Fan-deltas and braid deltas: Varieties of coarse-grained deltas

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ABSTRACT

Two types of coarse-grained deltas are recognized: fan-deltas and braid deltas. Fan-deltas are gravel-rich deltas formed where an alluvial fan is deposited directly into a standing body of water from an adjacent highland. They occupy a space between the highland (usually a fault-bounded margin) and the standing body of water. In contrast, *braid deltas* (here introduced) are gravel-rich deltas that form where a braided fluvial system progrades into a standing body of water. Braid deltas have no necessary relationship with alluvial fans, as exemplified by fluvioglacial braid deltas. Braid deltas have previously been classified as fan-deltas even though the geomorphic and sedimentologic settings of the two systems can be vastly different. Braid deltas are a common present-day geomorphic feature and are abundant in the geological record.

Fan-deltas and braid deltas can be distinguished in the rock record by distinctive subaerial components of these depositional systems; the shoreline and subaqueous components of both are similar. Fan-delta sequences have a subaerial component that is an alluvial-fan facies comprising interbedded sheetflood, debris-flow, and braided-channel deposits. Fan-deltas produce small (a few tens of square kilometres), wedge-shaped bodies of sediment, commonly displaying high variability in paleocurrent patterns and abrupt changes in facies. The deposits are generally very coarse grained (with large outsized clasts), very poorly sorted, matrix-rich, polymictic, heterolithic, partially cemented by penecontemporaneous carbonate, and have low porosity and permeability. Braid-deltas, in contrast, have a subaerial component consisting entirely of braided-river or braidplain facies. Their deposits display better sorting, roundness, and clast orientation than do fan-delta sediments; they lack a muddy matrix; they display size grading and bar migration; they commonly have a sheet geometry with high lateral continuity (tens to hundreds of square kilometres); and they exhibit moderate to high porosity and permeability. Valuable paleogeographic and tectonic information concerning the proximity of highlands and major fault zones may be misinterpreted or lost if these two coarse-grained deltaic systems are not differentiated.

INTRODUCTION

The purpose of this paper is to describe the geomorphic and sedimentologic characteristics of the principal types of coarse-grained deltas and, by doing so, illustrate and correct the current problem with the terminology of coarse-grained deltas. This has important implications for facies modeling, tectonic assessment, and hydrocarbon exploration and production.

Coarse-grained (dominantly gravel and coarse sand) deltas (fan-deltas,* Holmes, 1965; short-headed deltas, Flores, 1975; or fjord-deltas, Kostaschuk, 1985) have been widely quoted and invoked in the recent sedimentologic literature. The current interest stems largely from their potential as hydrocarbon reservoirs, with examples in such high-interest exploration targets as the North Sea (Harms and others, 1981; Kessler and Moorhouse, 1984) and the North Slope of Alaska (Melvin and Knight, 1984; McGowen and Bloch, 1985). Recently, questions have been raised concerning usage of the term "fan-delta," as well as recognition of depositional facies and related processes of fan-deltas and coarse-grained deltas in general (Postma and Ori, 1984; McPherson and others, 1986). We believe that there has been a broadening of the definition of fan-delta to the point of confusion over its meaning and sedimentologic implications. The term "fan-delta" is widely used to describe depositional settings embracing a range of coarse-grained delta types other than that of the fan-delta originally described by Holmes (1965). Many descriptions in the literature of ancient fan-delta sequences contain no evidence of the required presence of an alluvial fan; instead they consist of deltaic deposits comprising multilateral channel conglomerates and sandstones deposited from braided fluvial distributaries. It is important to clearly separate fan-deltas from other coarse-grained deltas in order to establish specific depositional and tectonic settings which may be utilized to predict facies and facies sequences.

Coarse-grained deltas comprise two major types, namely those formed from the progradation of an alluvial fan into a standing body of water (fan-deltas), and those deltas formed by the progradation of a braided river into a standing body of water (*braid deltas*). Coarse-grained deltas are distinguished from other deltas (the so-called "fine-grained deltas") principally by their coarse sediment size (mostly gravel and coarse sand). The independent variable of grain size is an important characteristic of deltas that has not been accommodated within the generally accepted classification schemes for deltas (see Fisher and others, 1969, and Galloway, 1975, for the classifications).

THE TERMINOLOGY PROBLEM

Holmes (1965) defined a fan-delta as an alluvial fan prograding directly into a standing body of water from an adjacent highland. Despite Holmes' clear geomorphic description of a fan-delta, it is apparent from a literature survey of the subject that his definition has been interpreted in widely differing ways. The AGI *Glossary of Geology* (Bates and Jackson, 1980) defines a fan-delta as "a gently sloping alluvial

*In this paper, the term "fan-delta" is hyphenated.

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deposit produced where a mountain stream flows out onto a lowland." Clearly this definition is both inadequate and misleading; it makes no mention of the fundamental characteristic of fan-deltas—that they comprise an alluvial fan deposited into standing water.

Many workers have made the direct association of coarse-grained, bedload-dominated, deltaic sedimentation with fan-deltas (McGowen, 1971; Erxleben, 1975; Galloway, 1976; Schumm, 1981; Vos, 1981; Hayes and Michel, 1982; Galloway and Hobday, 1983; Postma and Roep, 1985). Galloway and Hobday (1983) defined a fan-delta as forming "where braided rivers build into a standing body of water, and show a variable degree of peripheral modification." This definition removes any necessary association of a fan-delta with an alluvial fan and thus eliminates the very valuable diagnostic element of fan-deltas: that they are deposited immediately adjacent to a highland region (usually a fault-bounded margin) and occupy a relatively narrow space between the highland and a standing body of water. We consider that this broadening of the usage of the term "fan-delta" to include all braided-river deposits in a deltaic setting is unnecessary and incorrect, and it is the principal source of confusion in the literature.

Nilsen (1985) suggests that the term "fan-delta" is principally reserved for fan-shaped deltaic deposits, regardless of their source or character. Nilsen (1985) stated: "fan deltas are fan-shaped deltas built by rivers into standing bodies of water without the presence of either an adjacent highland or steep slopes." A fan-shaped delta, however, can be a product of many factors—for example, wave and current reworking. In fact, the very term "delta" comes from a comparison of the fan-shaped Nile delta with the Greek character Δ. Fan-deltas are usually fan shaped, but not all fan-shaped deltas are fan-deltas. The plan-view shape of a delta should not be the *sole* criterion by which to define a fan-delta.

Some of the early interpretations illustrated the general case of a fan-delta encompassing an alluvial fan with an associated, downdip braided-river system (Brown and others, 1973, their Fig. 9; Brown and Fisher, 1977). This view of a fan-delta system has subsequently been widely employed. Sykes and Brand (1976) recognized the potential dangers of such an interpretation and stressed the importance of restricting the meaning of the term "fan-delta" to its original definition. They noted that there are significant differences in the processes and deposits of deltaic systems involving (1) alluvial fans prograding directly into a standing body of water and (2) braided rivers prograding into a standing body of water.

Rust (1979), Hayward (1983), and Rust and Koster (1984) have suggested the term "coastal alluvial fan" as a substitute name for fan-delta on the basis of the fluvial dominance of fan-delta systems. We suggest that the term "delta" is simply a reference to the outbuilding of a shoreline directly related to a sediment input, regardless of the degree of basinal influences. The typically deltaic features of the shoreline zone of deltas, caused by reworking from waves and longshore currents, characterize many fan-deltas (and braid deltas) (Hayes and Michel, 1982;

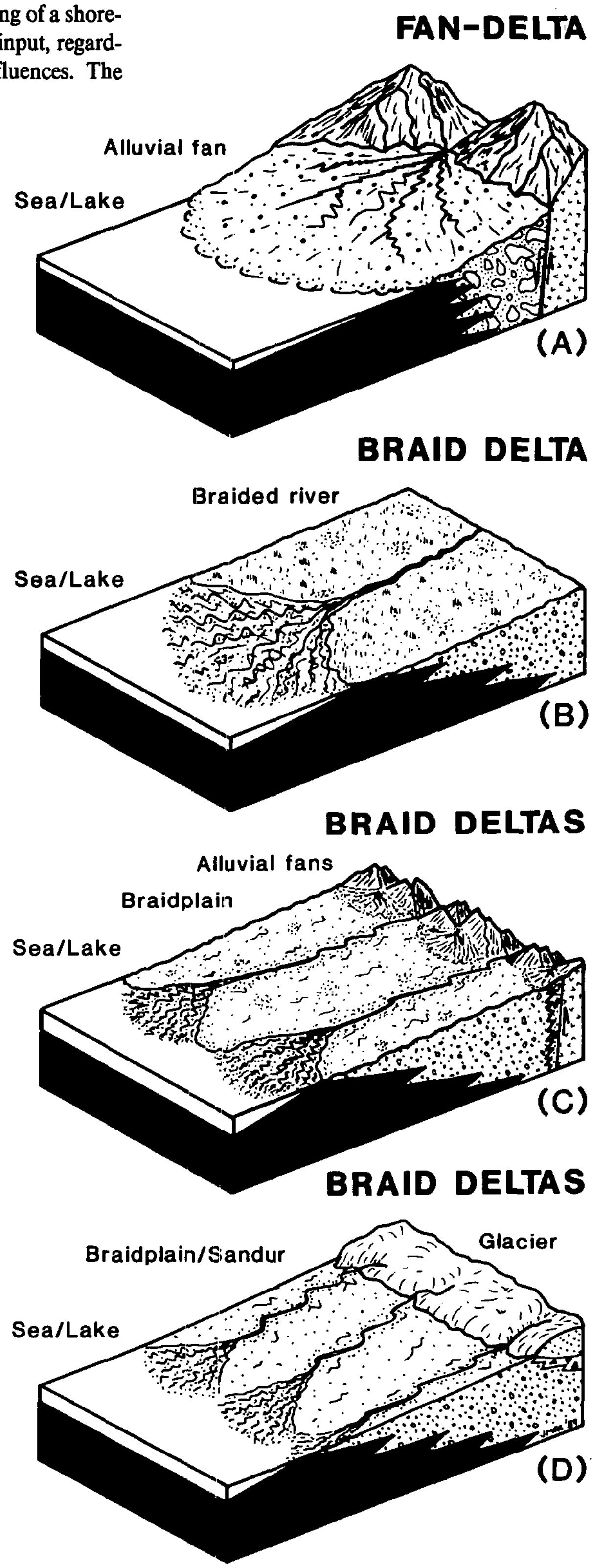

Figure 1. Schematic models to illustrate the depositional settings of the two coarse-grained delta types, including (A) a fan-delta; (B) a braid delta that had its source in distant mountainous uplands; (C) coalescing braid deltas related to an extensive braidplain developed downslope of, but not necessarily related to, mountain-front alluvial fans; and (D) coalescing braid deltas of fluvioglacial outwash plain (sandur) origin.

Figure 2. A fan-delta developed along an active fault scarp fronting the Sierra de los Cocopah and bordering the east side of Laguna Salada, northeast Baja California, Mexico. At the time the photograph was taken, Laguna Salada was at a low level, exposing a playa flat at the toe of the delta. Former shorelines are marked by lines of vegetation and ridges of beach sands and gravels rimming the base of the fan. Note the vehicle tracks in the lower center of the photograph for scale. (Photograph by Peter Kresan, 1978.)

Hayward, 1985; Link and others, 1985), and the subaqueous components display many deltaic characteristics (Pollard and others, 1982; Ethridge and Wescott, 1984; Postma, 1984). We suggest that the term "delta" is appropriate and should be retained.

One of the most widely cited examples of a fan-delta is the Gum Hollow delta in Nueces Bay, Texas (McGowen, 1971). It is a small (a few hundred metres across), artificially created, non-graveliferous delta that lacks an alluvial fan and is disproportionately affected by marine processes. Although it provides an analogy for high sand-load, fluvial-dominated deltas, it does not represent the processes or deposits of fan-deltas because of the vastly different geomorphic setting and grain size of natural fan-deltas.

In accordance with the application of the term "fan-delta" by the first workers in the field (Holmes, 1965; Sykes and Brand, 1976), we suggest that any definition should imply the intimate association of the elements of both alluvial fans and deltas. We re-emphasize the original definition by suggesting that a fan-delta comprises an alluvial fan that is deposited *directly* into a standing body of water, be it the ocean, a sea, or a lake (Figs. 1A and 2). Fan-deltas are deposited immediately adjacent to a highland region (usually a fault-bounded margin) and occupy a relatively narrow space between the highland and a standing body of water. A fan-delta is composed of a subaerial component, which is an alluvial fan, and a subaqueous component (including a reworked, beach zone). The characteristics of the subaqueous component will depend principally upon the interplay of river-mouth processes and numerous conditions of the basin, such as wave energy, tidal flux, littoral currents, basinal subsidence, and tectonic setting. Although this concept of a fan-delta is commonly invoked at the outset of publications dealing with ancient fan-delta systems, it is rarely applied with any rigor.

BRAID DELTAS

The broadening of the term "fan-delta" is a consequence of the need for a term to describe coarse-grained (gravel-rich) deltas whose upper and lower delta plain is composed of braided fluvial distributaries. An assumption, commonly made on the grounds of the coarseness of grain size and the braided-channel pattern, is that these systems are part of an alluvial fan, albeit the distal margins. For several reasons, this basic assumption can be invalid. First, braided rivers or braidplains may have no association whatsoever with an alluvial fan, as exemplified by fluvioglacial braided rivers and outwash braidplains (sandurs) such as the Alaskan or Icelandic coast (Gustavson, 1974; Boothroyd, 1976; Boothroyd and Ashley, 1975; Boothroyd and Nummedal, 1978). Secondly, even those braided alluvial plains juxtaposed with alluvial fans are commonly tens or even hundreds of kilometres in length and are not an integral part of the true alluvial-fan complex *sensu stricto.*

It is apparent that there is a type of coarse-grained delta, widely referred to as a "fan-delta," which does not fit the Holmes' (1965) definition of a fan-delta. We suggest that a solution to the ambiguities of the use of the term "fan-delta" is to restrict the term to its original definition and introduce a new term, *braid delta.* Braid delta encompasses all of those coarse-grained deltas composed predominantly of gravel and coarse sand sizes, that are formed by the progradation of a braided fluvial system into a standing body of water (Figs. 1B, 1C, and 1D). The term includes the specific cases of short-headed deltas (Flores, 1975) and fjord-deltas (Kostaschuk, 1985). Braid deltas have no necessary association with alluvial fans, unlike fan-deltas, for which the alluvial fan is a necessary and thereby distinguishing feature.

There are several possible geomorphic settings for braid deltas (Figs. 1B, 1C, 1D, and 3), and all form where a braided fluvial system progrades into a standing body of water. Regardless of the ultimate source of the braided river or braidplain (that is, glacial or non-glacial), the coastal-margin braid-delta deposits are expected to be similar. Braid deltas that develop from the progradation of coastal braidplains or sandurs into a standing body of water are likely to be laterally extensive in a direction normal to stream flow (for example, Figs. 1C and 1D). Specific examples of the types of braid deltas are given later.

CHARACTERISTICS OF COARSE-GRAINED DELTAS

The general sedimentologic characteristics of fan-deltas and braid deltas are summarized in Table 1, and a general comparison with the more common fine-grained deltas is illustrated in Figure 4. As can be seen, there are major differences in lithofacies, geometry, and size. The differences are principally in the subaerial component of fan-deltas and braid deltas; the subaqueous components are likely to be similar (Table 1). The separation of fan-delta and braid delta depositional environments in the rock record therefore depends upon a clear designation of the subaerial component as either of alluvial-

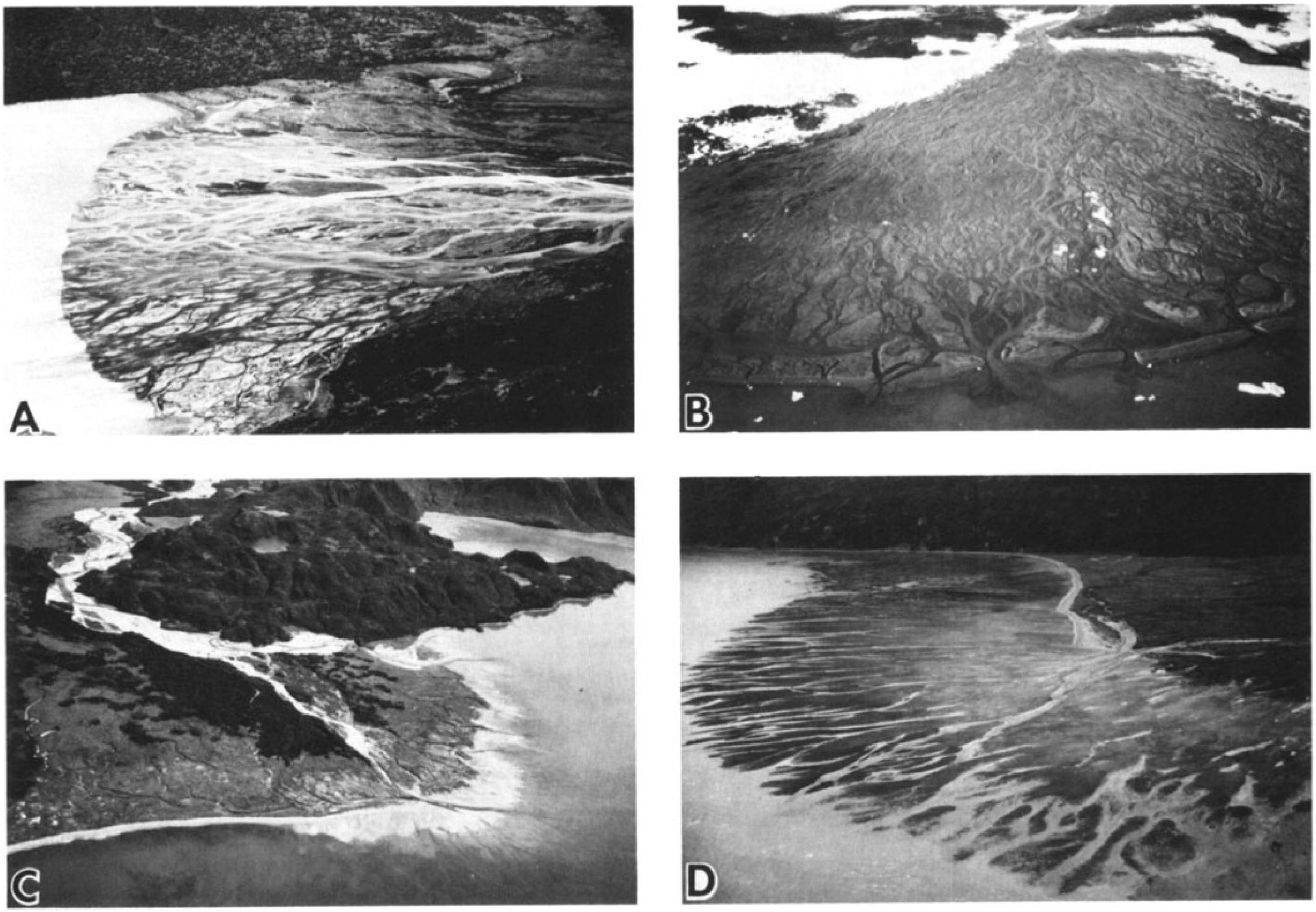

Figure 3. Braid deltas from different settings, including (A) a lacustrine braid delta from Chignik Lake, southeastern coast, Alaska Peninsula; (B) a braid delta from Scoresby Sound, east coast of Greenland, showing well-developed gravelly beaches produced by storm-wave reworking of the delta margin; (C) a braid delta in a macro-tidal inlet on the southeastern coast of the Alaskan Peninsula; and (D) a low-tide view of the braid delta (C), showing drainage channels on the delta margin. (Photographs by R. D. Kreisa: A, C, and D; and M. H. Link: B.)

fan or of braided-river origin. A typical vertical sequence of a prograding fan-delta will comprise a fine-grained basinal facies (marine or lacustrine mudstones) conformably overlain by a coarse-grained alluvial-fan facies (interbedded sheetflood, debris-flow, and stream-channel conglomerates and sandstones). If, however, a thick (tens of metres or more) braided-river, braidplain, or sandur sequence (predominantly channelized conglomerates with sandstone waning-flow beds) separates the basinal facies from the alluvial-fan facies, the sequence may be interpreted as a braid delta.

Subaerial Component of Coarse-Grained Deltas

The separation of alluvial-fan facies from braided-river or braidplain facies in the rock record has been the core of the problem with fan-delta terminology. It has been suggested (Boothroyd and Nummedal, 1978; Kochel and Johnson, 1984) that an end-member, wet-type of alluvial fan (the humid-glacial fan of Kochel and Johnson, 1984) is composed entirely of braided-river facies. Modern analogies given are the fluvioglacial Scott and Yana Rivers of Alaska (Boothroyd, 1972; Boothroyd and Ashley, 1975; Nummedal and Boothroyd, 1976), and the Icelandic sandurs. This being the case, there cannot be any separation of alluvial-fan and braided-river facies in the rock record. As a direct consequence, the term "fan-delta" would have to encompass the progradation of either an alluvial fan or a braided river into a standing body of water.

It is our view (and also suggested by LeBlanc, 1972; Brown and others, 1973; Rust, 1978 and 1979; Kerr, 1984; Rust and Koster, 1984; Amajor, 1986), however, that alluvial-fan sequences can and should be distinguished from braided-river or braidplain sequences. Alluvial fans are "conical, lobate or arcuate accumulations of mostly coarse-grained sediment, deposited by both water and gravity-induced density flow, and which extend from a mountain front or an escarpment across an adjacent lowland" (Fraser and Suttner, 1986, p. 1). Alluvial fans are distinctive geomorphic features with a relatively restricted size (generally less than 10 km in radial extent) and slope (1–5 degrees) (Anstey, 1965) that clearly distinguishes them from purely braided-river and other alluvial-plain systems (Fig. 5). The sedimentologic characteristics of alluvial fans are also distinctive (see the discussion of the subaerial component of coarse-grained deltas).

The fluvioglacial system does not provide a comparative model for a true alluvial-fan depositional environment because of the very

TABLE 1. GENERALIZED CHARACTERISTICS OF FAN-DELTAS AND BRAID DELTAS

Characteristics		Fan-delta	Braid delta
Tectonic setting		Active (synorogenic)	Active and passive
Physiographic setting		Fault blocks, mountain fronts, and volcanic highlands	Braided rivers, braidplains, and fluvioglacial outwash
Paleocurrents		Semi-radial and complex	Unimodal and simple
Depositional environments and processes	Subaerial	Sediment gravity flows Debris flows Mudflows Landslides Transitional flows* Streamflows (confined and nonconfined) Sheetflood	Streamflows Braided channels Sheetflood (minor)
	Subaqueous	Marine and lacustrine Tides Waves Density flows Sediment gravity flows Suspension settling	
Subaerial lithofacies		Conglomerates and breccias (clast- and matrix-supported) Sandstones (minor) Mudstones (mudflows) G_{ms}, G_m, G_h (minor G_t, G_p, S_t, S_h, S_p)†	Conglomerates (clast-supported) Sandstones G_m, G_h, G_t, G_p, S_t, S_p, S_h†
Maximum grain size		Boulders and cobbles very common	Boulders and cobbles uncommon
Sorting		Poor, grading uncommon	Moderate–good, grading common
Clast shape		Angular–subrounded	Subrounded–rounded
Subaerial profile		Very steep	Steep–moderate
Facies changes (vertical and lateral)		Complex, numerous, sharp	Simple, few, and gradational
Lateral continuity		Low	Moderate–high
Fossils		Plants, spores, pollen and vertebrates; marine and lacustrine fossils	
Soils and oxidation		Common	Uncommon
Geologic occurrence		Common	Very common
Geometry and size		Wedge and lenticular, tens of km^2 or less	Sheet, up to hundreds of km^2
Reservoir quality		Poor	Good–excellent

Note: data from multiple sources and this study.
*Wells and Harvey (1987); hyperconcentrated streamflow of Pierson and Costa (1984); hyperconcentrated flood-flow of Smith (1986).
†Modified from the lithofacies code of Miall (1978).

different geomorphic and sedimentologic characteristics of each setting. The end member, wet-type alluvial fan based entirely on the glacial outwash analogy is therefore considered to be non-representative of alluvial-fan processes or deposits; it is directly comparable with braided-river or braidplain depositional systems (Rust, 1978 and 1979; Rust and Koster, 1984).

In modern settings where an alluvial fan is juxtaposed with a braided-river or braidplain (Fig. 1C), the fan can be readily separated from the braided fluvial system. The base of the geomorphic unit of the alluvial fan is invariably denoted by a marked slope change, coupled with a loss of the distinctive radial pattern of sediment distribution in the fan. Although these geomorphic features may not be readily discernible in ancient sequences, each depositional system produces distinctive sedimentary characteristics.

Alluvial fans occur immediately adjacent to a highland that is most commonly a major and active fault scarp. The presence of alluvial-fan facies in the rock record is generally taken as direct evidence for the placement of a major active fault zone. This conclusion does not hold true if the identified facies are purely braided-river deposits. In many cases, braided rivers either have no association with fault zones or are found at great distances from them. Therefore, valuable paleotectonic and paleogeographic information is lost if alluvial-fan (and fan-delta) facies are not separated from braided-river (and braid-delta) facies in the stratigraphic record. Further evidence for the importance of separating these facies is demonstrated by the potentially complex interrelationships of the basinal drainage systems associated with many alluvial fans and potential fan-deltas. As pointed out by Rust (1978), most alluvial fans that occur juxtaposed with a braided-river system are not transitional downslope with the river system but are lateral tributaries to it. This is the typical setting in rift and pull-apart basins and in glacial valleys. Although the alluvial-fan and braided-river facies occur side by side, the alluvial fan system is almost entirely controlled from the fan catchment basin, with relatively little control by, or relationship to, the neighboring braided-river system. Erroneous conclusions are likely to be drawn if alluvial-fan and braided-river facies are not clearly separated in the rock record.

Fan-Deltas. Alluvial fans (that is, the subaerial component of fan-deltas) are characterized by coarse-grained sediment, deposited by water (channelized and unchannelized) and sediment-gravity processes (cohesive and noncohesive), very close to a mountain front or escarpment that is commonly an active fault scarp. The processes and deposits of modern and interpreted ancient alluvial fans have been discussed at length (Blissenbach, 1954; Denny, 1965; Hooke, 1967; Bull, 1972, 1977; Rust, 1978; Wasson, 1977, 1979; Nilsen, 1982; Kerr, 1984; Kochel and Johnson, 1984; Rust and Koster, 1984; Fraser and Suttner, 1986; Wells and Harvey, 1987), but little has been written about the vertical and lateral lithofacies associations of alluvial fans (see Blair, 1987). Although there is considerable variability in the relative importance of individual processes and deposits on different types of alluvial fans, there are generalities that can be made. Unconfined flow or sheetflood processes (see Hogg, 1982) are particularly common and characteristic of alluvial fan sedimentation. Confined or channelized-flow is also common but generally involves wide and shallow braided channels where sustained deepwater flow is uncommon. It is for this reason that large-scale migrating bedforms and their resultant cross-stratification are not an abundant facies in many alluvial-fan sequences. Stream-channel and sheetflood deposits can be considered intergradational in most alluvial-fan sequences (Rust and Koster, 1984). They give rise to the most abundant lithofacies of alluvial-fan sequences, which are unbedded (massive) and clast-supported conglomerates (G_m; terminology after Miall, 1978) and horizontally stratified gravel, commonly imbricate (G_h). The abundance of cross-stratified gravels and sands in alluvial-fan sequences (lithofacies G_t, G_p, S_t, and S_p), varies greatly, depending upon fan type and position on the fan with respect to source (Rust and Koster, 1984). Thin, waning-flow interbeds of sandstone (S_h) and mudstone (F_l/F_m) are also common alluvial-fan lithofacies.

Sediment-gravity deposits of both cohesive and noncohesive types are an important and in-

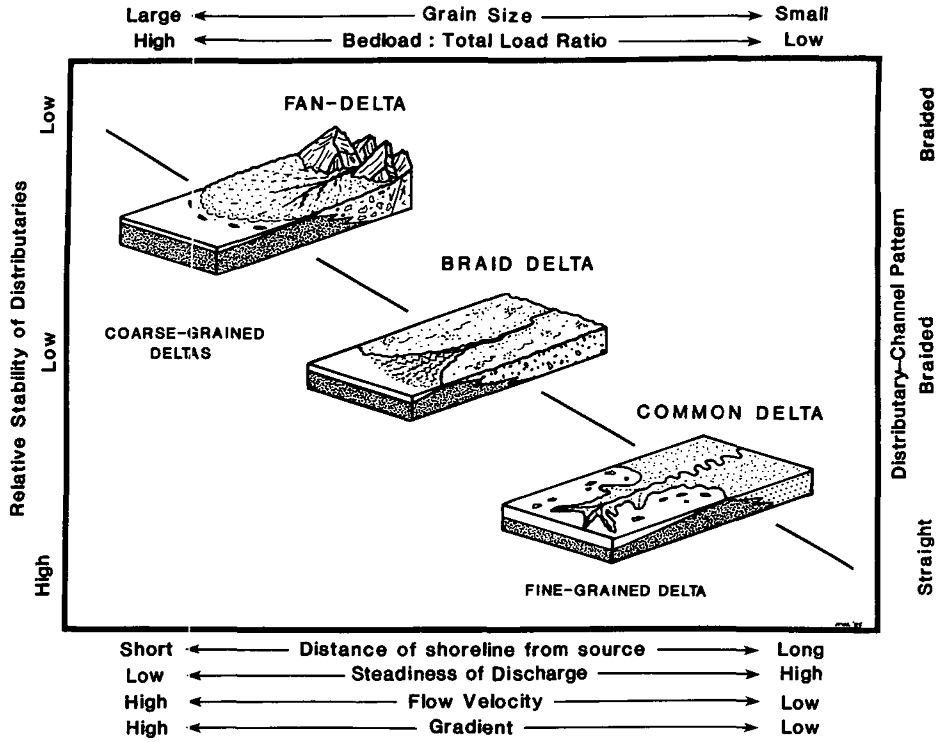

Figure 4. A comparison of fan-deltas, braid deltas, and fine-grained deltas based on distributary-channel patterns and stability, sediment load and size, stream gradient and velocity, and so on. Fan-deltas and braid deltas are "coarse-grained" deltas that contrast in shape, size, and composition with "fine-grained" deltas.

tegral component of alluvial fans and alluvial-fan sequences (Bull, 1972, 1977; Schultz, 1984; Wells and Harvey, 1987). The deposits may include debris flows, debris torrents, debris avalanches, hyperconcentrated floodflows/streamflows (Pierson and Costa, 1984; Smith, 1986), and mudflows (G_{ms}, matrix-supported conglomerates; and G_m, clast-supported conglomerates). Sediment-gravity deposits are generally interbedded with water-laid sediments, and their abundance and character changes both with fan type and position on the individual fan with respect to source (Bull, 1963; Rust, 1978; Kerr, 1984; Rust and Koster, 1984; McPherson and others, 1985). It is the presence of sediment-gravity and sheetflood deposits in alluvial-fan sequences that most readily identifies the sequence as an alluvial fan.

Other diagnostic features of alluvial-fan sequences are that they display considerable vertical and lateral variability of lithofacies. This is a product of the short transport distance from source to basin; the highly irregular, flashy, and often catastrophic nature of the discharge which is typical of all types of alluvial fans; and the consequent highly variable stream-flow power and sediment discharge that occurs on a fan during active sedimentation.

Several penecontemporaneous and post-burial features are also characteristic of alluvial-fan sequences and rare in braided-river or braidplain deposits. Post-depositional infiltration of porous fan gravels by clays is a common and potentially important modifier of alluvial-fan deposits (Walker and others, 1978). Infiltration is usually recognized by the presence of appreciable amounts of interclast clay in otherwise clast-supported conglomerates. The clay plugs interclast pore spaces and directly and indirectly affects cementation. Pedogenic and non-pedogenic carbonate cementation is also a feature of many alluvial-fan deposits, developing as a product of prolonged exposure and weathering on inactive and abandoned fan surfaces (Bull, 1972; Lattman, 1973).

Braid Deltas. Braided-river deposits (that is, the subaerial component of all braid-delta sequences) display marked sedimentologic differences from alluvial-fan deposits (that is, the subaerial component of fan-delta deposits). They show features that result from (1) the highly channelized character of braided rivers and (2) the deeper and more sustained flow of the fluvial system. The deposits of braided-river depositional systems are typified by an abundance of cross-stratification (facies G_t, G_p, S_t, and S_p) and normal size grading of gravel beds (commonly with sandstone caps, lithofacies S_h and S_r) (Boothroyd and Ashley, 1975; Church and Gilbert, 1975; Miall, 1977, 1978; Rust, 1978). These lithofacies and lithofacies assemblages are uncommon in alluvial-fan deposits (Rust, 1978) and, by implication, in fan-delta sequences. Lithofacies G_m and G_h, which are common to both alluvial-fan and braided-river deposits, are distinguished in braided-river sequences by their common association with cross-stratified and graded gravels and sands. Debris flows and mudflows, which are abundant in alluvial-fan sequences, are absent in braided-river deposits. Another important distinction is the high lateral continuity of individual lithofacies in braided-river (and braid-delta) deposits, and again this is in marked contrast to the lensing and interdigitating character of individual lithofacies in alluvial-fan (and fan-delta) sequences. On a larger scale, braided-river deposits commonly produce sheet-like bodies over the length and width of their flood plain, and where unrestricted, as in the case of braidplains, are likely to develop a very extensive (tens to hundreds of square kilometres) sheet geometry. Similarly, braid deltas developed from the progradation of coastal braidplains (Figs. 1C and 1D) will deposit extensive sheet-like bodies. This contrasts markedly with the characteristic wedge shape of alluvial-fan and fan-delta bodies.

Subaqueous and Shoreline Component of Coarse-Grained Deltas

Deltaic sedimentation in general depends upon a complex interplay of fluvial and basinal conditions which include sediment input (rate and type), waves, tides, longshore currents, basinal setting, basinal subsidence rates, and water chemistry. Basinal setting is a particularly important control on those fan-deltas in which the alluvial fan is feeding almost directly to a steep continental slope, as exemplified by the Yallahs fan-delta of Jamaica (Wescott and Ethridge, 1980). The contrast between the processes and deposits of a shelf versus a slope setting for fan-deltas has been discussed by Ethridge and Wescott (1984).

Because coarse-grained deltas are characterized by a high rate of coarse sediment input, it might be expected that they are somewhat less influenced by the basinal processes of waves, tides, and currents than are fine-grained deltas. Hayes and Michel (1982) showed that the shoreline depositional systems of braid deltas (their fan-deltas) on the southeast coast of Alaska reflect primarily the interaction of sediment supply and wave action, producing lobate deltas in sheltered areas and arcuate deltas in areas exposed

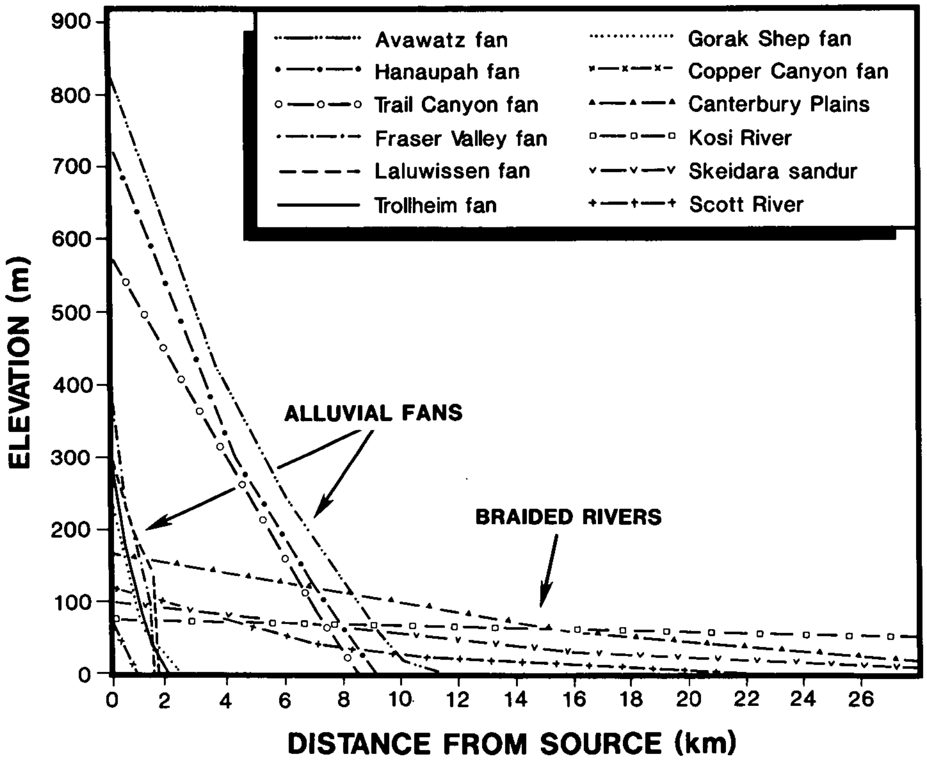

Figure 5. Longitudinal profiles of alluvial fans, and gravelly braided rivers commonly cited as examples of wet-type alluvian fans. The profiles illustrate the marked differences in gradient and size of the two systems. Data sources: Avawatz fan of California (Anstey, 1965); Hanaupah Canyon, Trail Canyon, and Copper Canyon fans of Death Valley, California (Denny, 1965); Fraser Valley and Laluwissen fans of British Columbia (Ryder, 1971); Trollheim and Gorak Shep fans of California (Hooke, 1967); Canterbury Plains of New Zealand (Cotton, 1958); Kosi River of India (Gole and Chitale, 1966); Skeidarásandur of Iceland (Boothroyd and Nummedal, 1978); Scott River of Alaska (Boothroyd and Ashley, 1975).

to storm waves. They observed that tidal influences have a minimal effect on braid deltas. In contrast, Kostaschuk (1985) reported that the main influence of a large tidal range (~4 m) on braid deltas (his fjord-delta) is to change the location of distributary mouths. This directly influences the morphologic development of the delta. Caution should be exercised when comparing the influence of tidal energy and wave energy of coarse-grained and fine-grained deltas because the river mouth morphodynamics are possibly very different. We speculate that the effects of wave- and tidal-energy flux on the shoreline modification of fan-deltas would be less than for braid deltas (given the same input intensity) simply because fan-deltas are commonly coarser grained and better indurated by clay and carbonate cements than are braid deltas.

It has been noted that shoreline-zone deposits are commonly the most critical for the recognition of fan-deltas (and our braid deltas) in the stratigraphic record (Wescott and Ethridge, 1980; Ricci Lucchi and others, 1981; Hayward, 1983, 1985). It is within the shoreline zone that the alluvial-fan or braided-river deposits are modified by marine processes and interfinger with marine or lacustrine deposits (Fig. 3B). Beach facies dominate, and can be separated into, depositional beaches and erosional or abandoned beaches (Wescott and Ethridge, 1980; Ethridge and Wescott, 1984; Hayward, 1985). Spits, bars, back-beach lagoons, and eolian dunes are all common features of the shoreline zone of both fan-deltas and braid deltas.

Studies of the delta-front and delta-slope facies of coarse-grained deltas (Howell and Link, 1979; Wescott and Ethridge, 1980, 1983; Pollard and others, 1982; Ethridge and Wescott, 1984; Kleinspehn and others, 1984; Nemec and Steel, 1984; Postma, 1984; Prior and others, 1984; Hayward, 1985; Link and others, 1985) suggest that there is considerable variability in the nature of the processes and deposits in the subaqueous environment. Sediment-gravity processes, including debris flows, grain flows, turbidity currents, slumping, and sliding, are particularly common in the subaqueous component of coarse-grained deltas (Postma, 1984). They are a product of several factors, including overpressuring during sediment accumulation (liquefaction), relatively steep basinal slopes, steep bedding surfaces (mega foresets), and possibly even triggering by seismic disturbance. In low-latitude areas, it is probable that fringing reefs will be a major component of coarse-grained deltas and will strongly influence the character of the subaqueous delta (for example, the fan-deltas of the Gulf of Aqaba; Hayward, 1985).

The subaqueous components of coarse-grained deltas (both fan-deltas and braid deltas) commonly display the large-scale (metres thick), coarse-grained foreset, topset, and bottomset bedding of Gilbertian deltas (Gilbert, 1885; Edwards, 1978; Casey and Scott, 1979; McLaughlin and Nilsen, 1982; Millberry, 1983; Ori and Ricci Lucchi, 1983; Ethridge and Wescott, 1984; Golia and Stewart, 1984; Postma and Roep, 1985). These features are developed in response to various traction-transport and sediment-gravity processes that dump relatively coarse-grained sediment onto moderately shallow-water shelves and platforms. Basinal influences of waves, tides, and currents on the delta foresets are usually relatively low. Coarse-grained Gilbertian deltas in the rock record have been genetically linked with fan-deltas. Although Gilbert foresets do occur in association with fan-deltas (for example, at Walker Lake; Link and others, 1985), they are far better developed (that is, thicker and with more pronounced size grading) in the quiet-water setting of lacustrine braid deltas, particularly those of fluvioglacial origin. Very few of the published studies of fan-deltas that were interpreted on the basis of Gilbert foresets are found to contain any documented association with an alluvial fan, and most are examples of braid deltas.

EXAMPLES OF FAN-DELTAS AND BRAID DELTAS

Although fan-deltas occur in restricted geomorphic settings, they are relatively common in the rock record because of their high preservation potential in a fault-bounded setting. Such a setting also results in exceptionally thick (several kilometres) sequences (the Hornelen Basin, Norway; Gloppen and Steel, 1981). Some of the better documented modern examples of what we class as true fan-deltas include the fan-deltas of the Dead Sea Rift (Sneh, 1979), those of the Gulf of Aqaba (Friedman and Sanders, 1978; Gvirtzman and Buchbinder, 1978; Hayward, 1985), the Yallahs fan-delta of Jamaica (Wescott and Ethridge, 1980), and an example from the western margin of Walker Lake, Nevada (Link and others, 1985). Some well-described ancient examples of fan-deltas include the upper Miocene Violin Breccia of Ridge Basin, California (Link, 1984), the middle Tertiary Simmler Formation of central California (Ballance, 1984), the Eocene Wagwater Group of Jamaica (Wescott and Ethridge, 1983), the Devonian Hornelen basin of Norway (Gloppen and Steel, 1981), and the Cambrian sequences of Kangaroo Island, South Australia (Daily and others, 1980). Other examples are given in Table 2.

Modern braid deltas are much more common than fan-deltas, undoubtedly because of their more widely occurring geomorphic setting. Braid deltas occur mostly in middle- to high-latitude regions, such as Alaska (Figs. 3A, 3C, and 3D) (Hayes and Michel, 1982), Greenland (Fig. 3B), Svalbard, Iceland, Canada (Kostaschuk, 1985), New Zealand, and northern Europe. This is because of high precipitation, a ready supply of coarse-grained sediment, and a minimum of sediment-stabilizing vegetation.

Undoubtedly braid deltas were a common feature of the valley trains and outwash plains of the Pleistocene and other glacial periods. It might also be expected that braid deltas were a common feature in pre-Devonian times because of the dominance of braided-river patterns in the period before the evolution of land vegetation in the Early Devonian (Schumm, 1968; Cotter, 1978; Fuller, 1985). Numerous notable examples of very extensive pre-Devonian braid-delta systems, including the Ordovician Haouaz Formation (Vos, 1981), the Precambrian Witwatersrand Supergroup (Minter, 1978), the Precambrian Skoadduvarri Sandstone (Bergh and Torske, 1986), and the Archean Moodies Group (Eriksson, 1978), bear witness to this suggestion.

Braid deltas and fan-deltas may have a spatiotemporal relationship in extensional basins. Braid deltas whose braided river or braidplain is juxtaposed with an alluvial fan or bajada (the example of Fig. 1C) are likely to be formed in the late stages of rift and pull-apart basin development. Typically, fan-deltas form on the basin margins in the youthful stages of basin evolution. This is in reponse to active faulting with fan development and ponding, or marine incursion, in the basin-margin depressions commonly associated with early basin evolution. Later, the fan-deltas give way to braid deltas as the highlands are worn down, the basin is at least partially infilled, and the alluvial fans are separated from the standing body of water by a broad alluvial plain. An example of this basin evolution is the Brazilian marginal basins which originated during the Early Cretaceous rift phase of the South American and African plates (Brown and Fisher, 1977, their Fig. 17; Ojeda, 1982).

Some of the well-documented ancient examples of what we have interpreted as braid deltas include the Miocene Kasaba Formation of southwest Turkey (Hayward, 1983), the Permo-Triassic Ivishak Formation of Alaska (Melvin and Knight, 1984; McGowen and Bloch, 1985), the Pennsylvanian Henrietta fan delta of north-central Texas (Erxleben, 1975), and the Precambrian Witwatersrand Supergroup of South Africa (Vos, 1975; Minter, 1978; Tankard and others, 1982; Kingsley, 1984). Other examples are given in Table 2.

TABLE 2. SELECTED EXAMPLES OF FAN-DELTAS FROM THE LITERATURE, AND OUR INTERPRETATION BASED ON VARIOUS SEDIMENTOLOGICAL PROPERTIES AS SUMMARIZED IN TABLE 1

Fan-deltas
Yallahs fan, Recent, Jamaica (Wescott and Ethridge, 1980).
Coastal fans, Recent, Gulf of Aqaba, Red Sea (Hayward, 1985).
Walker Lake basin, Quaternary, Nevada (Link and others, 1985).
Dead Sea rift, late Pleistocene, Israel (Sneh, 1979).
Basin fill, Neogene, Little Sulphur Creek basins, California (McLaughlin and Nilsen, 1982).
Violin Breccia, upper Miocene, Ridge basin, California (Link, 1984).
San Onofre Breccia, Miocene, Los Angeles basin, California (Stuart, 1979).
Simmler Formation, mid-Cenozoic, California (Ballance, 1984).
Wagwater Group, Eocene, Jamaica (Wescott and Ethridge, 1983).
Way Group, Lower Cretaceous, northern Chile (Flint and others, 1986).
South Viking Graben, Upper Jurassic, British North Sea (Harms and others, 1981; Kessler and Moorhouse, 1984). Described as a submarine fan (Stow and others, 1982; Stow, 1983).
Palo Duro basin, Pennsylvanian-Permian, Texas (Dutton, 1980; Handford and Dutton, 1980). Some braid deltas also present but not distinguished.
Hornelen basin, Devonian, Norway (Gloppen and Steel, 1981).
Kangaroo Island, Cambrian, South Australia (Daily and others, 1980).
Braid deltas (our interpretation)
Copper River, Recent, Alaska (Galloway, 1976). A fluvioglacial braid delta.
Lower Cook Inlet, Recent, Alaska (Hayes and Michel, 1982). Fluvioglacial braid deltas.
Canterbury Plains, Quaternary, South Island, New Zealand (Wescott and Ethridge, 1980). An extensive braidplain and braid delta system.
Intra-Apenninic basin, Pliocene, Italy (Ricci Lucchi and others, 1981). Although conglomeratic in part, the sequence shows many features of "normal" deltas, with meandering delta-plain channels.
Kasaba Formation, Miocene, southwest Turkey (Hayward, 1983).
Moosebar–Lower Gates, L. Cretaceous, W. Canada (Leckie and Walker, 1982). Described as a braided-river, beach, and offshore-bar sequence.
Cotton Valley Group, Upper Jurassic, East Texas basin (McGowen and Harris, 1984).
Ivishak Formation, Permo-Triassic, Prudhoe Bay, Alaska (Melvin and Knight, 1984; McGowen and Bloch, 1985).
Henrietta fan delta, Pennsylvanian, north-central Texas (Erxleben, 1975).
Haymond Formation, Pennsylvanian, Texas (Flores, 1975). Referred to as "short-headed stream deltas."
Atoka Group, Pennsylvanian, Fort Worth basin, Texas (Thompson, 1982). Probably includes some fan-deltas, but they are not distinguished.
Minturn Formation, Pennsylvanian, Colorado (Lindsey and others, 1986).
Lower Fountain Formation, Pennsylvanian-Mississippian, Colorado (Langford and Fishbaugh, 1984).
Haouz Formation, Ordovician, Libya (Vos, 1981).
Formation, lower Paleozoic, Cape Province, South Africa (Vos and Tankard, 1981).
Klipheuwel Formation, lower Paleozoic, Cape Province, South Africa (Vos and Tankard, 1981).
Witwatersrand Group, Precambrian, South Africa (Vos, 1975; Minter, 1978; Tankard and others, 1982; Kingsley, 1984).
Skoadduvarri Sandstone Formation, Proterozoic, northern Norway (Bergh and Torske, 1986).
Moodies Group, Archaean, South Africa (Eriksson, 1978).

Note: all above examples (with exceptions as given) were interpreted as fan-deltas by the original authors.

PREVIOUS MODELS

Wescott and Ethridge (1980) classified fan-deltas principally on the basis of the coastal tectonic setting. In doing this, however, they also made a distinction between fan-deltas whose subaerial component was an alluvial fan (the Yallahs fan-delta) and those whose subaerial component was a purely braided-river system (the "extended fan" model). The Yallahs model (their Fig. 14A), corresponds to our fan-delta and comprises alluvial-fan facies that pass directly into the marine basin via a narrow foreshore transitional zone. No alluvial plain, braided-river facies separates the alluvial fan from the marine basin. The "extended fan" model (their Fig. 14B) corresponds to our braid delta system and is based on the fluvioglacial outwash "fans" along the southeast coast of Alaska. As illustrated (their Fig. 14B), the subaerial component (referred to as the subaerial fan) is composed entirely of braided-river facies. For reasons given above, we suggest that the fluvioglacial outwash analogy for alluvial fans is invalid, and, by extension, so is the model for fan-deltas based upon fluvioglacial systems. We suggest that the "extended fan" model of Wescott and Ethridge (1980) is a braid-delta system as herein described.

Broadening the meaning of the term "fan-delta" to incorporate a non-fan, braided alluvial plain, deltaic setting removes the valuable feature of fan-deltas which is that they are a direct indicator of proximity to a highland and commonly fault-bounded basin margin. The broad definition also greatly diversifies and thus complicates the lithofacies assemblages and variabilities expected in fan-delta deposits. We suggest that if the distinguishing characteristics of an alluvial fan cannot be recognized in the delta-plain facies of a fan-delta, then the term "fan-delta" should not be used.

RESERVOIR POTENTIAL AND QUALITY

Fan-deltas and braid deltas are favorably placed as potential hydrocarbon reservoirs (see Fraser and Suttner, 1986). They occur updepositional-dip from, and are contiguous with, potential marine or lacustrine source beds. Although most producing fields in fan-delta and braid-delta sequences have been found on the basis of structural plays (Ethridge and Wescott, 1984), stratigraphic trapping is always of importance because of the considerable lithologic variability associated within coarse-grained delta sequences. Stratigraphic trapping is generally by encasement of reservoir sandstones within delta-plain shales (for example, the Upper Morrow reservoir, Anadarko basin; Shelby, 1980), marine or lacustrine shales (for example, the Brae Field, North Sea; Harms and others, 1981), "tight" limestones (for example, the granite wash, Mobeetie Field; Dutton, 1980), or a combination of the above (for example, the Atoka of north-central Texas; Tai Wai Ng, 1979). In the case of fan-deltas, the common updip trap is a sealing syndepositional fault that places fan strata against impermeable uplifted strata.

Fan-delta sequences generally have poor reservoir quality in terms of over-all geometry and size, lateral continuity of sand bodies, and porosity and permeability. They are generally small wedge-shaped bodies of sediment with multiple and abrupt lithofacies changes, an abundance of matrix-rich lithofacies, and a subaerial component that is commonly carbonate cemented. Braid-delta sequences, in contrast, have improved sorting and extended lateral continuity that greatly enhances their reservoir potential. Moderately sorted to well-sorted and matrix-free gravels and sandstones commonly generate high porosities and permeabilities in braid-delta sequences. This, coupled with the potential for high lateral continuity of units and a downdip association with possible marine or lacustrine source beds, makes braid deltas favorable targets for hydrocarbon exploration.

SUMMARY

1. Fan-deltas are coarse-grained deltas formed by the progradation of an alluvial fan directly into a standing body of water. The subaerial component of fan-delta sequences is composed entirely of alluvial-fan facies, and it displays an interbedded association with the subaqueous component. Fan-deltas are of limited areal extent (tens of square kilometres), but they may produce exceptionally thick sequences in the rock record because of their high-subsidence, fault-bounded setting.

2. Braid deltas are coarse-grained deltas formed by the progradation of a braided alluvial-plain system into a standing body of water. The delta plain of braid deltas is composed entirely of braided fluvial distributary channels. Braid deltas are commonly of very great areal extent (hundreds of square kilometres). They are common in the modern setting and in the geologic record, and have previously been classified as fan-deltas.

3. Fan-deltas and braid deltas can be distinguished in the rock record on the basis of distinctive features in the subaerial portion of the system, that is, a separation of alluvial-fan facies (interbedded sheetflood, debris-flow, and braided-channel deposits) from purely braided-river facies (braided-channel deposits). Distinctive lithofacies and lithofacies assemblages, unit and sequence geometries, and paleocurrent data can be used to separate fan-delta and braid delta depositional systems.

4. It is important for paleogeographic and paleotectonic evaluations to separate fan-delta facies from braid-delta facies in the rock record.

5. Fan-deltas are invariably of poor reservoir quality due to poor sorting, a high muddy matrix content (either depositional or infiltered), very limited extent of individual beds, and, commonly, a high degree of induration by clay and carbonate cementation. Braid deltas may have excellent reservoir quality because of moderately good sorting with coarse grain size and a low muddy matrix content, and the possibility of great lateral extent of individual lithofacies.

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