated deltas. The rapid seaward progradation of these deltas gives rise to the most characteristic feature of deltaic sediments, the coarsening-upward cycle. The complete cycle of a delta lobe (typically 50 to 100 m thick) and the distributary and crevasse cycles which are its component parts are summarized in Figure 10, and Figure 11 is an illustration of lateral changes that have been recognized in the coarsening-upward cycles of a Tertiary deltaic deposit in Banks Island, Arctic Canada.

Each cycle commences with a clay, generally laminated and sparsely fossiliferous. Prodelta clays tend to be organic-rich because of the abundant plankton growth which takes place in response to the influx of nutrient-rich river waters. They therefore make good petroleum source beds. The clays grade up into interbedded clay and silt or very fine sand, in which small-scale ripple marks and bioturbation are common. Distributary mouth sand bars or sheet sands may form the coarsest member of the cycle. The influence of strong unimodal currents near the distributary mouths generally is apparent in the form of abundant planar and trough crossbeds and ripple-marks. Organic remains, other than fragmented and transported debris (including plant material) are rare. The top of the cycle may be formed of delta marsh sediments, including paleosols and coal, or by distributary channel sands. These may be of finger- or shoestring-shape, as described in the classic work of Fisk. In some instances still more regressive facies are preserved, in the form of

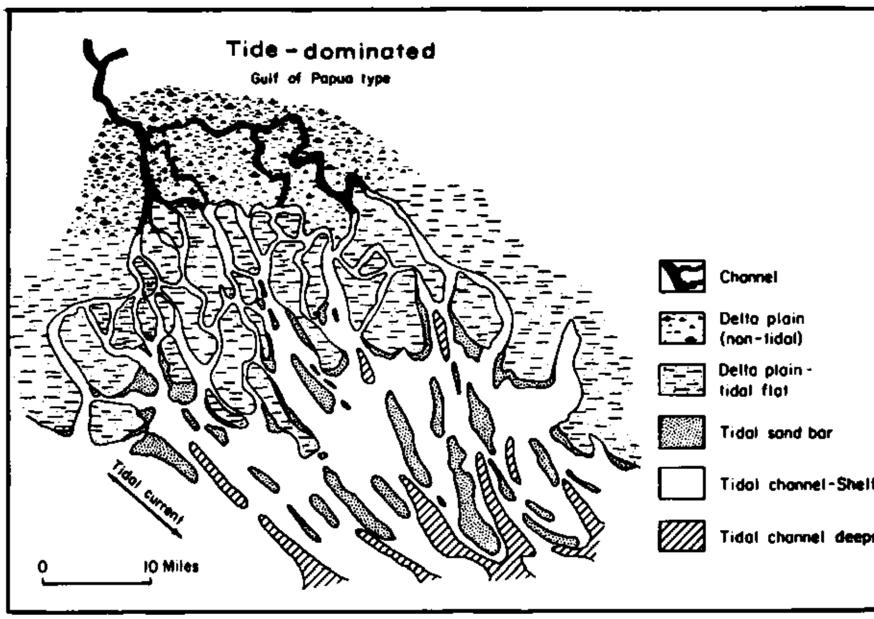

Figure 6
A tide-dominated delta; the modern Gulf of Papua (from Fisher et al., *1969, Fig. 47).*

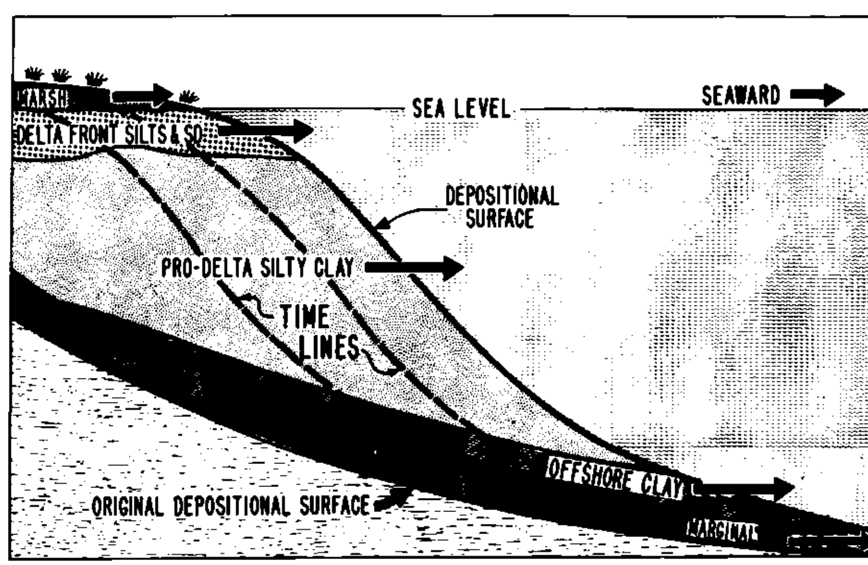

Figure 7
The "constructional" phase of the delta cycle (from Scruton, Fig. 9, in Shepard et al., *1960).*

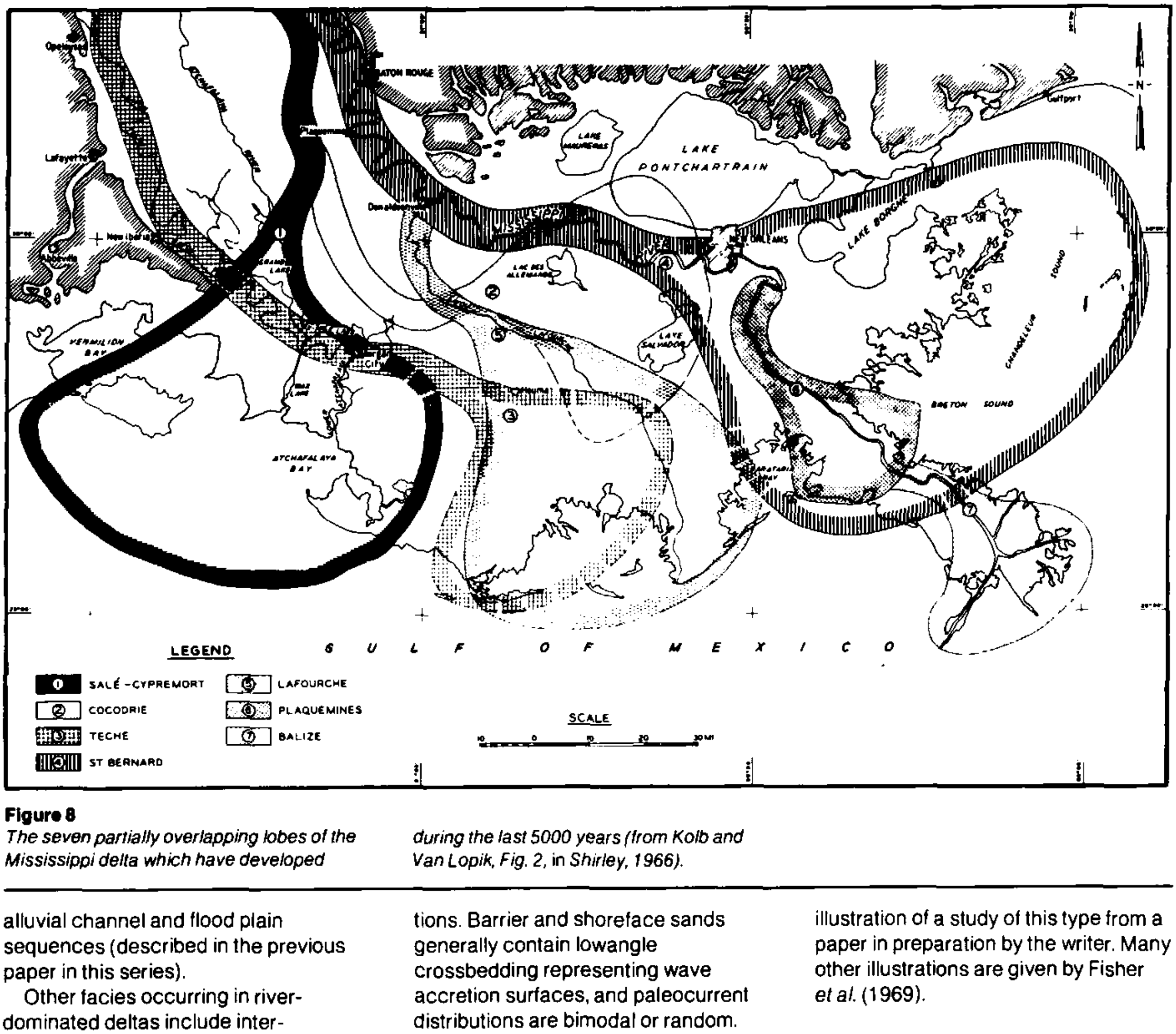

Figure 8
The seven partially overlapping lobes of the Mississippi delta which have developed during the last 5000 years (from Kolb and Van Lopik, Fig. 2, in Shirley, 1966).

alluvial channel and flood plain sequences (described in the previous paper in this series).

Other facies occurring in river-dominated deltas include inter-distributary bay deposits and marginal, reworked deposits derived from abandoned delta lobes. The former generally are fine grained and in some instances contain shell beds; the latter *commonly contain abundant shell* debris, are glauconitic and bioturbated, and may be mineralogically and texturally more mature than other delta deposits as a result of wave and current winnowing (Shepard *in* Shepard *et al.*, 1960).

It is important to distinguish deltaic coarsening-upward cycles from those of offshore bar, barrier-bar or shoreface origin. The greatest differences are apparent in the coarse, upper members of the cycles. Deltaic cycles tend to be *characterized by high-angle crossbeds* with unimodal paleocurrent distributions. Barrier and shoreface sands generally contain lowangle crossbedding representing wave accretion surfaces, and paleocurrent distributions are bimodal or random. Deltaic sedimentation tends to be more rapid and less bioturbation or sediment sorting takes place. Rapid deltaic loading of sand on to unconsolidated prodelta muds commonly results in *convolute bedding or the development* of mud lumps or diapirs. Lastly, deltaic cycles of all types commonly are capped by coal beds whereas these are unusual in barrier island and shoreface sequences.

River-dominated deltas can be mapped most readily, particularly in the subsurface, by measuring the total sand content, or the sand/shale ratio in a given stratigraphic unit. Areas of high sand content may outline lobate areas perpendicular to the basin margin, *corresponding to the principal paths of* deltaic progradation. Figure 12 is an illustration of a study of this type from a paper in preparation by the writer. Many other illustrations are given by Fisher *et al.* (1969).

Wave-dominated deltas. As noted earlier, wave-dominated deltas are characterized by stacked beach-ridge sequences (Fig. 10). Some of the criteria by which to distinguish these from progradation cycles were given in the previous section. Beach-ridge sequences can develop in nondeltaic settings as a result of longshore drift, and additional criteria are necessary in order to identify a specific sequence as deltaic in origin. Bars forming on nondeltaic coastlines commonly are backed by lagoons, the sediments of which may cap the bar sequence, whereas in deltaic settings the bars develop in front of swamps and fluvial channel complexes, the deposits of which should be quite distinctive. Coal may be an important constituent. Figure 13 is a schematic illustration of the sediments and facies relationships occurring *in the modern Niger delta, which* contains prominent beach-ridge deposits and is cut by tidal channels (Allen *in* Morgan, 1970a).

The geometry of wave-dominated delta deposits is quite different from those where wave influence is low. Beach-ridge sands form linear sand maxima sub-parallel to the basin margin, *ideally forming a convex-seaward, arc-*, cusp-, or chevron-shaped body. Associated fluvial sands will trend sub-perpendicular to the basin margin. The "classic" delta - that of the Nile - is a good example of a wave-dominated type; the Rhône delta (Fig. 5) is another (Oomkens *in* Morgan, 1970a).

Tide-dominated deltas. Deltas of this type may be difficult to recognize in ancient rocks. The coarser sediments are dispersed by tidal currents into offshore sand ridges parallel to the coastline, such as have been described by Off (1963), and the subaerial part of the delta consists largely of tidal flats comprising mainly fine-grained deposits. Distributaries may contain well-sorted sands, and large quantities of clay and silt will tend to be flushed into the delta marsh environment by overbank flooding during high tides. A typical modern tide-dominated delta is that of the Klang River in Malaysia (Coleman *et al.*, *in* Morgan, 1970a; Coleman and Wright, *in* Broussard, 1975).

None of the characteristics of tidal delta deposits are distinctively "deltaic". Tide-generated sand ridges and tidal flats are widespread at the present day in areas without significant fluvial sediment input. The thickness of the deposit, reflecting the nearby presence of a major river mouth, may be the only clue in the ancient record to the presence of a tide-dominated delta. Few published descriptions of such a deposit are known to the writer. A generalized and partly hypothetical stratigraphic section through a tidal delta is shown in Figure 10.

Concluding remarks

The delta of the Mississippi is pre-eminent in the minds of most geologists as the all-purpose typical delta. There are obvious historical reasons for this, such as the abundance of oil and gas in deltaic deposits in the Gulf Coast, which has stimulated great research efforts into Mississippi sedimentation. The result has been that many river-dominated deltas now are recognized in ancient rocks, whereas the literature on other delta types is sparse. It may be that many beach-ridge and tidal flat sequences are actually deltaic in origin, and more research into wave- and tide-dominated deltas clearly is needed.

Acknowledgements

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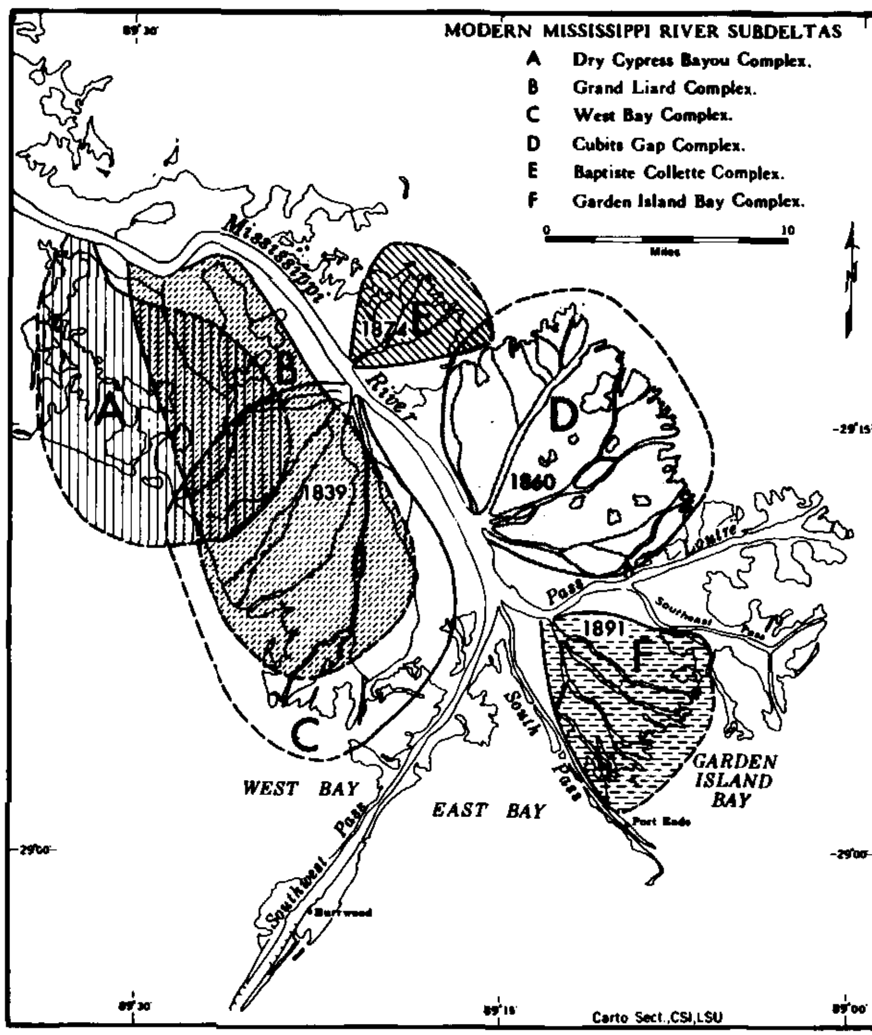

Figure 9
The sub-deltas of the modern Mississippi delta, showing year of initiation, where known (from Coleman and Gagliano, 1964, Fig. 5).

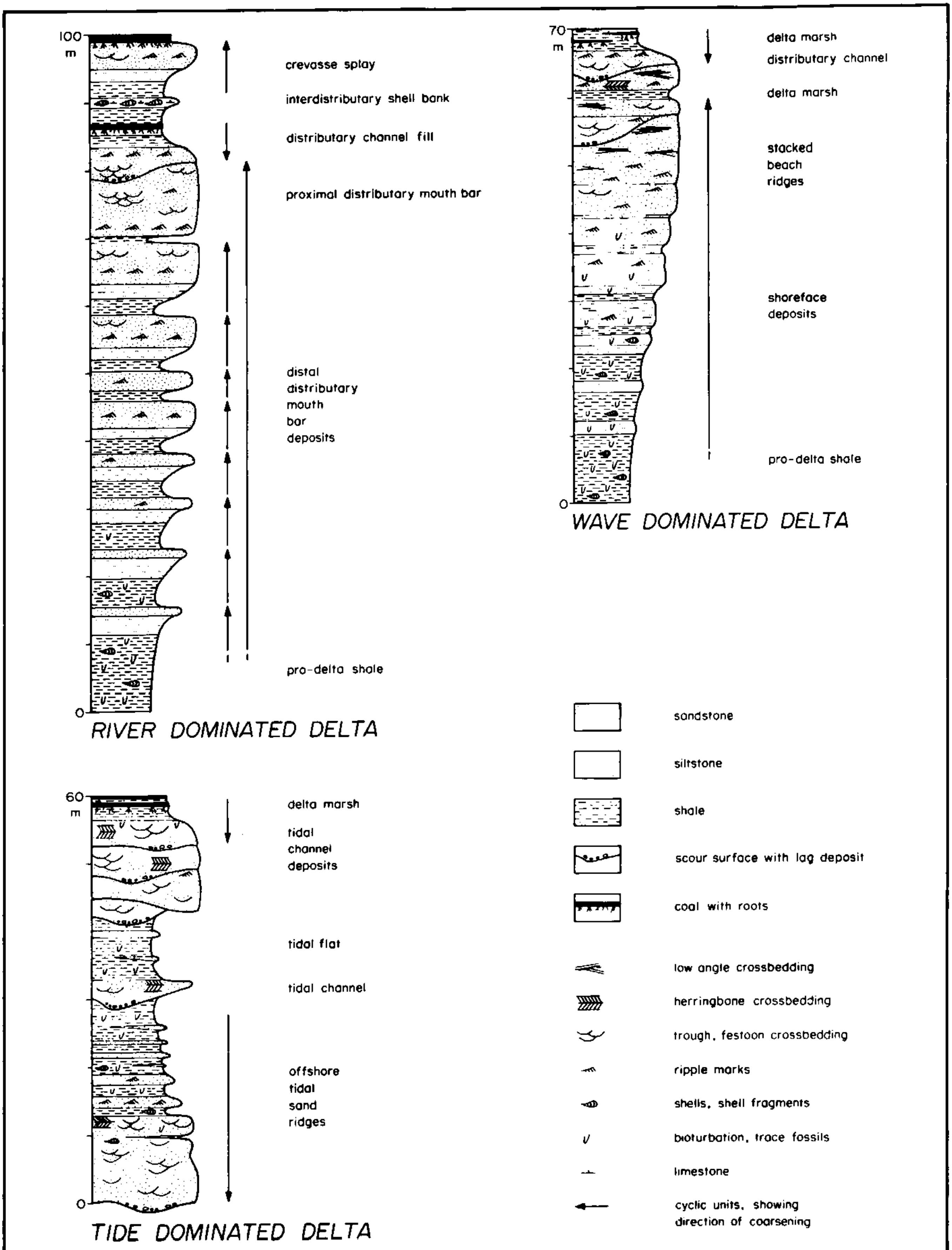

Figure 10
Generalized stratigraphic sections through the three principal types of delta. The stratigraphic order of the various facies types is more or less constant, but their thickness and relative abundance varies markedly from one example to another.

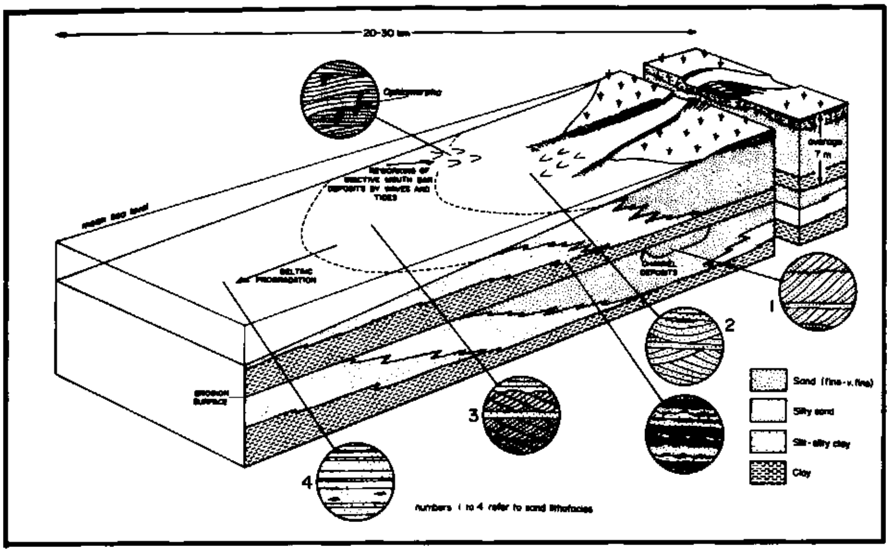

Figure 11
Lateral variability in distributary-mouth sheet sands, Eureka Sound Formation (Tertiary), Banks Island, Arctic Canada (from Miall, in prep.).

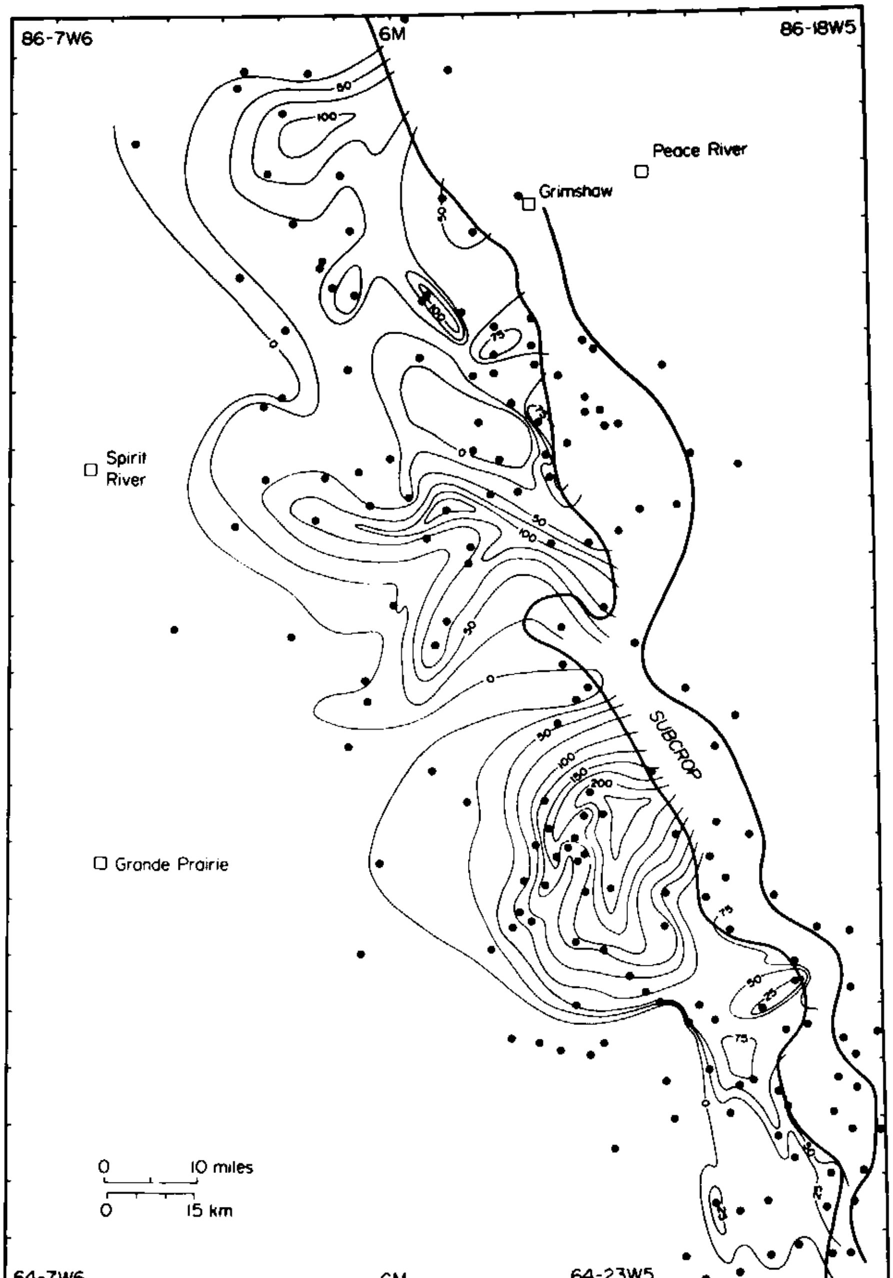

Figure 12
Delta lobes in a member of the Triassic Toad-Grayling Formation, northwestern Alberta. Contours show the distribution of net porous section, in feet. Map location is given by township and range. From an unpublished subsurface study by Miall.

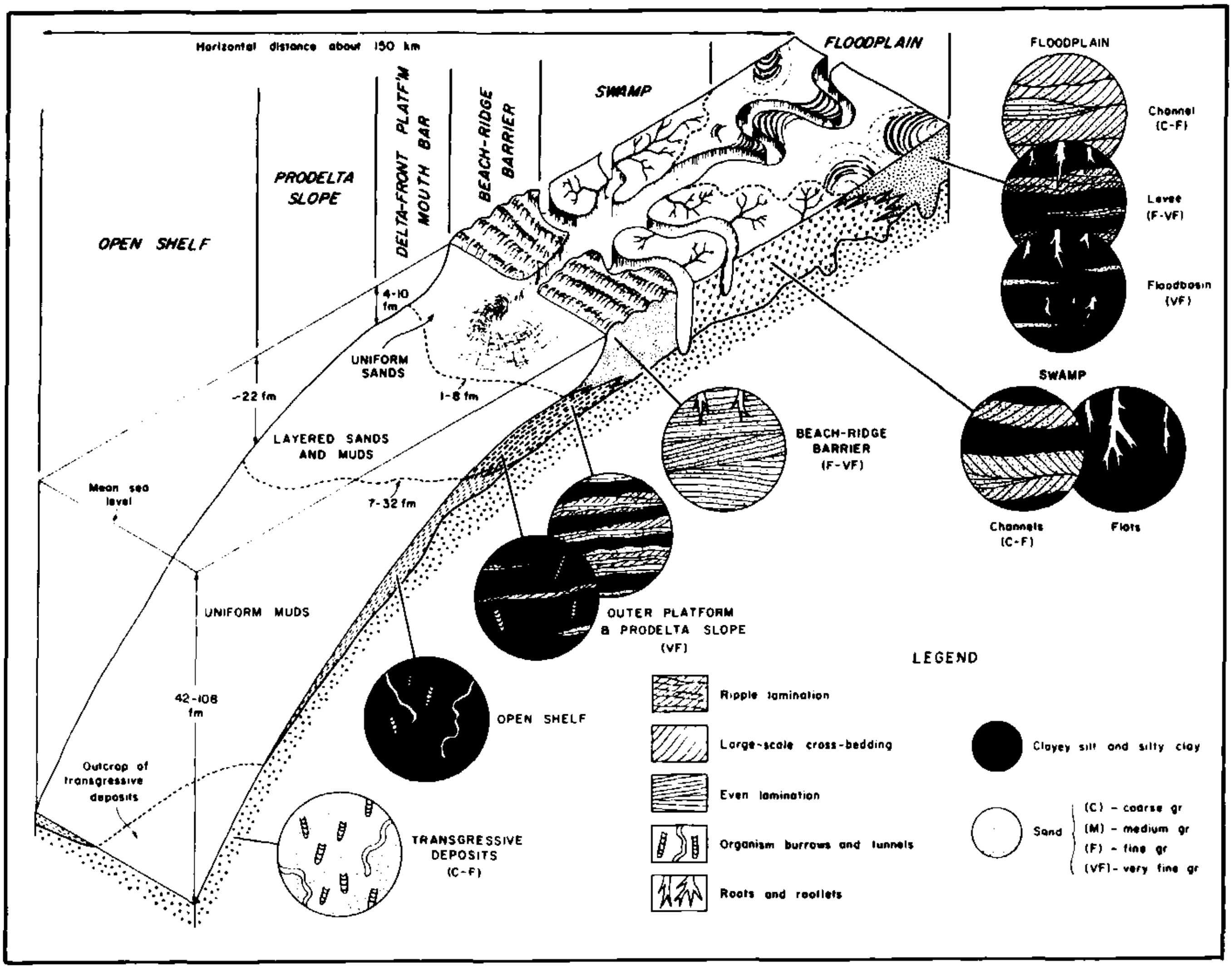

Figure 13
Depositional environments in the modern Niger delta (from Allen, Figure 4, in Morgan 1970a).

Bibliography

1. Primary reference list

Treatment of deltas in sedimentological textbooks tends to be sketchy, and the Mississippi is over-emphasized. The papers listed below are "all you really need", especially those in Broussard (1975) and Fisher *et al.* (1969), in which sedimentation models and ancient and modern examples are fully covered.

Broussard, M. L., *ed.*, 1975. Deltas, *models for exploration: Houston Geol.* Soc., 555 p.

Papers on process variability and delta classification by Galloway and by Coleman and Wright and a historical survey by Leblanc are the most useful contributions.

Curtis, D. M., J. R. Duncan, and D. S. Gorsline, (organizing committee) 1975. Finding and exploring ancient deltas in the subsurface: Amer. Assoc. Petrol. Geol., Marine Geology Committee workshop, Introductory papers and notes.

Useful papers on interpretations from geophysical logs and seismic data.

Fisher, W. L., L. F. Brown, Jr., S. J. Scott, and J. H. McGowen, 1969. Delta Systems in the exploration for oil and gas: Bureau Econ. Geol., Texas.

Modern and ancient deltas are described and classified. The abundant illustrations are particulary useful.

Morgan, J. P., *ed.*, 1970a. Deltaic sedimentation, modern and ancient: Soc. Econ. Paleont. Mineral. Spec. Publ. 15, 312 p.

A somewhat mixed bag of papers, but including much data unavailable elsewhere, including reviews of the Niger (Allen) and Rhône (Oomkens) deltas and a description of a tidal delta (Coleman *et al.*).

Smith, A. E. and M. L. Broussard, 1971. Deltas of the world: modern and ancient - bibliography: Houston Geol. Soc.

2. Secondary reference list

Much important information is contained in the following references, but most are specialized in scope and can be passed over by the beginner.

Barrell, J., 1912, Criteria for the recognition of ancient delta deposits: Geol. Soc. Amer. Bull., v. 23, p. 377-446.
Classic delta paper dealing with the Devonian Catskill complex.

Bates, C. C., 1953, Rational theory of delta formation: Amer. Assoc. Petrol. Geol. Bull., v. 37, p. 2119-2162.
The first description of flow dispersal patterns at river-mouths.

Coleman, J. M., and S. M. Gagliano, 1964, Cyclic sedimentation in the Mississippi river deltaic plain: Gulf Coast Assoc. Geol. Soc. Trans., v. 14, p. 67-80.

Coleman, J. M., and S. M. Gagliano, 1965, Sedimentary structures: Mississippi River deltaic plain: *in* G. V. Middleton, *ed.*, Primary sedimentary structures and their hydrodynamic interpretation: Soc. Econ. Paleaont. Mineral. Spec. Publ. 12, p. 133-148.
Two important papers on sediments and sedimentary processes in a river-dominated delta.

Elliott, T., 1974, Interdistributary bay sequences and their genesis: Sedimentology, v. 21, p. 611-622.
A series of vertical profiles for recognizing some of the minor subenvironments in river-dominated deltas.

Fisher, W. L., and J. H. McGowen, 1967, Depositional systems in the Wilcox Group of Texas and their relationship to occurrence of oil and gas: Gulf Coast Assoc. Geol. Soc. Trans., v. 17, p. 287-315.
Detailed regional subsurface study.

Morgan, J. P., 1970b, Deltas - a résumé: Jour. Geol. Education, v. 18, p. 107-117.
Brief historical summary of the development of the delta concept and a résumé of sedimentary processes in the Mississippi delta.

Off, T., 1963, Rhythmic linear sand bodies caused by tidal currents: Amer. Assoc. Petrol. Geol. Bull., v. 47, p. 324-340.
Characteristic structures found in front of tide-dominated deltas.

Oomkens, E., 1974, Lithofacies relations in the Late Quaternary Niger Delta complex: Sedimentology, v. 21, p. 195-222.
Supplements Allen's work.

Shepard, F. P., F. B. Phleger, and T. H. Van Andel, *eds.*, 1960, Recent *sediments, Northwest Gulf of Mexico,* 1951-1958: Amer. Assoc. Petrol. Geol., 394 p.
The results of API Project 51. See especially papers by F. P. Shepard and P. C. Scruton. The latter was the first to describe the delta cycle.

Shirley, M. L., *ed.*, 1966, Deltas and their geologic framework: Houston Geol. Soc.
The first Houston compilation, now a little dated.

Wright, L. D., J. M. Coleman, and M. W. Erickson, 1974, Analysis of major river systems and their deltas: morphologic and process comparisons: Coastal Studies Institute, Lousiana State University, Technical Report No. 156.
A study of 34 modern alluvial-deltaic systems using multivariate statistical techniques.

3. Modern Canadian deltas

Investigations in this area are rather patchy. The Fraser delta seems to have received the most attention.

Johnson, W. A., 1921, Sedimentation of the Fraser River delta: Geol. Surv. Can., Mem. 125, 46 p.

Johnson, W. A., 1922, The character of the stratification of the sediments in the recent delta of the Fraser River, British Columbia, Canada: Jour. Geol. v. 30, p. 115-129.
Important early papers on deltaic sedimentation.

Kellerhals, P., and J. W. Murray, 1969, Tidal flats at Boundary Bay, Fraser River delta, British Columbia: Can. Petrol. Geol. Bull., v. 17, p. 67-91.
Surface geology, including description of sediments, bedforms, flora and fauna.

Luternauer, J. T., and J. W. Murray, 1973, Sedimentation of the western delta-front of the Fraser River, British Columbia: Can. Jour. Earth Sci., v. 10, p. 1642-1663.
Sedimentology of the intertidal and shallow subtidal portion of the delta.

Mackay, J. R., 1963, The Mackenzie delta area, Northwest Territories: Geol. Surv. Can., Geographical Branch, Mem. 8 (Reprinted 1974 as Geol. Surv. Can., Misc. Rept. 23).
Concerned primarily with physical geography.

Mathews, W. H., and F. P. Shepard, 1962, Sedimentation of Fraser River delta, British Columbia: Amer. Assoc. Petrol. Geol. Bull., v. 46, p. 1416-1438.
Physiography, submarine surface geology, growth rate of modern delta.

Pezzetta, J. M., 1973, The St. Clair River Delta: sedimentary characteristics and depositional environments: Jour. Sediment Petrol., v. 43, p. 168-187.
Investigations mainly on U.S. side of delta. Factor analysis and trend surface analysis help discriminate subenvironments in a small, lacustrine birdsfoot delta.

Smith, N. D., 1975, Sedimentary environments and late Quaternary history of a "Low energy" mountain delta: Can. Jour. Earth Sci., v. 12, p. 2004-2013.
A small modern delta in a freshwater lake in Banff National Park, investigated with the use of auger sampling. Silts and clays predominate but bar-finger channel gravels are also present.

4. Ancient deltaic deposits in Canada

Deltaic deposits are particularly abundant in the Jurassic-Paleogene of the Western Interior, but detailed regional sedimentological studies are sparse. Atlantic Canada appears to be the only major region of the country which lacks any important deltaic deposits.

A. Cordilleran region

Eisbacher, G. H., 1974a, Deltaic sedimentation on the northeastern Bowser Basin, British Columbia: Geol. Surv. Can., Paper 73-33.
Brief facies description of river-dominated delta of Jurassic-Cretaceous age in a successor basin.

Eisbacher, G. H., 1976, The successor *basins of the western Cordillera:* GSC Paper 76-1, Part A., p. 113-116.
More field data from Bowser Basin (*see* Eisbacher, 1974a).

Jeletzky, J. A., 1975, Hesquiat Formation (new), a neritic channel and inter-channel deposit of Oligocene age, western Vancouver Island, British Columbia: Geol. Surv. Can. Paper 75-32.
A shallow-water marine fan deposit.

Muller, J. E. and M. E. Atchison, 1971, Geology, history and potential of Vancouver Island coal deposits: Geol. Surv. Can. Paper 70-53.

Muller, J. E. and J. A. Jeletzky, 1970, Geology of the Upper Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia: Geol. Surv. Can. Paper 69-25.
Primarily deals with stratigraphy and biochronology, with two paleogeographic maps. Data in this and the preceeding paper suggest deposition in a wave-dominated delta.

B. Western Interior (Alberta and British Columbia)

Many detailed stratigraphic studies of deltaic rocks are available, but most of these are omitted in the following list. Only those publications which include sedimentological and paleogeographic data are included.

Caldwell, W. G. E., ed., 1975, The Cretaceous system in the western Interior of North America: Geol. Assoc. Canada Spec. Paper 13.
Proceedings of a symposium held at Saskatoon, May 1973. Contains a useful historical paper by K. M. Waage and several excellent stratigraphic-paleogeographic studies.

Carrigy, M. A., 1967, Some sedimentary features of the Athabasca Oil Sands: Sediment. Geol., v. 1, p. 327-352.
Illustrations of sedimentary structures.

Carrigy, M. A., 1971, Deltaic sedimentation in Athabasca tar sands: Amer. Assoc. Petrol. Geol., v. 55, p. 1155-1169.
A good description of a fresh-water delta using outcrop data and subsurface spontaneous potential and resistivity logs. The distribution of heavy oil is shown to relate to that of the coarsest and most porous sand bodies.

Eisbacher, G. H., M. A. Carrigy, and R. B. Campbell, 1974, Paleodrainage pattern and late-orogenic basins of the Canadian Cordillera: *in* W. R. Dickinson, ed., Tectonics and sedimentation: Soc. Econ. Paleont. Mineral. Spec. Publ. 22, p. 143-166.
A regional summary, including a discussion of the two major foreland basin molasse assemblages (Kootenay-Blairmore; Belly River-Paskapoo).

Gibson, D. W., 1974, Triassic rocks of the southern Canadian Rocky Mountains: Geol. Surv. Can. Bulletin 230.
Some distal deltaic rocks outcrop in the Rocky Mountains but the main belt of deltaic rocks is in the subsurface of central Alberta and has yet to be described (work in preparation by Miall).

Jansa, L. F., 1972, Depositional history of the coal-bearing Upper Jurassic-Lower Cretaceous Kootenay Formation, Southern Rocky Mountains, Canada: Geol. Soc. Amer. Bull., v. 83, p. 3199-3222.
Surface and subsurface facies analysis of coal-bearing deltaic rocks and tidal flat deposits.

Jansa, L. F., and N. R. Fischbuch, 1974, Evolution of a Middle and Upper Devonian sequence from a clastic coastal plain-deltaic complex into overlying carbonate reef complexes and banks, Sturgeon-Mitsue area, Alberta: Geol. Surv. Can., Bull. 234.
Facies analysis based on subsurface geophysical logs and cores. Relationship of cementation to depositional environments.

McLean, J. R., 1971, Stratigraphy of the Upper Cretaceous Judith River Formation on the Canadian Great Plains: Sask. Research Council, Geology Division, Rept. No. 11.
Primarily a stratigraphic and petrographic study, but with illustrations of sedimentary stuctures and an environmental interpretation of one fully cored borehole.

Mellon, G. B., 1967, Stratigraphy and petrology of the Lower Cretaceous Blairmore and Mannville Groups, Alberta Foothills and Plains: Research Council Alberta, Bull. 21.
Mainly a stratigraphic and petrologic study, with brief description of sedimentary cycles.

Mellon, G. B., J. W. Kramers, and E. G. Seagel, eds., 1972, Proceedings first geological conference on western Canadian coal: Research Council Alberta, Inf. Series No. 60.
Concerned mainly with stratigraphy and coal petrography, but contains a useful paper on the Early Cretaceous Gething Delta of B.C. by D. F. Stott.

Shawa, M. S., 1969, Sedimentary history of the Gilwood sandstone (Devonian) Utikuma Lake area, Alberta, Canada: Can. Petrol. Geol. Bull., v. 17, p. 392-409.
A detailed local core study with a discussion of sedimentary structures, grainsize distributions and limited paleocurrent data derived from oriented core.

Shawa, M. S., ed., 1975, Guidebook to selected sedimentary environments in southwestern Alberta, Canada: Can. Soc. Petrol. Geol. Field Conference 1975.
An illustrated guide to several Cretaceous outcrop sections, including several well-exposed deltaic sequences.

Shepheard, W. W., and L. V. Hills, 1970, Depositional environments, Bearpaw-Horseshoe Canyon (Upper Cretaceous) transition zone, Drumheller "Badlands", Alberta: Can. Petrol. Geol. Bull., v. 18, p. 166-215.
Detailed local sedimentological study based on surface mapping.

C. Western Interior (Yukon and Northwest Territories)

Bowerman, J. N., and R. C. Coffman, 1975, The geology of the Taglu gas field in the Beaufort Basin, N.W.T.: *in* C. J. Yorath, E. R. Parker and D. J. Glass, eds., Canada's continental margins and offshore petroleum exploration: Can. Soc. Petrol. Geol., Mem. 4, p. 649-662.
Brief description of subsurface stratigraphy of Tertiary, gas-bearing deltaic rocks.

Holmes, D. W., and T. A. Oliver, 1973, Source and depositional environments of the Moose Channel Formation, Northwest Territories: Can. Petrol. Geol. Bull., v. 21, p. 435-478.
Deltaic and fluvial facies are described. Emphasis on grainsize distributions using factor analysis and probability plots.

Myhr, D. W. and F. G. Young, 1975, Lower Cretaceous (Neocomian) sandstone sequence of Mackenzie Delta and Richardson Mountains area: Geol. Surv. Can. Paper 75-1, Part C. p. 247-266.
Regional subsurface facies reconstruction, with some core illustrations.

Young, F. G., 1973, Mesozoic epicontinental, flyschoid and molassoid depositional phases of Yukon's north slope: *in* J. D. Aitken and D. J. Glass, eds., Proc. Symp. Geology of the Canadian Arctic: Geol. Assoc. Can. and Can. Soc. Petrol. Geol., p. 181-202.

Young, F. G., 1975, Upper Cretaceous stratigraphy, Yukon coastal plain and northwestern Mackenzie Delta, Geol. Surv. Can., Bull. 249.
Alluvial, deltaic and littoral facies are described but little detailed information is available regarding the interrelationships of these facies.

D. Innuitian region

Agterberg, F. P., L. V. Hills, and H. P. Trettin, 1967, Paleocurrent trend analysis of a delta in the Bjorne Formation (Lower Triassic) of northwestern Melville Island, Arctic Archipelago: Jour. Sed. Petrol., v. 37, p. 852-862.
Application of a trend-analysis smooths out irregularities and reveals a fan-shaped deltaic dispersal system. (*See* also Trettin and Hills, 1966).

Dineley, D. L. and B. R. Rust, 1968, Sedimentary and paleontological features of the Tertiary-Cretaceous rocks of Somerset Island, Arctic Canada: Can. Jour. Earth Sci., v. 5, p. 791-799.
Facies analysis and paleocurrents of a small remnant of a deltaic succession.

Embry, A. F., III, 1976, Middle-Upper Devonian clastic wedge of the Franklinian Geosyncline: Univ. Calgary, Unpublished Ph. D. Thesis.
A detailed regional stratigraphic and sedimentological study.

Miall, A. D., 1970, Continental-marine transition in the Devonian of Prince of Wales Island, Northwest Territories: Can. Jour. Earth Sci., v. 7, p. 125-144.
Part of the facies spectrum includes thin deltaic redbeds interbedded with marine shales and carbonates. Brief description of sedimentary structures and fossils.

Miall, A. D., in prep., Sedimentary structures and paleocurrents in a Tertiary deltaic succession, Northern Banks Basin, Arctic Canada.
Facies analysis of a river-dominated delta system. Gross geometry of delta lobes can be outlined from scattered outcrop data.

Roy, K. J., 1973, Isachsen Formation, Amund Ringnes Island, District of Franklin: Geol. Surv. Can., Paper 73-1, Part A, p. 269-273.

Roy, K. J., 1974, Transport directions in the Isachsen Formation (Lower Cretaceous), Sverdrup Islands, District of Franklin: Geol. Surv. Can., Paper 74-1, Part A, p. 351-353.
Brief facies descriptions. Paleocurrent patterns suggest a fan-shaped deltaic dispersal system.

Trettin, H. P. and L. V. Hills, 1966, Lower Triassic tar sands of north-western Melville Island, Arctic Archipelago, Geol. Surv. Can. Paper 66-34.
Stratigraphy, petrography, sedimentary structures and paleocurrents, plus descriptions of tar deposits.

Young, G. M., 1974, Stratigraphy, paleocurrents and stromatolites of Hadrynian (Upper Precambrian) rocks of Victoria Island, Arctic Archipelago, Canada: Precamb. Research, v. 1, p. 13-41.

Young, G. M. and C. W. Jefferson, 1975, Late Precambrian shallow water deposits, Banks and Victoria Islands, Arctic Archipelago: Can. Jour. Earth Sci., v. 12, p. 1734-1748.
Brief facies descriptions and paleocurrent analysis of deltaic rocks interbedded with tidal sequences.

E. Appalachian-St. Lawrence Lowlands region

Lumsden, D. N. and B. R. Pelletier, 1969, Petrology of the Grimsby sandstone (Lower Silurian) of Ontario and New York: Jour. Sediment. Petrol., v. 39, p. 521-530.
Grainsize and petrographic summary of a deltaic sandstone.

Martini, I. P., 1971, Regional analysis of sedimentology of Medina Formation (Silurian), Ontario and New York: Amer. Assoc. Petol. Geol., v. 55, p. 1249-1261.
Sedimentary petrography, paleocurrent analysis (including grain orientation) and sedimentary structures in a deltaic-tidal flat-longshore bar complex. Interpretations are strictly two dimensional because data were derived solely from outcrops along the nearly straight Niagara escarpment.

Martini, I. P., 1974, Deltaic and shallow marine sediments of the Niagara Escarpment between Hamilton, Ont. and Rochester, N.Y., - a field guide: Maritime Sediments, v. 10, p. 52-66.

F. Canadian Shield

Very few of the sedimentary rocks in the Shield have been studied sedimentologically. Many clastic units are described in the literature as being of "shallow-marine" origin, and many of these probably are deltaic rocks.

Donaldson, J. A., 1965, The Dubawnt Group, Districts of Keewatin and Mackenzie: Geol. Surv. Can., Paper 64-20.
Deltaic and fluvial rocks - brief description and paleocurrent analysis.

Hoffman, P. F., 1969, Proterozoic paleocurrents and depositional history of the East Arm Fold Belt, Great Slave Lake, Northwest Territories: Can. Jour. Earth Sci., v. 6, p. 441-462.

Palonen, P. A., 1973, Paleogeography of the Mississagi Formation and Lower Huronian cyclicity: *in* G. M. Young, Huronian stratigraphy and sedimentation: Geol. Assoc. Can. Spec. Paper 12, p. 157-168.
Deltaic cycles and paleocurrents.

MS received May 18, 1976.