Stow et al (Controls) 1985

Reprint from
Frontiers in Sedimentary Geology
Series Editor: *Arnold H. Bouma*

Submarine Fans and Related Turbidite Sequences

Edited by Arnold H. Bouma, Neal E. Barnes, and William R. Normark

Springer-Verlag
New York Berlin Heidelberg Tokyo

CHAPTER 4

Sedimentary, Tectonic, and Sea-Level Controls

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Abstract

To help understand factors that influence submarine fan deposition, we outline some of the principal sedimentary, tectonic, and sea-level controls involved in deep-water sedimentation, give some data on the rates at which they operate, and evaluate their probable effects. Three depositional end-member systems, two submarine fan types (elongate and radial), and a third nonfan, slope-apron system result primarily from variations in sediment type and supply. Tectonic setting and local and global sea-level changes further modify the nature of fan growth, the distribution of facies, and the resulting vertical stratigraphic sequences.

Introduction

Numerous modern fans have been studied over the past 15 years, and many examples of ancient turbidite sequences have been interpreted as fans or parts of fans. Several different descriptive models have been developed from both modern and ancient examples to characterize morphological features and the pattern of facies distribution. Clearly, several different fan types exist, but it is equally clear that many turbidites and associated sediments are deposited in other settings, including slope aprons in small and large basin systems, submarine canyons, and trenches.

We believe it is possible to gain further insight into where, why, and what types of fan systems are formed by considering the primary and secondary controls on their development [1–4]. In this paper, we first outline these main controls, giving some data on the rates at which they operate, and then discuss their probable effects.

Controls and Rates

Three primary controls on fan development and deep-sea sedimentation can be identified (Figure 1): (1) sediment-type and supply, (2) tectonic setting and activity, and (3) sea-level variations. These controls are by no means independent; for example, tectonic factors play an important part in determining sediment supply or local sea-level changes.

Sediment Type and Supply

Various types of sediment are available for redeposition. Terrigenous material is the most abundant worldwide, with muds being between two and ten times as important volumetrically as sands and gravels. Biogenic debris from carbonate reefs and platforms is common at low latitudes, and calcareous and siliceous oozes may be locally redeposited from areas of high pelagic accumulation. Evaporites, volcaniclastics and organic-carbon-rich sediments can all occur as turbidites and associated facies but rarely form a complete submarine fan complex. The sediment grain size affects the process and distance of transport and hence the geometry of the deposit. Biogenic particles behave differently from terrigenous grains during transport, so that carbonate facies and fans differ from their clastic counterparts [5].

The volume and rate at which sediments are supplied to an area and therefore made available for redeposition are other important variables. Major river-delta systems, such as the Ganges, Indus, and Mississippi, can provide a large and rapid supply of sediment to the shelf, although the availability of

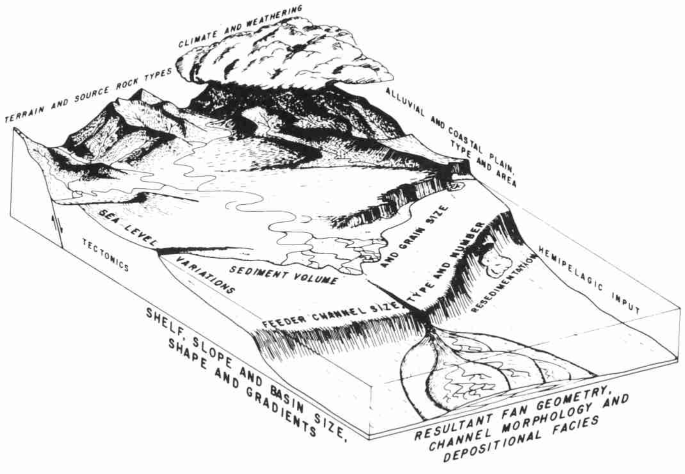

Figure 1. Schematic diagram highlighting the variety of physical processes that control submarine fan development.

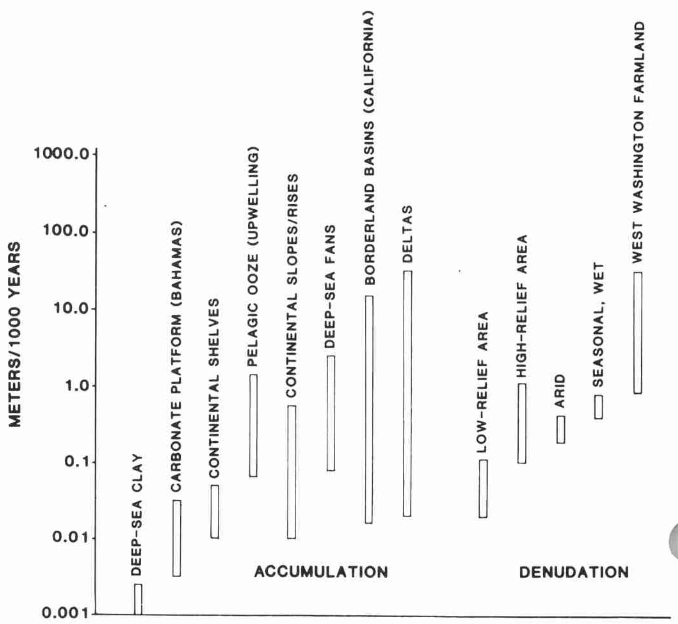

Figure 2. Log-plot comparing span of rates for sedimentary accumulation and denudation. Based on data in Howell and Von Huene [6] and Blatt and others [7] (1980).

this material for downslope resedimentation will depend on sea-level and shelf width. Wave-stirred, canyon-indented shelves will generally provide less sediment to the outer margin. In high latitudes, glaciers and floating ice shelves may greatly increase the supply of terrigenous material to the shelf margin. Low-latitude carbonate platforms and topographic highs covered with pelagic material commonly provide lower rates of sediment supply.

The number and spacing of input points along a given margin will determine whether single or isolated fans are developed, or whether an overlapping-fan/slope-apron system is produced.

Secondary factors that influence sediment type and supply are also illustrated schematically in Figure 1. They include: (1) the original source-rock type that affects composition, size, and erodability of detritus; (2) climate and vegetation that affect the nature and degree of weathering and the mode of supply (fluvial, glacial, wind, etc.); (3) the relief and tectonic activity in the hinterland that affect the rate of denudation and of supply to the transitional source; (4) the distance between the original and transitional sources and the mode of transport that affect the compositional and textural maturity of sediments; (5) the topography, tectonic activity, and sediment residence time in the transitional source area that affect sediment compaction, erodability, and type; and (6) local marine conditions (currents, Coriolis force, water temperature, upwelling, etc.) that affect the supply of biogenic detritus and organic carbon, bioturbation, or physical reworking and suspension of sediment, as well as the final sediment distribution.

The rate at which land areas are eroded (Figure 2) will have an effect on sediment supply [6,7]. On average, denudation of a low-relief terrain is at a rate of 0.01 to 0.1 m/1000 yr, whereas for high-relief areas the rates are as much or an order of magnitude higher, 0.1 to 1 m/1000 yr. Areas of high seasonal precipitation tend to erode at twice the rate as those that are semiarid. The rates of sediment accumulation (Figure 2), particularly in the transitional source area, are equally important. In the long term, these rates rarely exceed 50 mm/1000 yr. Local rates can be as high as 1 m/yr, such as in front of active delta distributaries. Typical long-term accumulation rates on carbonate or clastic shelves are from 10 to 40 mm/yr. Pelagic ooze sedimentation will normally not exceed 30 mm/1000 yr, although under upwelling areas it may reach 0.1 m/1000 yr.

Resedimentation of material to deeper water results in accumulation rates on modern deep-sea fans from 0.1 to 2 m/1000 yr, and up to 10 m/1000 yr in small tectonically active basins. Turbidity currents are one process by which resedimentation occurs, and estimates of their frequency mostly range from 1 per 500 to 10,000 years for deep-sea clastics and from 1 per 20,000 to 100,000 years for carbonates [2,6]. Muddy turbidity currents off some active river-delta systems may occur with a frequency as high as one per year.

Tectonics

The major tectonic settings in which submarine fans and associated deep-water systems can develop include mature passive margins (eastern North American and Gulf of Mexico), active rifting margins (Red Sea, Gulf of California), convergent margins with arc or trench systems (Aleutian Trench, Nan Trough), transform margins (California Continental

Borderland, offshore Venezuela), marginal seas and back-arc basins (Lau Basin, Phillipine Sea), oceanic basins flanked by ridges and seamounts (Indus Cone), and intracratonic basins on continental shelves and within continents (Bering Sea Shelf, Cretaceous seaway of North America).

These tectonic settings exert a first-order control on the types of fans developed by affecting the rates of uplift and denudation, drainage patterns, coastal plain and shelf widths, continental margin gradients, gross sediment budgets, the morphology of receiving basins, and local sea-level changes. The specific tectonic parameters that immediately determine fan type are the size and internal geometry of the basin, including gradients of the basin margin and floor [8]. The style and frequency of seismic activity and faulting, both in the original and transitional source areas, are also of primary significance since these factors influence the frequency and volume of sediment gravity flows feeding the basin, e.g., mature passive margins experience infrequent, but commonly large, earthquakes, which may trigger very large slumps that develop into debris flows and turbidity currents. Frequent earthquakes along active margins do not permit a large build-up of sediment in transitional settings.

Secondary factors involved in tectonic activity include the rates of horizontal and vertical motion, the maturity of the margin, and the relationship of a particular setting to neighboring plates. The rates of motion can be critical. If deposition rates are slower than tectonic rates, fan growth will be controlled by tectonism rather than by sedimentary factors such as fluctuating gradients and migrating channels, distributaries, and terminal lobes.

The rates at which various tectonic processes operate are illustrated in Figure 3 [6,7]. Rates of uplift in mountains, mainly along convergent and transform margins, are relatively fast, ranging from 1 m to as much as 75 m/1000 yr, although they are generally between 3 and 10 m/1000 yr. Such uplift is generally of short duration (10^5 to 10^6 yr). More long-term epeirogenic uplift in nonmountainous areas is commonly from 0.1 to 3.7 m/1000 yr, although isostatic uplift (and subsidence) can be an order of magnitude greater, from 4 to 40 m/1000 yr. All uplift is probably episodic with short periods of rapid vertical movement alternating with longer periods of stability or only very slow movement.

Subsidence is equally variable and also episodic in nature. The greatest rates, up to 12 m/1000 yr, occur locally in small basins within transform margins and in arc and trench basins (up to 5 m/1000 yr) along convergent margins. Average rates outside of these tectonically active regions rarely exceed 1 m/1000 yr and are significantly lower (10 to 40 mm/1000 yr) along passive margins and adjacent oceanic basins.

By comparison with vertical motion, horizontal plate movements may be an order of magnitude greater, from 10 to 100 m/1000 yr. Spreading rates across oceanic ridges and displacement rates within transform zones are often of these magnitudes.

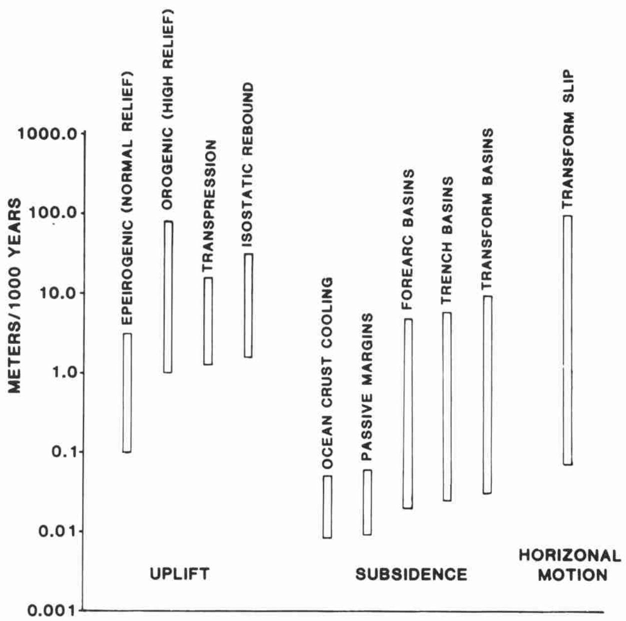

Figure 3. Log-plot comparing span of rates for tectonic uplift, subsidence, and horizontal plate motion. Based on data in Howell and Von Huene [6] and Blatt and others [7].

Sea-Level

Fluctuation in sea-level not only affects the nearshore realm of sedimentation, but also profoundly influences deep-sea depositional and resedimentation patterns. Shoreline sources such as rivers or littoral drift cells either may have direct access to basin slopes during periods of low sea-level or indirect access through paralic and continental shelf environments during periods of high sea-level [8].

Sea-level changes may be global (eustatic) or regional in nature. Eustatic fluctuations occur as a result of a change in the total volume of ocean basins or a change in the volume of sea water. The volume of ocean basins is affected by four secondary factors, for which Pitman [9] has estimated the maximum sea-level change that can result: (1) Variation in sediment input can cause sea-level fluctuation of up to 2.0 mm/1000 yr; (2) continental collision and subduction has been calculated to change sea-level by 1.6 mm/1000 yr in the case of the collision of India into the Asian plate; (3) growth of seamount chains causes minimal sea-level change of only 0.2 mm/1000 yr; whereas (4) swelling and shrinking of midocean ridge systems can cause changes of up to 6.7 mm/1000 yr.

The variation in the total volume of sea water as a result of subduction, volcanism, and sea-floor spreading processes seems unlikely to produce sea-level changes in excess of 2 mm/1000 yr [9]. However, the locking-up of very large amounts of water in expanded polar ice sheets during glacial periods and its release during warm climatic epochs can cause

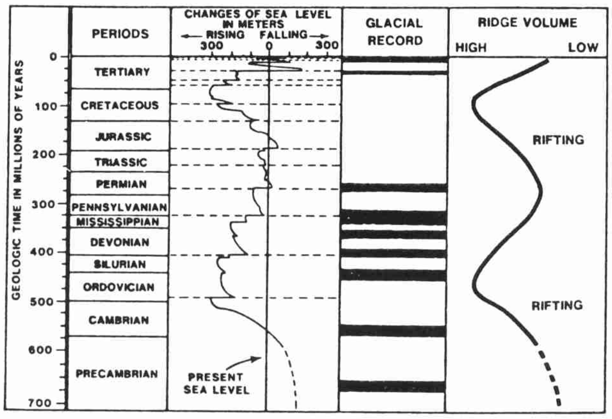

Figure 4. Comparison of global changes of sea level, glacial record, and midoceanic ridge volume. After Shanmugam and Moiola [32] 1982.

enormous sea-level fluctuations of up to 10 m/1000 yr.

These rates, apart from those induced by climate, appear too small in comparison with tectonic rates of uplift and subsidence to have any appreciable effect on fan growth along active margins (Figure 3). However, prolonged eustatic changes, due to changes in spreading rate and volume of midocean ridges, will have a significant effect on sea-level along the more stable coastlines.

Regional fluctuations in sea-level that result from local tectonic and isostatic factors can be much greater than eustatic changes, as evidenced by the rates of tectonic processes discussed in the preceding section. They are not always readily distinguished from and may completely mask the eustatic change. Nonetheless, efforts have been made to chronicle the eustatic fluctuations and to construct an average worldwide sea-level curve [10] (Figure 4).

Effects and Examples

We are able to identify the likely effects on fan sedimentation of the major controls by assessing the features and controls of numerous modern and ancient fans. Clearly, as our examples show, many of the controlling influences interact to produce "hybrid" fan types that combine features of several end-member models. In this relatively short summary, we have not attempted to be exhaustive, but point out basic relationships that exist between fans and the controls that produce these patterns.

Sediment Type and Supply

We identify two end-member submarine fan types and a third end-member nonfan system (slope-apron) (Figure 5) that result primarily from variations in sediment type and in the nature and rate of sediment supply.

The *elongate fan* develops in response to a medium to high sediment input of mixed size grades, but with mud and very fine sand as the dominant sediment type. These fans have a single major primary source (e.g., large river, delta, ice channel) and commonly have one active channel at any given time and one or more abandoned or periodically active feeder channels across the slope. These channels may have elaborate tributary systems, and the major fan valleys may have extensive distributary networks. An elongate shape with an irregular to smooth downfan morphology is developed by the effective funnelling of sands and coarser material to terminal lobes at the ends of channels on the distal fan.

Numerous authors have described fans of this type and various synonyms exist: large deep-water or open-basin fan [8,11], high-efficiency fan [12], muddy fan (D. J. W. Piper, personal communication, 1982), delta-fed fan [3], and morphologically poorly-developed fan [13]. Modern examples include the Astoria, Bengal, Indus, Mississippi, Amazon, Laurentian, and Rhone Fans among others, and the facies distribution is best characterized by Stow [11] and Nelson [8]. Recognition of the very large elongate fans in the ancient record is almost impossible, but some examples from the Italian flysch [14,15] and from the North Sea Tertiary [16] may be similar types on a smaller scale. Mutti and Ricci Lucchi's fan model [17] best describes these ancient sequences and their facies distribution.

The *radial fan* results from a smaller sediment input than elongate fans, commonly with the sand grade sediment of equal or greater abundance than mud. There is a single general source area, although not necessarily a single river or delta system, and a single feeder canyon or channel across the slope. A main upper fan valley generally divides into a limited distributary network in the midfan. The fan shape is typically radial, and the classical [18] tripartite morphological divisions are developed.

This type of fan has been variously termed a restricted-basin fan [8], low efficiency fan [12], sandy fan (D. J. W. Piper, personal communication, 1982), canyon-fed fan [3], small fan, and morphologically well-developed fan [13]. Among many modern examples are La Jolla, Navy, San Lucas, and Redondo Fans on the western margin of North America from which Normark has derived his model [3,18]. A number of ancient turbidite sequences have been related to the Normark model, although, strictly speaking, we do not generally have the morphological evidence to ascertain that they are indeed radial fans. Subsurface examples such as the Magnus [19] and Frigg [20] Fans from the North Sea Tertiary, or the Stevens and related fans [21] of the Great Valley, California, may fit into this category. Walker [22] has developed a composite model to describe the facies types and distributions on this type of fan.

The *slope-apron* (also debris-apron) system, which includes both the slope and base-of-slope associations, has been placed at the third apex of our ternary diagram (Figure 5). It is *not* a submarine fan because of the absence of channels,

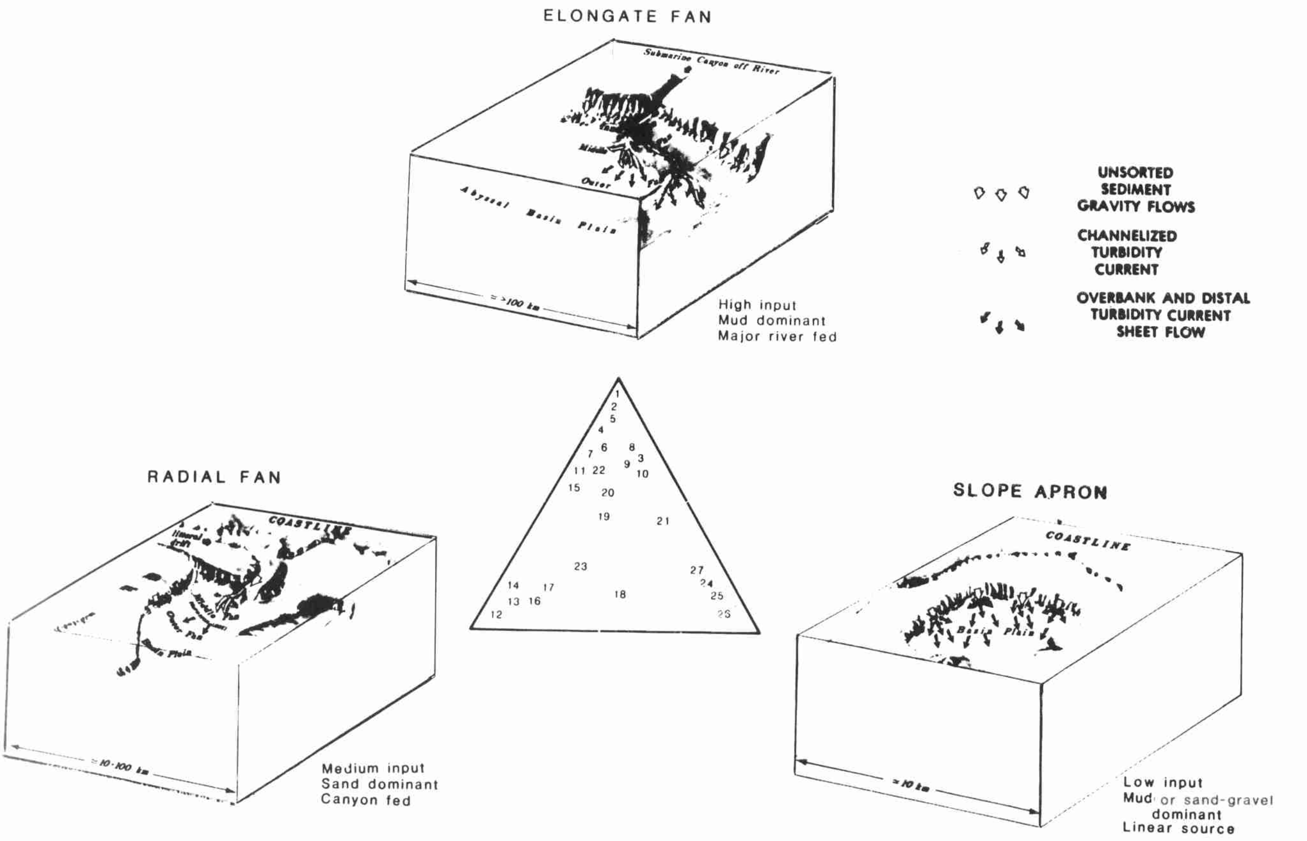

Figure 5. Triangular diagram showing estimated positions of various modern fans with respect to the three end-member modes: elongate fan, radial fan, and slope-apron system (fan block diagrams modified from Nelson [33] © Kendall-Hunt Publishing Co.).

1. Bengal
2. Indus
3. Mississippi
4. Zaire
5. Amazon
6. Reserve
7. Rhone

Laurentian

9. Monterey
10. Delgada
11. Astoria
12. La Jolla
13. Redondo
14. Navy
15. Nitinat
16. Coronado
17. San Lucas
18. Ebro
19. Hudson
20. Orange
21. Crati
22. Nile (Rosetta)
23. Menorca
24. Normal slopes and rises
25. California Continental Borderland basin slopes

but is a closely related turbidite system. It is characterized by a low to medium sediment supply rate, and a mixed sediment type that is commonly sand and even gravel-rich in very small tectonically active basins, but may be mud dominated along muddy continental slopes. There is a multiple or linear sediment source feeding directly across a nonchannelized or "straight"-gullied slope. Most present-day oceanic slopes and rises as well as small slope basins fit into this general category, of which several subdivisions can be made. Recently, Stow [23] has attempted to synthesize a slope-apron morphological and facies model similar to that developed for carbonate slopes [24]. Several examples of probable slope-apron deposits have also been described from the ancient record [22,26,30].

Hybrid fan types that are gradational between our end-member models are probably the norm rather than the exception (Figure 5). Even the examples listed above may not be true end-members; for example, the Laurentian Fan is considered a typical elongate fan type, but it has many elements of the normal slope-apron development as shown by the adjacent Scotian and Grand Banks margins. The Ebro "Fan" in the western Mediterranean combines elements of a slope-apron system and a radial fan system because tectonic subsidence has disrupted fan development [27]. The Monterey, Delgada, and Astoria Fans appear to lie somewhere between the radial and elongate types. The Astoria system clearly has elongate growth and facies patterns because it fills a trench parallel to the margin. Channels have migrated to parallel the margin and funnel sand to outer fan depocenters. In the absence of competing tectonic or sea-level controls, normal sedimentary processes (channel erosion and filling, lobe switching, and so on) will produce characteristic horizontal facies distributions and vertical facies sequences (Figure 6), [11,17,22]. These will differ somewhat for each end-member system; the sandy facies, for example, will be distributed concentrically on the radial fan, in more linear channels and terminal lobes on the elongate fan, and in sheets, stringers and isolated lobes in the slope-apron system. The small-scale compensation cycles recently described by Mutti and Sonnino [28] are also the result of normal sedimentary controls.

Tectonic Setting and Activity

First-order tectonic factors clearly exert a primary control on both the sediment type and supply by their influence on relief, rock types, resedimenting processes, and eustatic or local sea-level changes. More specifically, tectonic setting determines the basin size and shape and the slope gradients that confine and control depositional patterns, and the rate of tectonic processes that my disrupt normal fan growth.

On stable and *mature passive margins,* rates of fan deposition exceed rates of tectonic motion (Figures 2 and 3). In these relatively quiescent settings large, mature fans of either type may develop, depending on sediment type and supply factors; very thick slope-apron systems may form between fans, such as the Atlantic rise prisms [11].

On *transform margins* and *convergent margins* (arc basins, trenches), rapid uplift, subsidence, or horizontal movement along fault zones may disrupt normal growth patterns in fans that have typical sedimentation rates (Figures 2 and 3). Short-term fans usually develop along these margins since supply areas, feeder channels, and receiving basins tend to be transient and subject to varied tectonics. The exception is in trench floor areas where, if a large sediment source exists, "elongate" fans can form as a result of structural confinement. For the most part, relatively small radial fans develop in at least two different configurations [6]: In the first case (e.g., Baranof Fan, off southwest Alaska), the primary slope feeder channel is landward of the transform fault so that fans are continuously transported away from the sources by slip on the fault; in the second case (e.g., Delgada and Monterey Fans, off California), the major slope feeder channel is seaward of the fault and allows a single larger fan to develop.

The slope-apron systems between fans accumulate relatively thin deposits and are subject to considerable slumping and other mass movements.

Immature *rifted passive margins* and portions of *marginal seas* and *transform margins* will all evolve through periods of predominantly vertical tectonics. In this case, considerable quantities of sediment may be shed across a steepened and fault-scarp slope into the adjacent rapidly subsiding basin. No well-defined fan morphology will develop, but in-

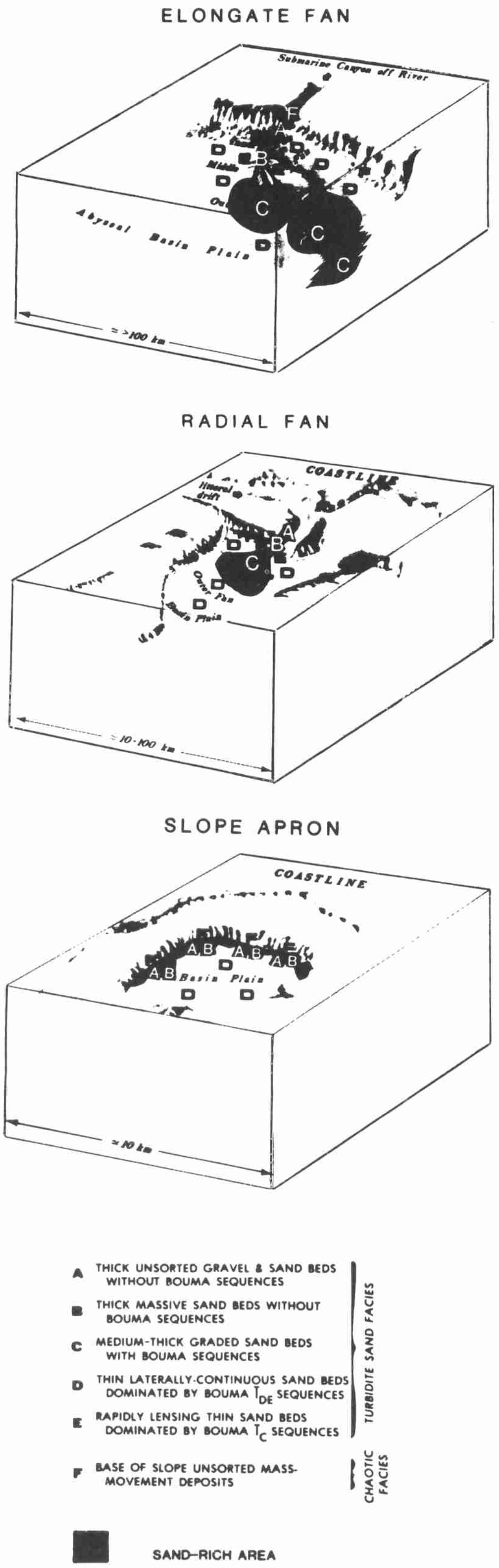

Figure 6. General organization of facies in elongate fan, radial fan, and slope-apron systems (modified from Nelson [33] © Kendall-Hunt Publishing Co.).

stead a very thick and somewhat irregular sediment fringe will accumulate in a narrow band in the base-of-slope area that forms a fault-scarp slope-apron system analogous to that seen at the base of the Crater Lake Caldera walls. Modern examples are found along parts of the Mediterranean Sea margins [27,29], south of the Arabian peninsula in the Gulf of Aden (J. C. Faugeres, personal communication, 1983), and elsewhere. Ancient examples include some of the Mesozoic-Cenozoic basin margins off California [6], and the Jurassic rifted margins of eastern Greenland [30], and the North Sea [1].

Along active convergent or transform margins, small morphologically constricted basins are developed with variable shapes, sediment supplies, and duration. There is a strong morpho-tectonic control exerted on the style of sediment accumulation in these basins. The complex combinations of slope aprons and fans may be better termed "basin-fill systems," rather than submarine fans or slope aprons because they have their own characteristic facies distribution, sequences, and morphological evolution. These are not discussed further here, but a preliminary synthesis of basin models has been made by Stow [23].

In addition to the general tectonic setting, the magnitude, location, and periodicity of tectonic activity are very significant controlling factors on fan development. Channel erosion, filling, abandonment, or rejuvenation can all be influenced by local tectonic activity. Vertical facies sequences will evolve that mirror the coarsening- or fining-upward sedimentary sequences, but that have tectonic rather than sedimentary causes.

Diapiric activity in thick slope successions of either active or passive margins will exert further specific controls on the distribution of facies and on the development of different fan, slope, and basin types [31].

Sea-Level Fluctuations

Changes in global and local sea-level clearly have profound effects on sedimentation throughout the marine realm [6] as dramatically displayed by the late Cenozoic fluctuations of fan depositional regimes in response to glacial cycles [8]. Local changes in sea-level are a major factor in controlling turbidite sedimentation and fan growth within a specific basin, but these sea-level fluctuations do not always reflect a worldwide eustatic variation and may be only a local event.

High stands of sea-level coincide with relatively inactive phases in many fans. Sediment transport across the shelf and into canyons will be at reduced levels since most detritus is trapped in estuaries, lagoons, and other nearshore environments (e.g., Astoria [8], Laurentian [11], Cap Ferret [4], Ebro [27], and Monterey Fans [3]). Various types of bottom currents other than turbidity currents may remain or become active over the fan and help to mold fluvial-like features (braided and meandering channels, point bars, etc.) and leave traction-current deposits (thick cross-bedded sets, lag deposits) [11,20]. Off major rivers and deltas, large elongate fans or slope-aprons may continue to grow, but at reduced rates, even during high stands of sea-level, e.g., Mississippi (J. M. Coleman, personal communication 1982), Ebro [27], and Amazon Fans (J. E. Damuth, personal communication 1982), because thick Holocene deposition of river mud on the slope results in deposition of major debris sheets over the fan surface.

Low stands of sea-level, on the other hand, will lead to narrower shelves with more rapid sedimentation as well as the direct funnelling of sediments through canyons and fan valleys to deeper basins. Several authors have noted the probable correlation of low sea-level with more frequent turbidity current activity and greater supply of sands and gravels to the deep sea [6,8,32].

Fluctuation in sea-level will result in different styles of fan growth: progradational sequences, rejuvenation, and channel incisement during lowering of sea-level, and regradational sequences with channel and lobe abandonment during raising of sea-level. Cyclicity in vertical sequences may thus be related to repeated sea-level fluctuations as well as to normal channel abandonment and compensation cycles [28].

Summary

We have attempted, in this brief survey, to show that there may be some coherence in the plethora of fan types and models that have been described over the past 15 years. We do this by addressing not the models themselves, but the primary and secondary controls that influence fan development and the rates at which these controls operate.

Two end-member fan types and the third nonfan slope-apron system result primarily from variations in sediment type and supply. Elongate fans are mud-dominated with high input rates and are fed by major rivers, deltas, and one or more delta-front troughs or canyons; radial fans are sand-dominated with medium input rates and are canyon-fed from local rivers and littoral drift cells; and slope-apron systems are mostly low-input, mud- or sand-gravel dominated with a linear source. Hybrid fan types are the rule rather than the exception.

The tectonic setting exerts a first-order control of fan development. Large mature fans of either type and thick slope-apron sequences develop along parts of transform and convergent margins. Where there is significant vertical movement on these margins, a thick narrow belt of sediment accumulates as fault-scarp slope-apron systems.

High stands of sea-level are often periods of relative fan dormancy, except perhaps for large "delta-fed" elongate fans where the delta has prograded to the slope edge, or fans where the canyon head incises into estuaries or near littoral drift cells. Low stands of sea-level commonly result in active fan growth. The complex variation of sea-level fluctuation as well as tectonic activity and normal sedimentary factors will all affect the style of fan growth, facies distribution, and vertical sequences.

Acknowledgments

We are grateful to many colleagues for helpful discussion in the evolution of our ideas for this paper. Particularly stimulating was the COMFAN meeting in September 1982 hosted by GULF Research and Development Company. DAVS acknowledges personal support from the Royal Society of Edinburgh and secretarial and drafting assistance at the Grant Institute of Geology. CHN thanks Lee Baily and Tau Rho Alpha for assistance with drafting. We thank Arnold Bouma, Michel Cremer, and William Normark for helpful comments on an earlier version of the manuscript.

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