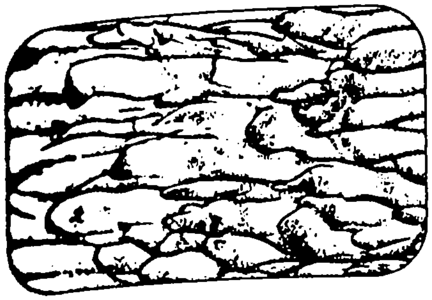

Turbidites and Associated Coarse Clastic Deposits

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Figure 1
Experimental turbidity current in a flume at Caltech. Water depth is 28 cm. Note characteristic shape of the head of the current, and eddies behind the head. Sediment is thrown out of the main flow by these eddies - the main flow is only about half of the height of the head.

INTRODUCTION

The turbidity current concept is both simple and elegant. Each turbidite is the result of a single, short-lived event, and once deposited it is extremely unlikely to be reworked by other currents. The concept is elegant because it suggests that the deposition of thousands of graded sandstone beds, alternating with shales, is the result of a series of similar events. It can safely be stated that no similar volume of clastic rock can be interpreted so simply.

This review is presented in six parts, following closely the philosophy of facies models outlined in the "General Introduction" to this volume;

1) Introduction to turbidity currents and turbidites.
2) The variety of turbidites in the geologic record (the model as descriptor).
3) Turbidites in modern oceans (model as descriptor).
4) Combination of ancient and modern examples (to distill a model).
5) Use of the model (the model as predictor).
6) Feedback - facies sequences refining existing models and defining new ones.

TURBIDITY CURRENTS AND TURBIDITES

Density currents flow downslope on the ocean floor, being driven by gravity acting on the density difference between the current and the surrounding sea water. The density could be due to colder temperatures, higher salinities, or suspended sediment in the current. When the density is due to suspended sediment, the flow is termed a *turbidity current* (Fig. 1). A *turbidite* is defined as the deposit of a turbidity current.

The concept of turbidity currents was introduced to the geological profession in 1950. At that time, nobody had observed a modern turbidity current in the ocean, yet the evidence for turbidity currents had become overwhelming. The concept accounted for graded sandstone beds that lacked evidence of shallow water reworking, and it accounted for transported shallow water foraminifera in the sandstones, yet with bathyal or abyssal foraminifera in the interbedded shales. Low density currents were known in lakes and reservoirs, and they appeared to be competent to transport sediment fairly long distances. Many of these different kinds of evidence were pulled together by Kuenen and Migliorini (1950) when they published experimental and field observations in a now classic paper on "Turbidity currents as a cause of graded bedding". A full review of why and how the concept was established in geology was published by Walker (1973).

It is now known that turbidity currents operate on vast scales. In 1935, a slump removed 480 m of breakwater at the mouth of the Magdalena River in Colombia. The slump cut a channel 10 m deep through a bar, evolved into a turbidity current, and several hours later broke a submarine telegraph cable 24 km from the river mouth in 1400 m water depth (Heezen, 1956; Menard, 1964, p. 197). Surveys of the sea floor before and after the slump indicate that the minimum volume of sediment lost was $3x10^8$ m^3. This is an unimaginably large volume of sediment - it would require 2.14 million standard 50-foot box cars to transport this sediment by railroad. The resulting train would be 35,000 km long. However, the largest turbidite known makes the Magdalena flow seem small. The "black shell" turbidite, named for the distinctive corroded shells that it contains, covers an area about 500 km long and 200 km wide on the Hatteras Abyssal Plain off the eastern margin of North America. Its volume has been estimated at over 100 km^3 (Elmore *et al.*, 1979), about 333 times that of the Magdalena flow.

Relatively little is known about flow velocities. The classic data comes from the 1929 earthquake near the Grand Banks of Newfoundland, which triggered a flow that broke a sequence of submarine cables. Recently recalculated velocities of the head of the flow (Uchupi and Austin, 1979) give 20.3 m/sec at the cable broken 183 minutes after the quake, 14.4 m/sec (541 minute break), 12.8 m/sec (618 minute break), and 11.4 m/sec at the 797 (13 hours 17 minutes) minute break. At a velocity of 11.4 m/sec, the current could suspend by fluid turbulence alone low concentrations of quartz pebbles up to about 3 cm in diameter.

The Grand Banks flow appears to have travelled several hundred kilometres across the essentially flat Sohm Abyssal Plain. Similarly, the "black shell" flow must have travelled at least 500 to 600 km along the Hatteras Abyssal Plain.

Turbidity currents can be triggered by earthquakes (as in the Grand Banks), by rivers in flood (as in the Congo, Heezen *et al.*, 1964) and by spontaneous failure of rapidly deposited piles of sediment, commonly with relatively fine grain sizes and high pore pressures (the Magdalena flows [Heezen, 1956; Menard, 1964] seem to have been of this type). It has been suggested recently that cyclic wave loading by major storms can liquefy enough sediment near the shoreline to generate turbidity currents; see, for example, "Shelf and Shallow Marine Sands" in this volume.

Turbidity currents must be considered commonplace in modern seas and oceans. Their deposits are likely to be extensive and volumetrically important. To preserve the sedimentary structures made by the turbidity currents (i.e., to be able to *recognize* the beds as turbidites), deposition must take place below effective wave base. It has been suggested that turbidites have been deposited in some epeiric seas (see "Shelf and Shallow Marine Sands", in this volume), as well as in the more traditional "deep water" turbidite habitat of submarine fans and basin plains.

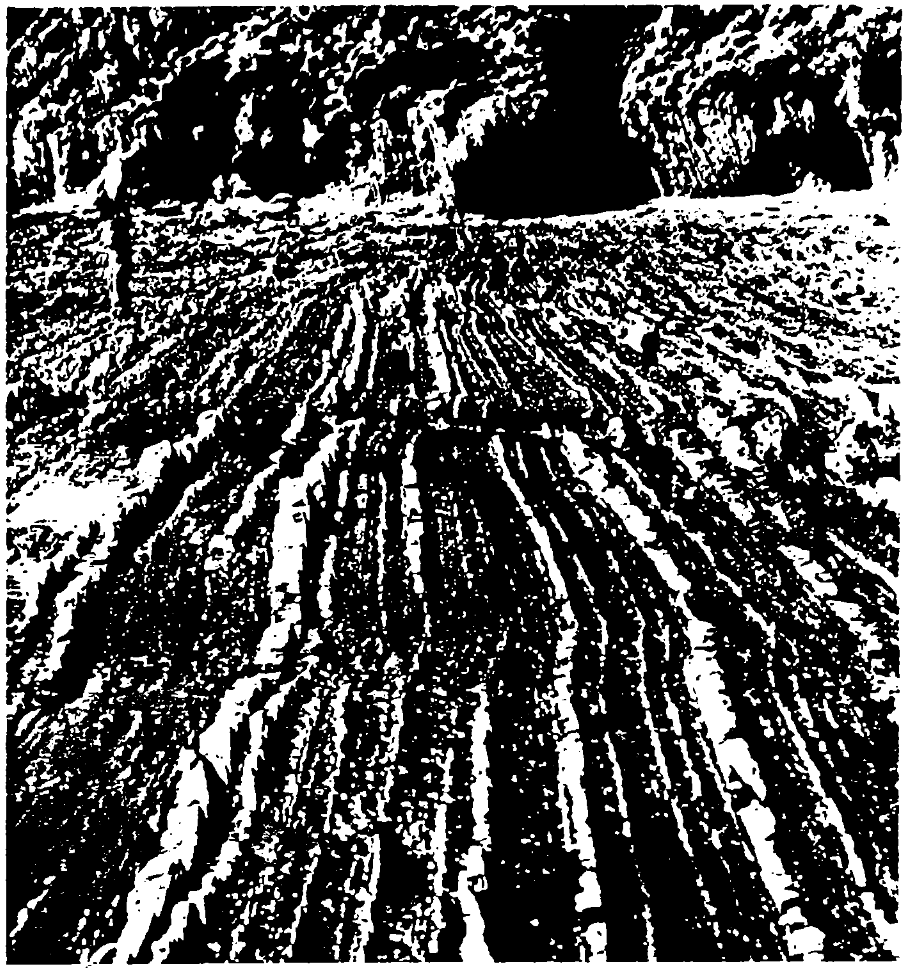

Figure 2
Monotonous interbedding of thin, sharp-based sandstones and mudstones. No sea-floor topography (channels, levees) visible. Stratigraphic top to right. Devonian, Cape Liptrap, South Australia.

TURBIDITES IN THE GEOLOGIC RECORD

After its introduction in 1950, the turbidity current concept was applied to rocks of many different ages, in many different places. Emphasis was laid upon describing a vast and new assemblage of sedimentary structures, and using those structures to interpret paleocurrent directions. In the absence of a turbidite facies model, there was no norm with which to compare individual examples, no framework for organizing observations, no logical basis for prediction in new situations, and no basis for a consistent hydrodynamic interpretation. Yet gradually during the years 1950-1960, a relatively small but consistent set of sedimentary features began to be associated with turbidites. These are considered in the following list, and can now be taken as a set of descriptors for *classical turbidites:*

1) Sandstones and shales are monotonously interbedded through many tens or hundreds of metres of stratigraphic sections (Fig. 2). Beds tend to have flat tops and bottoms, with no scouring and channelling on a scale greater than a few centimetres.
2) Sandstone beds have sharp, abrupt bases, and tend to grade upward into finer sand, silt and mud. Much of the mud was brought into the basin by the turbidity current (it contains a shallow water transported faunal assemblage), but the uppermost very fine clay may contain a bathyal or abyssal benthonic fauna and hence represent slow hemipelagic deposition between turbidity current events.
3) On the undersurface (sole) of the sandstones there are abundant markings, now classified into three types; *tool* marks carved into the underlying mud by rigid objects (sticks, stones) in the turbidity current; *scour* marks cut into the underlying muds by fluid scour; and *organic* markings representing trails and burrows filled in by the turbidity current. Tool and scour marks give accurate indications of local paleoflow directions, and by now, many thousands have been measured to reconstruct paleoflow patterns in hundreds of turbidite basins.
4) Within the sandstone beds, combinations of parallel lamination (Fig. 3), ripple cross lamination (Fig. 3), climbing ripple cross lamination, convolute lamination and graded bedding (Fig. 3) have been noted by many authors. An ideal,

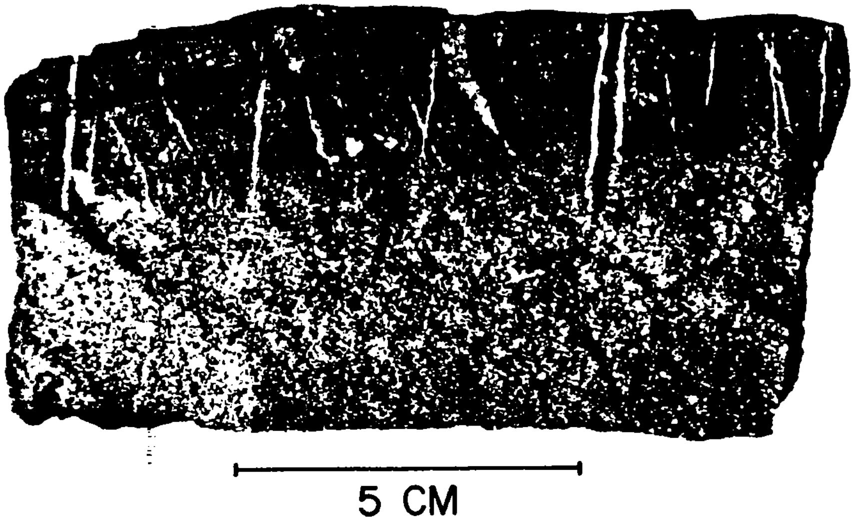

Figure 3
Complete Bouma sequence, beginning with a graded division A, overlain by parallel laminated division B and cross-laminated division C. Divisions D and E (see Fig. 4) broke off this specimen, which is from the Cote Frechette road cut, Levis Formation (Cambrian), Québec.

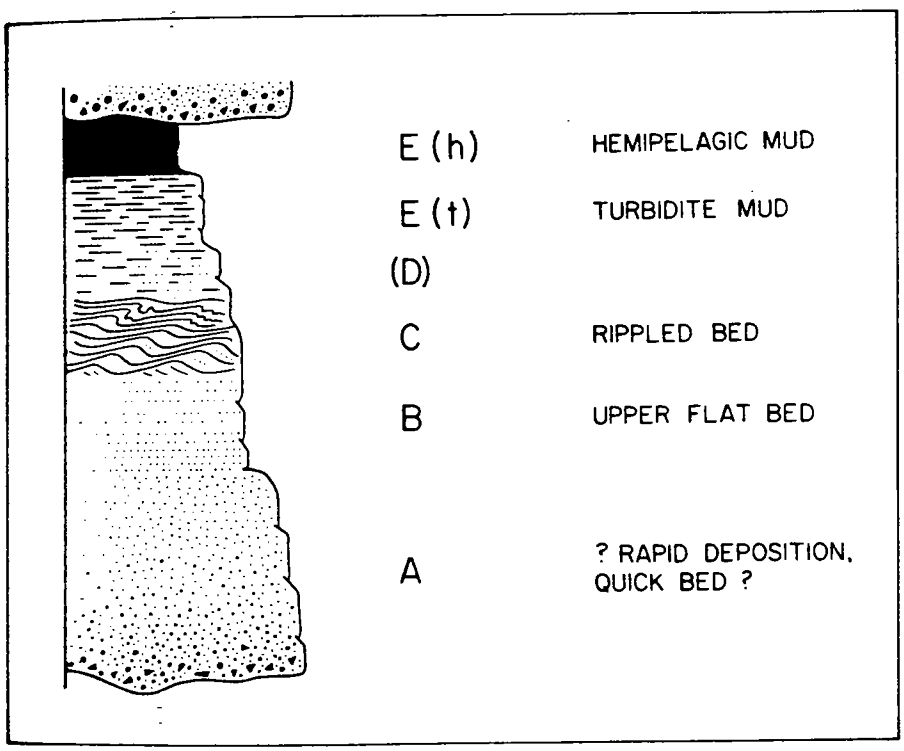

Figure 4
Five divisions of the Bouma sequence: A) massive or graded; B) sandy parallel laminations C) rippled and/or convoluted; D) delicate parallel interlaminations of silt and mud; E(t)) mud introduced by the turbidity current and E(h)) the hemipelagic background mud of the basin. See text for details.

or generalized sequence was proposed by Arnold Bouma in 1962. and the Bouma sequence (Figs. 3 and 4) can be regarded as an excellent facies model for *classical* turbidites (see "General Introduction", especially Fig. 9).

THE BOUMA SEQUENCE AS A FACIES MODEL

On a small scale, the Bouma sequence has functioned so well as a facies model that I will digress briefly to illustrate some of the ideas developed in the introductory paper to this volume. First, the Bouma sequence has been distilled from a vast number of examples - literally thousands of individual beds. It can therefore be regarded as a homogeneous model of great generality. It functions well as a *norm* (Fig. 4), or point of comparison, and hence helps to explain those turbidites without the full sequence (Walker, 1967). For example, without a norm we would not know that BDE turbidites were any more or less common than ABCDE turbidites. The *norm* establishes a general point of reference. The model has acted well as a *guide* for further observations, making one aware both of the features presented by any one bed, and of features embodied in the model that might be missing in any specific bed.

The model has acted well as a *predictor.* For example, if an outcrop shows beds that begin only with Bouma's division C, the model predicts that these were deposited from slower turbidity currents, perhaps in a more distal geographic setting than beds which begin with Bouma's division A (Fig. 5; Walker, 1967). Alternatively, groups of beds beginning with division C might be proximal levee deposits, laterally adjacent to beds beginning with division A in a nearby channel.

Finally, the model has acted as a general basis for hydrodynamic interpretations. Before the Bouma sequence, varied interpretations were offered for individual beds or groups of beds. The Bouma sequence suggests a single coherent interpretation (Fig. 4), with division A suggesting very rapid settling of grains from suspension, possible in such quantities and at such a rate that water is rapidly expelled upward, and momentaily the grain/water mixture becomes fluidized. Fluidization would

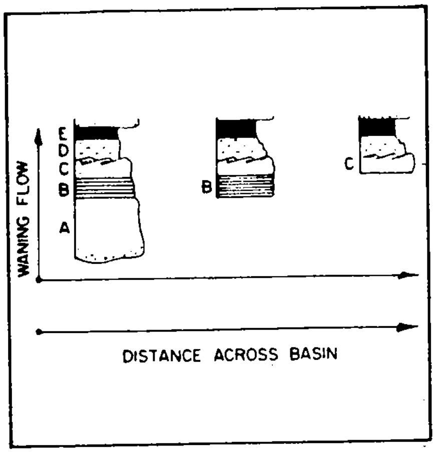

Figure 5
The ABCDE sequence in one individual turbidite suggests waning flow at the depositional site. Using the Bouma sequence as a predictor, we could suggest that groups of beds beginning with division B, and with division C, must represent deposition from progressively slower currents. Waning flow in the lateral sense can be correlated with distance flowed across the basin. There are limitations to this prediction - see text.

destroy any possible sedimentary structures except graded bedding. The second phase of deposition involves traction of grains on the bed, with division B representing the "upper plane bed" of experimental work (Harms *et al.*, 1982), and division C representing a rippled bedform. The upper flat bed passes directly into a rippled bed (with no formation of dunes) if the grain size is finer than about 0.15 mm (Southard, in Harms *et al.*, 1982, Figs. 2 to 5), as it is in many turbidites. If there is a high rate of deposition from suspension during rippling, climbing ripple cross lamination will form. Finally, as the flow dies away, turbidity current mud will blanket the bed (division (D) and E(t)), followed by hemipelagic mud E(h) (Fig. 4).

GENERAL TURBIDITE FACIES CLASSIFICATIONS

The above discussion was concerned with *classical turbidites,* those which consist of monotonous alternations of sandstones and shales, parallel bedded without significant scouring or channelling, and where all the beds can reasonably be described using the Bouma sequence.

It is interesting that the turbidite system was the first in which a universal facies scheme was proposed, by Mutti and Ricci Lucchi (1972). A universal scheme for fluvial deposits has recently been introduced and is discussed by Rust and Koster ("Coarse Alluvial Deposits", this volume). The Mutti and Ricci Lucchi scheme has been modified over the years (Mutti and Ricci Lucchi, 1975; Mutti, 1979), and is a more detailed scheme than is required here. I will use the simpler scheme introduced by Walker (1978), namely:

1) classical turbidites (discussed above),
2) massive sandstones,
3) pebbly sandstones,
4) conglomerates,
5) slumps, slides, debris flows and other exotic facies.

Both descriptive schemes serve their purposes well, and both can be related to deposition on various parts of submarine fans, as discussed below.

MASSIVE SANDSTONES

This facies consists of thick sandstones with thin (or absent) interbedded shales (Fig. 6). Individual sandstone beds range in thickness from about 50 cm to many metres, and the only Bouma division normally present is division A. A typical sequence of beds would be measured as A.A.A.A. using the Bouma model. However, I would consider this to be a mis-application of the Bouma model, because it is characteristically a five-part model being applied to beds that charateristically only contain one part. The functions of the model as norm, guide, predictor, and basis for interpretation are all seriously weakened to the point of uselessness if the beds only show an A.A.A.A. sequence.

The massive sandstones are commonly not so parallel sided as the classical turbidites; channelling is more common, and one flow may cut down and weld onto the previous one ("amalgamation") giving rise to a series of multiple sandstone beds.

The one common sedimentary structure found in the massive sandstones is termed "dish" structure, and is indicative of abundant fluid escape during deposition of the sandstone (Lowe, 1975). It indicates rapid deposition of a large amount of sand from a "fluidized flow" (akin to a flowing quicksand). This does not imply that the massive sandstone facies was transported all the way from source into the basin by a fluidized flow. However, it does imply that a turbidity current, which normally maintains its sand load in suspension by fluid turbulence, can pass through a stage of fluidized flow during the final few seconds or minutes of flow immediately preceding deposition. The massive sandstone facies is prominent in the Cambrian Charny Formation around Québec City and Lévis, and dish structures in massive sandstones are common in the Cambro-Ordovician Cap Enragé Formation (Hein,1982) near Rimouski,. Québec. Massive sandstones are also well represented in many of the Cretaceous and Tertiary turbidite sequences of California and Oregon (e.g., Link and Nilsen, 1980; Link *et al.*, 1981; Nilsen and Abbott, 1981; Link and Welton, 1982; Chan and Dott, 1983).

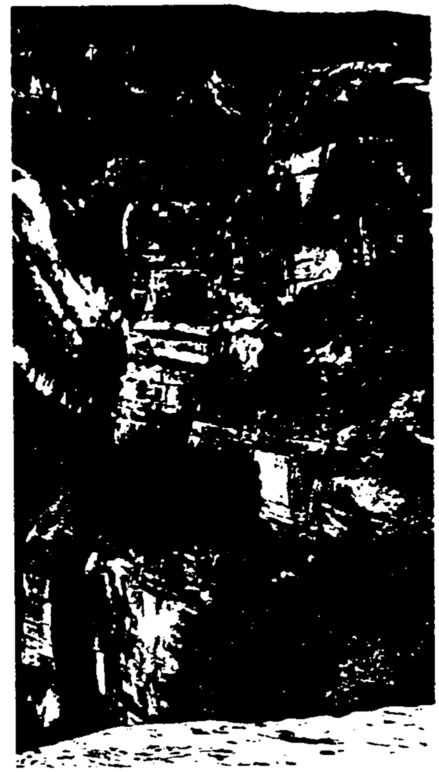

Figure 6
Massive sandstone facies: the Upper Eocene Annot Sandstone, southern France. About 180 m of section can be seen in the photograph. Note thickness of individual sandstone beds, and absence of mudstone interbeds.

PEBBLY SANDSTONES

The pebbly sandstone facies cannot be described using the Bouma model, nor does it have much in common with the massive sandstone facies. Pebbly sandstones tend to be well graded (Fig. 7),

Figure 7
Graded bed of pebbly sandstone, followed abruptly by a second bed without a mudstone interbed. St. Damase Formation (Orodvician) near Kamouraska, Québec.

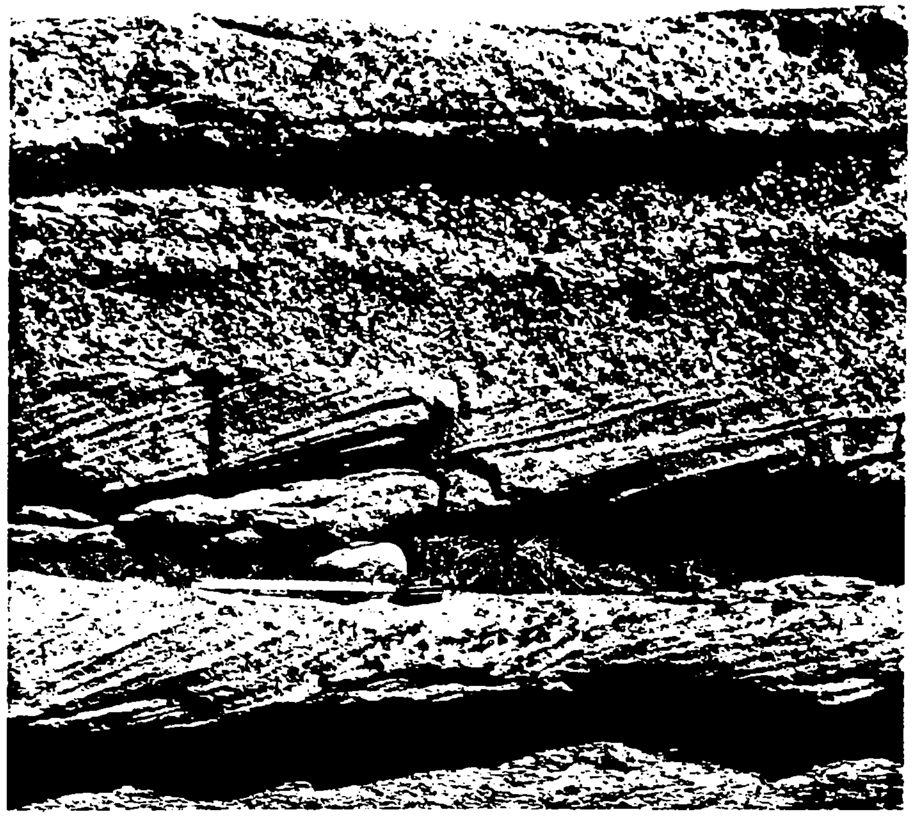

Figure 8
Pebbly sandstone facies showing medium scale cross bedding. In isolation, this photograph could easily be confused with one of fluvial gravels. In fact, it is from the Cambro-Ordovician Cap Enragé Formation, and the cross beds are interbedded with classical turbidites and graded pebbly sandstones.

and stratification is fairly abundant. It can either be a rather coarse, crude, horizontal stratification, or a well developed cross bedding of the trough, or planar-tabular type (Fig. 8). Imbrication of individual pebbles within the bed is common. At present, there is no "Bouma-like" model for the internal structures of pebbly sandstones; the sequence of structures, and their abundance and thickness has not yet been distilled into a general model. Models based on the characteristics of the Cap Enragé Formation have been proposed by Hein (1982). Pebbly sandstone beds are commonly channelled and laterally discontinuous, and interbedded shales are rare.

It is clear that with abundant channelling, and the presence of cross bedding in pebbly sandstones, this facies could easily be confused with a coarse fluvial facies (see "Coarse Alluvial Deposits", this volume). The differences are subtle and can be misleading to sedimentologists – the safest way to approach the interpretation of pebbly sandstones is to examine their context. If associated with, or interbedded with classical turbidites, the pebbly sandstone interpretation would be clear. Similarly, if associated with non-marine shales, root traces, caliche-like nodules, mud cracks, and other indicators of flood plain environments, the interpretation would also be clear. This facies highlights the fact that environmental interpretations cannot be based upon a "checklist" of features: the relative abundance and type of features, in their stratigraphic context, must always be the basis of interpretation.

Pebbly sandstones are particularly well exposed in the Cambro-Ordovician Cap Enragé Formation (Hein, 1982) at St. Simon (near Rimouski, Québec), where grading, stratification and cross bedding are prominent. The facies is also abundant in the Cambrian St. Damase Formation near Kamouraska, Québec, and in the Cambrian St. Roch Formation at L'Islet Wharf (near St-Jean-Port-Joli, Québec) (Walker, 1979). Many examples exist in the Cretaceous and Tertiary turbidite sequences of California and Oregon (e.g., Nilsen and Abbott, 1981).

CONGLOMERATES

Although volumetrically less abundant than classical turbidites, conglomerates are an important facies in deep water environments. They are abundant in California and Oregon (e.g., Walker, 1977; Nilsen and Abbott, 1981), and are particularly well exposed at many localities in the Gaspé Peninsula (Davies and Walker, 1974; Hendry, 1978; Johnson and Walker, 1979; Hein, 1982). Sedimentologists have tended to ignore conglomerates, probably because without a facies model, there has been no framework to guide observations, and hence the feeling of "not being quite sure what to measure in the field". I have proposed some generalized "Bouma-like" models for conglomerates (Walker, 1975a), but because the models are based upon

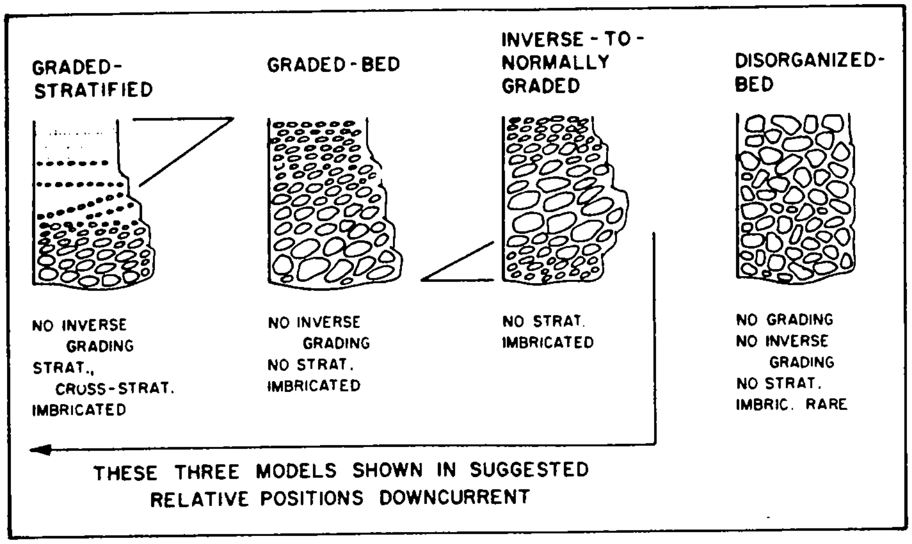

Figure 9
Four models for resedimented (deep water) conglomerates, shown in their inferred downcurrent relative positions. See text for details.

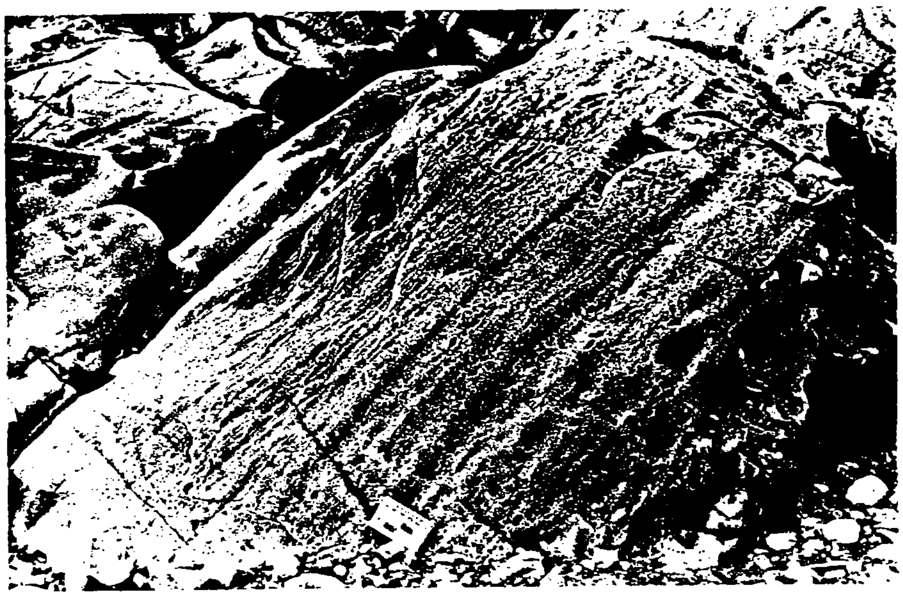

Figure 10
Normally-graded and stratified conglomerate, Cambro-Ordovician Cap Enragé Formation, Bic, Québec. Basal conglomerate rests on slates, and grades up into stratified conglomerate, very coarse sandstone with crude "dish structure", and finally into massive structureless sandstone.

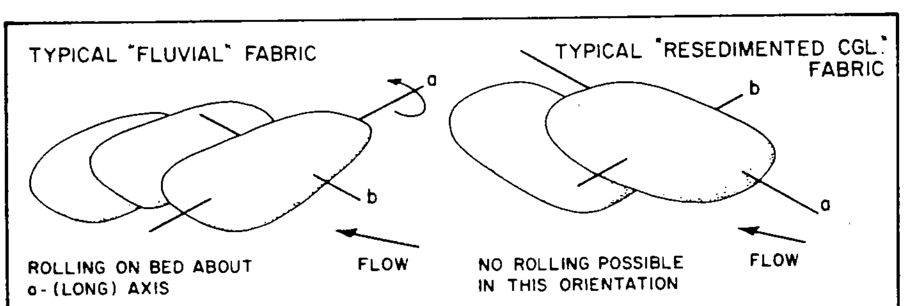

Figure 11
Contrast between a fabric produced by clast rolling (a-axis transverse), and a fabric characteristic of resedimented conglomerates (a-axis parallel to flow and dipping upstream). The a-axis-parallel fabric is incompatible with clast rolling, and is believed to form by clasts colliding in the flow, whilst dispersed above the bed.

fewer than thirty studies, they lack the universality and authority of the Bouma model for classical turbidites. The paper (Walker, 1975a) discusses the models, their relationships, and how they were established. In Figure 9, it can be seen that the descriptors include the type of grading (normal [Fig. 10] or inverse), stratification (Fig. 10), and fabric; in different combinations they give rise to three models which are probably intergradational, and a fourth (disorganized-bed) characterized only by the absence of descriptors.

One of the most important features of conglomerates is the type of fabric they possess. In fluvial situations, where pebbles and cobbles are rolled on the bed, the long (a-) axis is usually transverse to flow directions, and the intermediate (b-) axis dips upstream, characterizing the imbrication. However, for most conglomerates associated with turbidites, the fabric is quite different: the long axis is parallel to flow, and also dips upstream to define the imbrication (Fig. 11). This fabric is interpreted as indicating no bedload rolling of clasts. The only two reasonable alternatives involve mass movements (debris flows), or dispersion of the clasts in a fluid above the bed. Mass movements in which clasts are not free to move relative to each other do not produce abundant graded bedding, stratification, and cross-stratification, so I suggest the clasts were supported above the bed in a turbulent flow. The support mechanism may have been partly fluid turbulence, and partly clast collisions. Upon deposition, the clasts immediately stopped moving (no rolling), and the fabric was "frozen" into the deposit.

In the absence of experimental work on cobbles and boulders, the interpretation of the conglomerate models must be based largely on theory. I suggest a downcurrent trend from the inverse-to-normally-graded model, into the graded-stratified model. This trend does not necessarily exist in any one bed: rather, deposition from a particular current in one of the three downstream positions in Figure 9 will be of the type indicated in the figure.

Clast supported conglomerates are abundant in the Ordovician Grosses Roches Formation (Hendry, 1978) and Cambro-Ordovician Cap Enragé Formation (Hein, 1982; Hein and Walker, 1982), Gaspé Peninsula, Québec, and also make up part of the Cambrian St. Roch Formation east of Rivière-du-Loup, Québec. They are abundant in California and Oregon (Walker, 1977 and in press; Nilsen and Abbott, 1981).

SLUMPS, SLIDES, DEBRIS FLOWS AND EXOTIC FACIES

This facies includes a diverse group of rocks which are generally poorly to unstratified, which are commonly poorly sorted (blocks and boulders in a fine grained matrix), and which may show evidence of sedimentary deformation.

The debris flow deposits have clasts supported in a muddy matrix - they may show basal inverse grading and preferred clast alignment. Because the larger clasts in a debris flow are maintained above the bed by the strength of the matrix, the deposit commonly has large blocks projecting up above the top of the bed, or even resting almost entirely on top of the bed. The deposit shows no internal evidence of slumping.

By contrast, other exotic facies commonly show evidence of slumping, and represent the mixing of sediment within the depositional basin by post-depositional slumping. The deposits can range all the way from very cohesive slumps involving many beds, to very watery slumps generated by the deposition of coarse sediment on top of wet, poorly consolidated clays. The latter process gives rise to the classical pebbly mudstones (Crowell, 1957; Howell and Joyce, 1981).

Inasmuch as subaqueous debris flows, and slumps, require greater slopes than classical turbidity currents, the chaotic facies is most abundant at the foot of the slope into the basin. Very few examples have been described in Canada. Large scale slumps are known in Upper Ordovician turbidites in northeastern Newfoundland (Helwig, 1970), and pebbly mudstones are known in several units in western Newfoundland (Stevens, 1970). The best described debris flows are Devonian reef-margin examples adjacent to the Ancient Wall, Miette and Southesk-Cairn reef complexes in Alberta (Cook *et al.*, 1972; Srivastava *et al.*, 1972). Elsewhere, slumps have been described from the Tortonian of northwestern Italy (Clari and Ghibaudo, 1979), the Plio-Pleistocene of northern California (Piper *et al.*, 1976) and the Miocene of New Zealand (Gregory, 1969).

TURBIDITES IN MODERN OCEANS

Effective facies models must combine data from ancient and recent sediments, and hence it is necessary to review briefly what is known about turbidites in modern oceans. The main depositional environments are submarine fans (which may coalesce laterally to build up the Continental Rise) and basin plains. By far the greatest volume of modern turbidites occur in the submarine fans.

Many different submarine fans have now been described, and general models that try to summarize this work have been presented by Normark (1970, 1978). In his 1970 paper ("Growth patterns of deep-sea fans"), Normark proposed a general model, widely accepted by the profession, that was built essentially on data from only two California Borderland fans, La Jolla and San Lucas. The model consisted of three parts - a leveed valley on the upper fan, a mid-fan built up of suprafan lobes that periodically switched position, and a flat lower fan without channels. Many more examples were incorporated in Normark's (1978) later statement of the model (Fig. 12).

The most detailed study of the evolution of a small fan is that of Normark *et al.* (1979) and Piper and Normark (1983) for Navy Fan, California Borderlands. Based on precision echo sounding, seismic reflection profiling and side scan sonar, a three-dimensional physiographic map of Navy Fan was produced, showing the surface and subsurface locations of six suprafan lobes. By studying the way in which these lobes overlap, an evolutionary sequence was determined (Fig. 13).

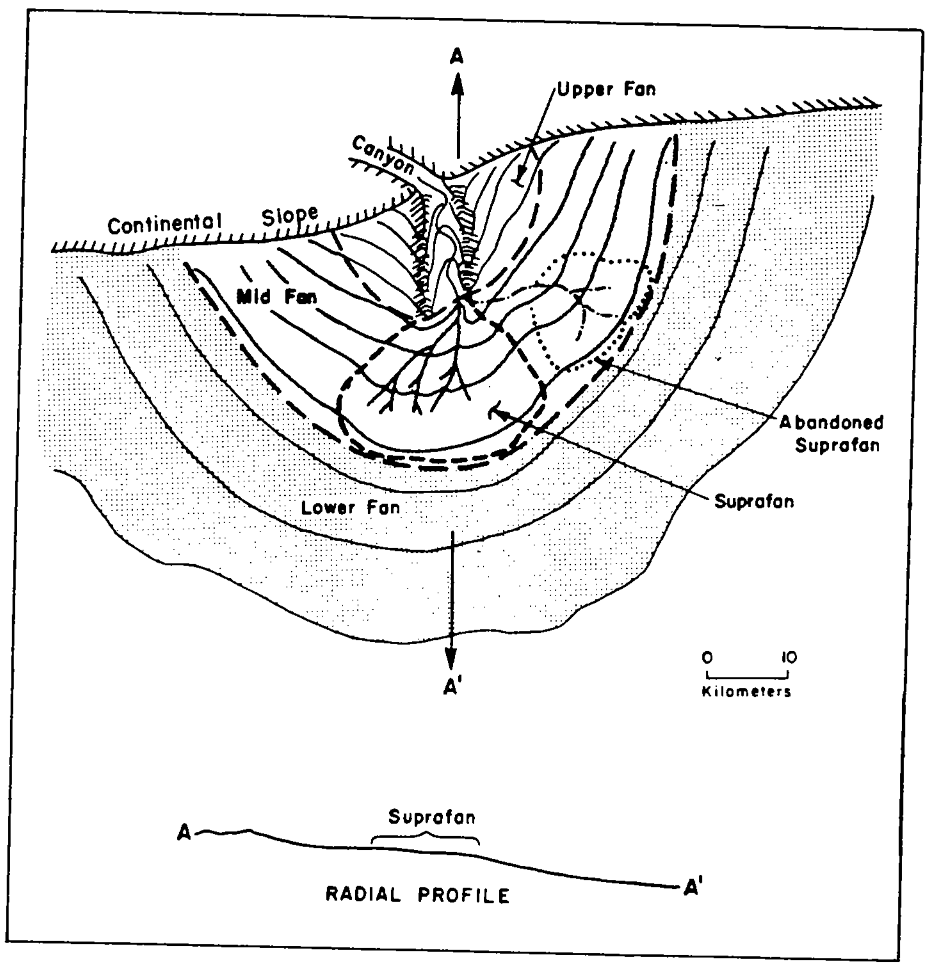

Figure 12
Submarine fan model of Normark (1978), based on several studies of modern fans. This model for fan growth emphasizes active and abandoned depositional lobes termed suprafans.

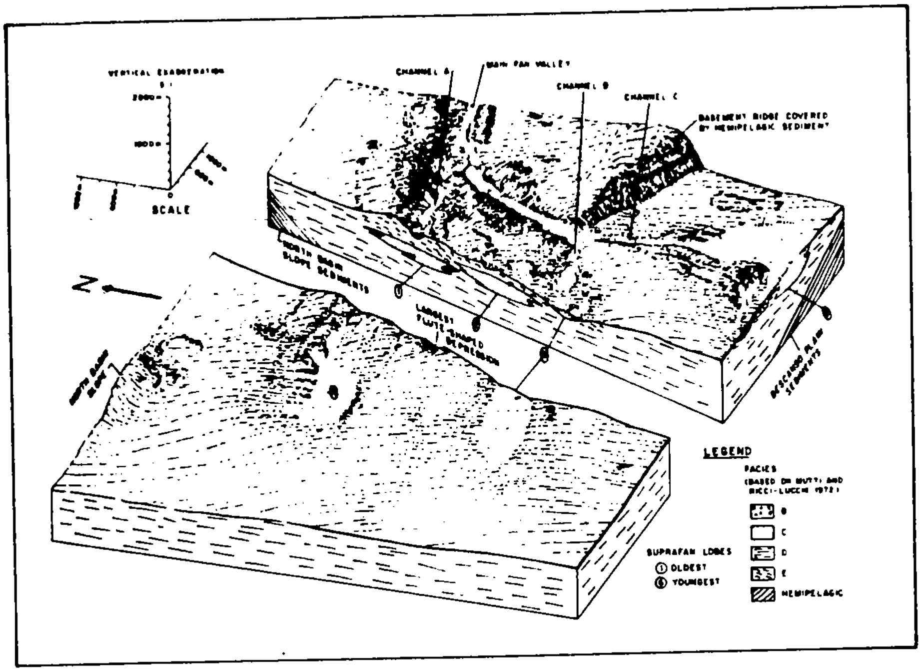

Figure 13
Block diagram of Navy Fan, California, based on seismic reflection profiling. Note suprafan lobes at ends of channels, with lobe 6 at the end of channel B being the youngest. From Normark et al. (1979) - these authors discuss in detail the pattern of channel and lobe switching. This fan strongly supports the ideas embodied in Normark's fan model (Fig. 12).

The upper fan has a single leveed channel that is about 400 m wide, but decreases in depth from 50 to 15 m over a length of 8 km. Only distributary channel B (Fig. 13) is presently continuous with the upper fan leveed channel. The pattern of channel switching suggests that as one lobe grows, and its feeder channel aggrades (or backfills), it eventually initiates a levee break and turbidity currents are diverted to a lower part of the mid-fan surface to begin construction of a new lobe. Thus on Navy Fan, the mid-fan is built up of a series of individual lobes formed by distinct jumps in the positions of distributary channels (not gradual lateral channel migration). The implication is that when lobe 5 (say) is active, lobes 1,2 and 4 receive only fine grained muds spilled over the distributary channel margins. In other words, when one suprafan lobe is active, other lobes and their former distributary channels are being blanketed by mud. This process is important in forming stratigraphic traps over potential suprafan oil and gas reservoirs. The geometry of individual beds, and their mode of deposition, has been studied in detail by Piper and Normark (1983).

Although Navy Fan has been studied in the most detail, Normark's (1978) later model was based particularly on Astoria, Monterey, Amazon and Bengal Fans (large fans built on oceanic crust), and Redondo, La Jolla, Navy and San Lucas Fans from the California Borderland. Since 1978, there have been detailed studies of Laurentian Fan (Uchupi and Austin, 1979; Stow, 1981; Piper and Normark, 1982; Normark *et al.*, 1983), Mozambique Fan (Kolla *et al.*, 1980), Amazon Cone (Damuth and Embley, 1981; Damuth *et al.*, 1983a, 1983b), Zodiac Fan (Aleutian Abyssal Plain, Stevenson *et al.*, 1983), Magdalena Fan (Colombia; Kolla *et al.*, 1984) and La Jolla Fan (Graham and Bachman, 1983).

These studies cannot easily be combined with Normark's (1978) model. For example, the Amazon Cone appears to have three huge "slump/debris flow complexes" which cover areas of 32,500 km^2, 28,850 km^2 and 21,200 km^2 (Damuth and Embley, 1981, p. 633–637). The thicknesses are less than 75 m, 10 to 50 m and up to 50 m, respectively. It is not clear how these complexes formed on the very low slopes of the fan. Also on Amazon Cone are a series of channel-levee complexes, with amazingly sinuous channel patterns (Damuth *et al.*, 1983a) which cannot be related to present concepts of turbidity current flow.

Remarkably little is known about the ages and thicknesses of major submarine fans. Few have been penetrated completely during the Deep Sea Drilling Program. Many appear "to have built out substantially since Miocene time, and especially during Pleistocene time" (Kelts and Arthur, 1981). Thicknesses range from about 300 m (margin of Astoria Fan) to well over 10 km (Bengal Fan). Rates of deposition can be incredibly high; at DSDP site 222 on the Indus Cone, sediment was deposited at 600 m/m.y. in the late Miocene, 135 to 350 m/m.y. in the Pliocene, and at less than 50 m/m.y. in the Quaternary (Whitmarsh *et al.*, 1974).

Fan sediments tend to pass distally into basin plain deposits. Here, the turbidites tend to be very extensive and continuous (Pilkey *et al.*, 1980), with more abundant and thicker sands close to points of entry onto the basin plains. Thicknesses on modern abyssal plains tend to be only a few hundred metres (Horn *et al.*, 1972). These few generalities constitute the essence of a "model" for abyssal, or basin plains.

The problem of coring deep sea facies, particularly the sands, and preserving long (several metres) sections with sedimentary structures, makes the comparison of modern and ancient turbidite facies rather difficult. Modern fan studies have contributed data on fan morphology on a rather large scale, whereas most studies of ancient rocks have been of a smaller scale. Studies such as those by Normark *et al.* (1979) and Damuth *et al.* (1983a, 1983b) are beginning to show the fine topographic details of modern fans – the problems of comparison are addressed below.

GENERAL FAN MODELS: COMPARISON OF ANCIENT AND RECENT SEDIMENTS

Interpretations of ancient sediments as fan deposits began in the early 1960s (Sullwold, 1960; Walker, 1966), but became more common as more modern fans were studied (Normark, 1970). Emiliano Mutti and his colleagues in Italy contributed extremely influential work (especially Mutti and Ricci Lucchi, 1972; Mutti and Ghibaudo, 1972), proposing a fan model based upon ancient rocks in Italy. This model was so similar

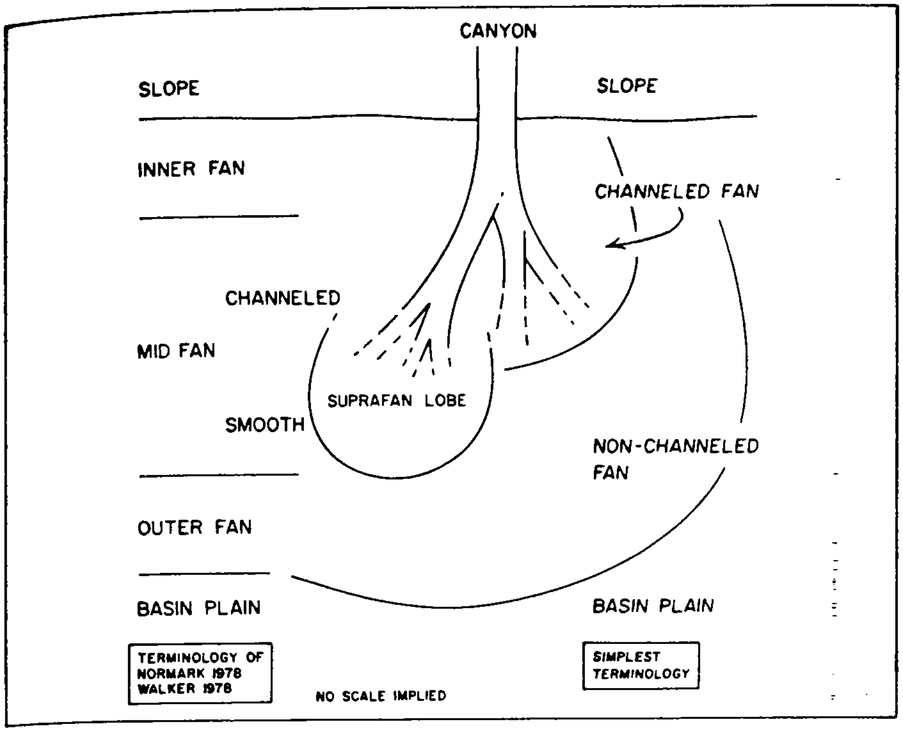

Figure 14
Simplified fan model. On the right is the simplest possible terminology, showing the absolute basics of almost all ancient and modern fans. On the left is a terminology which, although a little more complex, embodies the salient characteristics of Normark's model (Fig. 12) for modern fans along with the characteristics proposed by Mutti and colleagues for many inferred ancient fans.

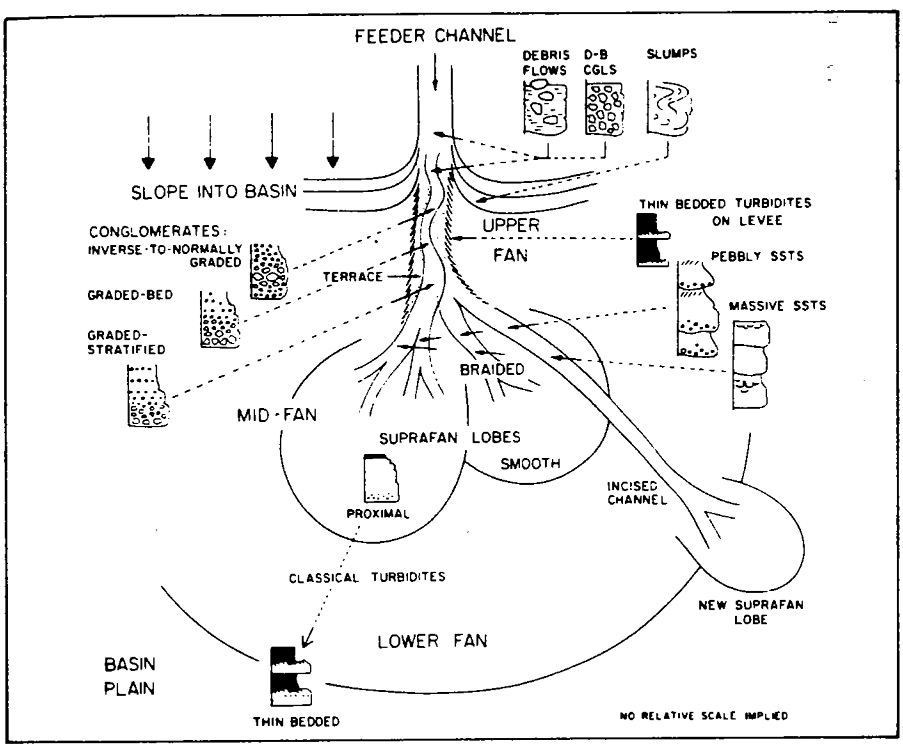

Figure 15
Fan model proposed by Walker (1978). Note that it incorporates features (terraces, inner fan meandering channel, levees, etc.) which although common, may not occur on all fans. Facies defined in ancient rocks are shown in their inferred positions on the fan. An incised channel is also shown, indicating a phase of downcutting, fan extension, and new lobe development (as in the modern La Jolla Fan of California).

to that of Normark's for modern fans that modern and ancient studies were distilled together to form the first modern-ancient integrated model (Walker and Mutti, 1973). As more work has been done, this model has evolved and diversified (see Walker, 1980, p. 1101-7), and I use the sketch in Figure 14 as a starting point. In the simplest possible terminology, almost all modern fans can be subdivided into a *channelled* fan, a *smooth* fan, and a basin plain. Many modern fans can be described by the terminology on the left (Fig. 14):

1) an inner (or upper) fan with a single channel
2) a mid fan, consisting of shallower branching channels which feed a depositional lobe (the "suprafan" of Normark, 1978)
3) a topographically smooth outer (lower) fan, which grades into
4) a basin plain.

Details can be added to this scheme; for example, the inner fan channels on some fans have prominent levees, and a flat aggradational floor with a smaller thalweg. This is typical of the inner fan channel of La Jolla Fan, where the main channel is 1 to 2 km wide, and about 140 m deep. The incised channel meanders within the main channel, and is about 200 to 300 m wide and 20 m deep. An example of a more complex fan model is given in Figure 15.

Currently, variations on this simple statement of the model (Fig. 14) include fans with prominent channel deposits but apparently no lobes, fans with abundant lobe deposits but fewer channels, and coalesced inner fan deposits that consist largely of channel-levee complexes. Because there are only one or two examples of each of these, it is probably premature to suggest many different fan *models*. It is important to understand how the existing general model(s) can be adapted to account for these new situations.

FACIES AND FAN MORPHOLOGY

Mutti and Ricci Lucchi (1972) assigned their turbidite facies to three associations - slope, fan, and basin plain. The schemes in Figures 14 and 15 are developed from this. The data base for the diagrams is a blend of ancient rock characteristics (especially grain size and observed frequency of channelling associated with the facies) and mor-

…ology of modern fans. The weakest …t of the model is the relative lack of …ore data from modern fans.

Classical turbidites are spectacularly …arallel bedded and unchannellized in …he field, and hence are assigned to …mooth fan environments - smooth …uter parts of suprafan lobes, lower fan, …d basin plain (Fig. 15). Beds change …om being relatively coarse, thick-…edded and beginning with Bouma's …vision A to beds that are finer, thinner …edded, and beginning with divisions B …d or C with increasing distance from …e ends of the distributary channels.

Massive and *pebbly sandstones* are …mmonly channellized in the field, and …nce are assigned to channellized fan …vironments (Fig. 15). The finer facies …cur in the distributary channels, and …arse facies occur higher on the fan …face, toward the inner fan channel.

Conglomerates, if supplied to the …n, tend to occur in the inner fan …annel, or as a lag in some of the dis-…utary channels (Fig. 15).

Major complications occur in the …er fan channel-levee complexes, …ere thin bedded classical turbidites …ginning with Bouma's division B or … may occur on channel margins or …ees, or in the basins behind the …ees. Local facies changes may also …ive finer beds on the terraces and …arser beds plugging the incised inner … channel.

… general, these facies assignments … accepted by most workers, and they …w the development of specific facies …uences that seem to be characteris-… particular fan environments.

…IES SEQUENCES

…uences are basically related to lobe …gradation and aggradation, and to …nnel filling. The formative ideas are …se of Mutti and Ghibaudo (1972), … it is now fair to state that:

most fan interpretations are based on facies sequences;
facies sequences are being used to modify fan models; and
some alleged facies sequences exist only in the eye of the beholder!

…epositional lobes, the marginal …es will tend to be thinner bedded … those near the apex of the lobe; …sequently, if the lobe progrades it … produce a *thickening-upward* …uence (Fig. 16). As well as thickening-upward, the sequence may also become coarser grained upward, and beds that begin with Bouma's division C and B will tend to be replaced upward by beds beginning with division A. Thickening-upward sequences are very common in the geological record – prograding lobe fringes may form sequences only a few metres thick composed of relatively thin bedded turbidites, whereas an entire lobe may form a sequence typically a few tens of metres in thickness.

By contrast, *thinning-upward sequences* (Fig. 17) were interpreted by Mutti and Ghibaudo (1972) to represent gradual channel filling and abandonment. Thinning-upward sequences tend to be a few metres to about 50 m thick, and in those cases where a channel morphology can be observed in the field, the lower beds of the fill are commonly pebbly or massive sandstones, rather than classical turbidites. Many channels on modern fans are deeper than 50 m, especially on the inner fan, but systematic thinning-upward sequences more than 50 m thick are

Figure 16
Ordovician Cloridorme Formation, Québec, showing beds slightly overturned with stratigraphic top to left. Note prominent thickening-upward sequence (arrowed), with abrupt return to thin-bedded turbidites and mudstones at the top.

Figure 17
Cambrian St. Roch Formation near St. Jean-Port-Joli, Québec. Note prominent thinning-upward sequence (arrowed) which begins with a massive sandstone facies (compare with Fig. 18), and is interpreted as a channel fill.

Figure 18
Thinning-upward sequence (arrowed) in the Paleocene turbidites at Shelter Cove, Point San Pedro, Calfiornia. The spectacular continuity of the turbidites, and absence of a massive sandstone facies suggest that this sequence is not necessarily a channel fill. It may result from lateral lobe switching, with the thicker beds at the lobe centre, and the thinner beds representing lobe fringe. Alternatively, the turbidites may be interchannel, the thinning-upward sequence representing channel migration away from this area.

Figure 19
Thinning-upward sequence (arrowed) from turbidites, via a soft sediment slump (small arrows show way up) into mudstones. Stratigraphic top to right; Cretaceous tubidites at Wheeler Gorge, California. Compare this sequence with those in Figures 17 and 18. It probably represents neither channel filling nor lobe switching - its context, and especially the slumping, suggests deposition on a levee. The thinning-upward may reflect migration of the main turbidite channel away from the levee. See Walker (in press).

uncommon in the geological record. This suggests that deeper turbidite channels fill in a more complex way than the shallower ones. For example, well logs from the Miocene Rosedale Channel of California (Martin, 1963, Figs. 5, 6 and 7) indicate several packets of sand alternating with finer grained sediments in a channel fill up to about 400 m thick. There is certainly no suggestion of an overall fining-upward sequence. Similarly, channel-levee complexes in the Paleocene Frigg Fan of the North Sea (Heritier *et al.*, 1979, Figs. 9, 10, 12, and 13) may be 200 m or more in thickness, but are apparently compound, and not single channel fills. Relief on any single channel (floor to levee crest) is indicated to be about 60 m (Heritier *et al.*, 1979, Fig. 13).

The association of *thinning-upward sequences* with *channel filling* has become a standard part of the fan model, but it is becoming apparent that some thinning-upward sequences, especially those composed only of relatively thin-bedded classical turbidites, imply other processes. For example, the sequence shown in Figure 18 exhibits convincing thinning-upward, but the thin-bedded classical turbidites and smooth sea floor do not suggest channelling. The sequence could indicate gradual lateral lobe shifting, from a lobe centre to lobe fringe environment. Similarly, the sequence in Figure 19 also shows thinning-upward, but the soft-sediment slumping and thin-bedded turbidites could indicate deposition on the back of an inner fan levee, the sequence being due to gradual migration of the channel away from the depositional area.

If an entire fan complex were to prograde, an idealized sequence predicted by the fan model as its various lobe and channel sequences build up would be similar to that shown in Figure 20, which is largely self-explanatory. One of the most useful aspects of thickening- and thinning-upward sequences is that they can be recognized in sub-surface well logs. In Figure 21, I show one possible interpretation of an SP and resistivity log (see "Subsurface Facies Analysis", this volume) from Devonian turbidites in Pennsylvania. Again, the comparison of Figures 20 and 21 is obvious, and shows how the fan model can be used as a basis for interpretation. Many other examples are given by Walker (1978), and by Tillman and Ali (1982) who have compiled a very useful series of turbidite papers into a reprint volume of the American Association of Petroleum Geologists.

FEEDBACK: THE EVOLUTION OF FAN MODELS

In the first paper of this volume, it was emphasized that models are formed by the "distillation" of many local examples. It follows that as new examples are studied, there is more input, or feedback, into the model, and hence the possibility for the model to evolve. Currently, fan models are evolving as the result of more studies of ancient rocks, and better studies of modern fans.

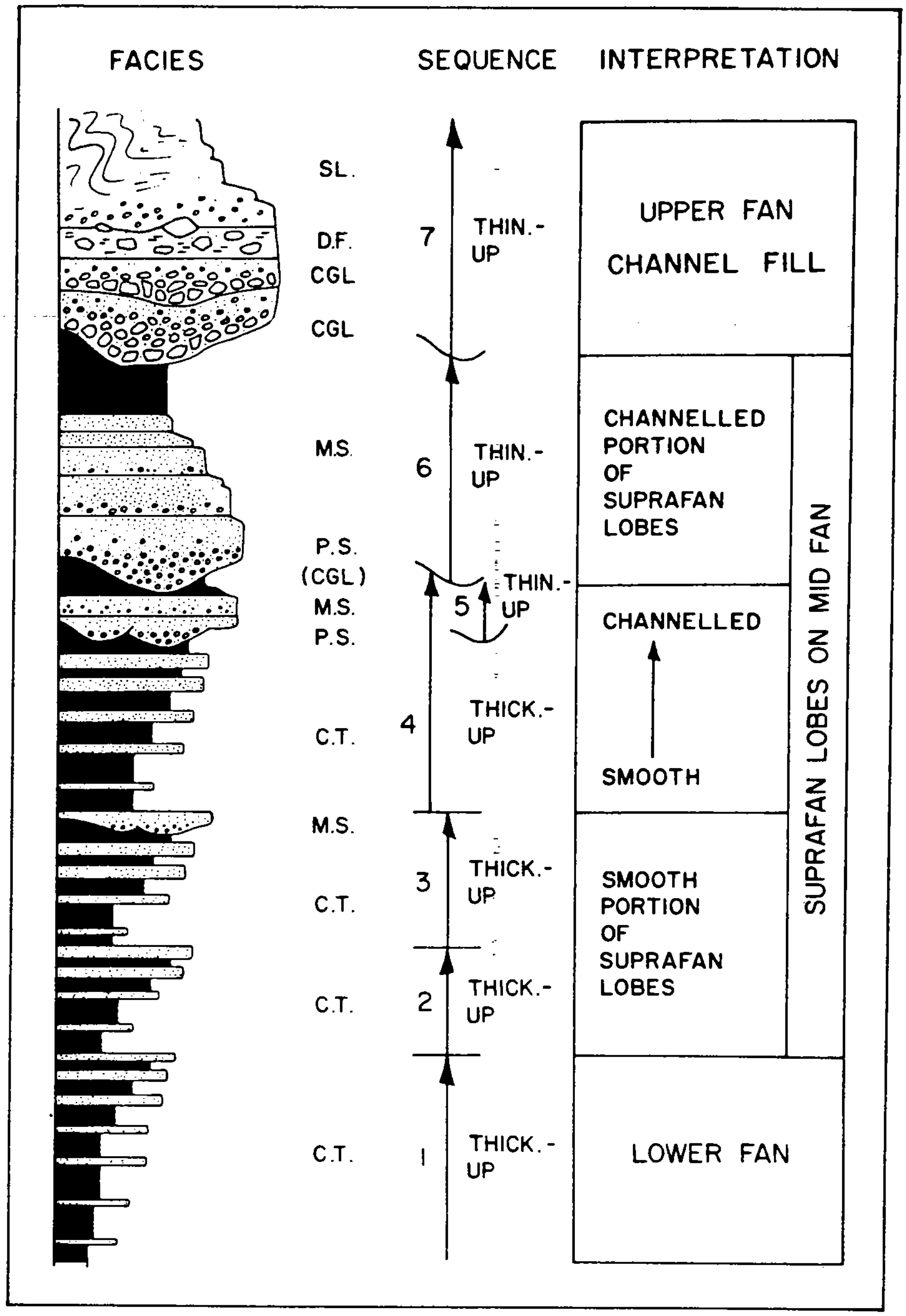

Figure 20
Generalized hypothetical sequence produced during over-all fan progradation. CT = classical turbidites; MS = massive sandstones; PS = pebbly sandstones; CGL = conglomerate; DF = debris flow; SL = slump. Sequences shown by arrows are THIN.-UP (thinning upward) or THICK.-UP (thickening upward).

The input from ancient rocks comes particularly from work on facies sequences. I mentioned earlier that some of these sequences perhaps exist only in the eye of the beholder – this is illustrated in Figure 22, and the general problem has been addressed by Hiscott (1981). One modification of the general fan model of Figure 14 is the "fan of low transport efficiency" (Mutti, 1979), in which most of the sand is deposited in channel complexes rather than on lobes. The evidence comes both from observations of channel contacts in the field, and from the abundance of thinning-upward sequences observed in units such as the Eocene Tyee Formation of Oregon (Chan and Dott, 1983) and The Rocks Sandstone of California (Link and Nilsen, 1980). A measured section of The Rocks is shown in Figure 23, where the thinning and fining-upward sequences are shown. Note that sequences average about 10 m in thickness; they mostly have erosional bases, and involve individual sandstone beds up to 7.5 m thick.

In using this example to modify existing models, note that two levels of interpretation are involved – first, the existence of the sequences themselves is an interpretation (and some of the sequences involve very few beds, and/or unconvincing thickness trends, Fig. 23), and second, it is an interpretation to suggest that the sequences necessarily involve channel filling. However, in view of the bed thickness and erosional bases, the latter interpretation seems reasonable and convincing.

A second modification of the basic fan model of Figure 14 is the recognition of channel-levee complexes, rather than a single channel with a levee. Channel-levee complexes exist on modern fans such as the Amazon (Damuth *et al.*, 1983a, 1983b), Indus, Laurentian (Stow, 1981) and Crati (Colella *et al.*, 1981), and are possibly present in ancient examples such as the Paleocene-Lower Eocene Frigg Fan (North Sea; Heritier *et al.*, 1979).

A channel-levee complex is essentially a central channel with fine-grained sediment wedges on either side. The wedges stand up above the general topography of the basin floor, but gradually lose their relief away from the channel and merge with the basin floor. Most active levees appear to be constructed by spill-over from turbidity currents using the channel. Dimensions are extremely variable – on the Amazon Cone, mid-fan channel-levee complexes are up to 500 m thick and 25 km wide and those on the Laurentian Fan are a little thinner and perhaps a little wider (Stow, 1981). On a much smaller scale, the upper fan channel-levee complex on Crati Fan (Southern Italy; Colella *et al.*, 1981) is a total of 5 km wide, and is built up from at least 3 channels a little over 10 m deep.

Channel-levee complexes differ from fans of low efficiency, in that the latter are sand-rich, whereas the bulk of the channel-levee complex is relatively fine-grained. In the Amazon example, channels appear to switch abruptly by avul-

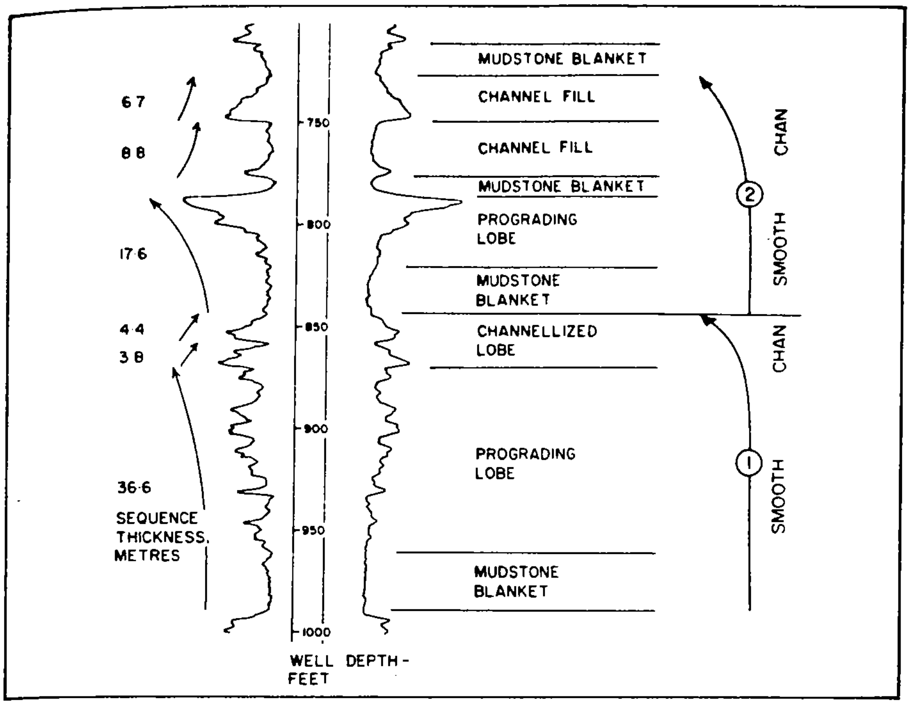

Figure 21
SP and resistivity logs from a turbidite formation in Pennsylvania. I have interpreted the shapes of the SP/resistivity trends as channel fill ("bell-shaped") or lobe progradation ("funnel-shaped"), with some mudstone blankets in between. Note that two overall lobe-to-channel sequences can be defined (see Fig. 20), the lower one having a greater proportion of lobe deposits (smooth fan surface), the upper one having a greater proportion of channel deposits.

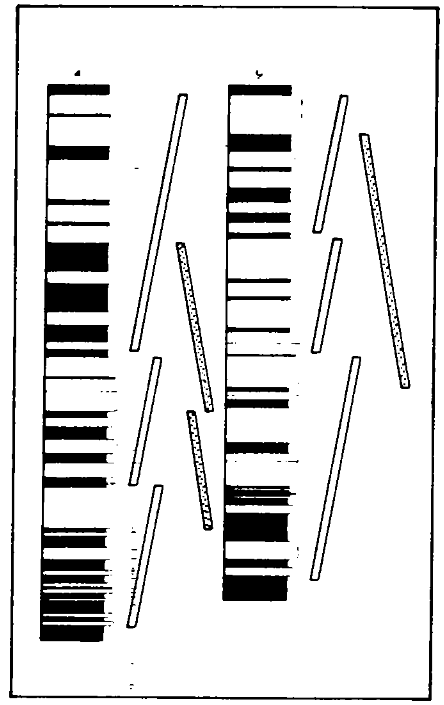

Figure 22
Some sequences in turbidites are "in the eye of the beholder". This diagram is from Mutti and Ghibaudo (1972) and shows part of their Figure 15 from the Miocene Arenarie di San Salvatore. Open bars show "negative megasequences", that is, thickening-upward sequences as proposed by Mutti and Ghibaudo. However, I have added some extra bars, stippled, which propose positive megasequences, or thinning-upward sequences. The reader should decide which sequences are preferable, remembering that one implies lobe fringe progradation, the other implies channel filling on a different part of a fan.

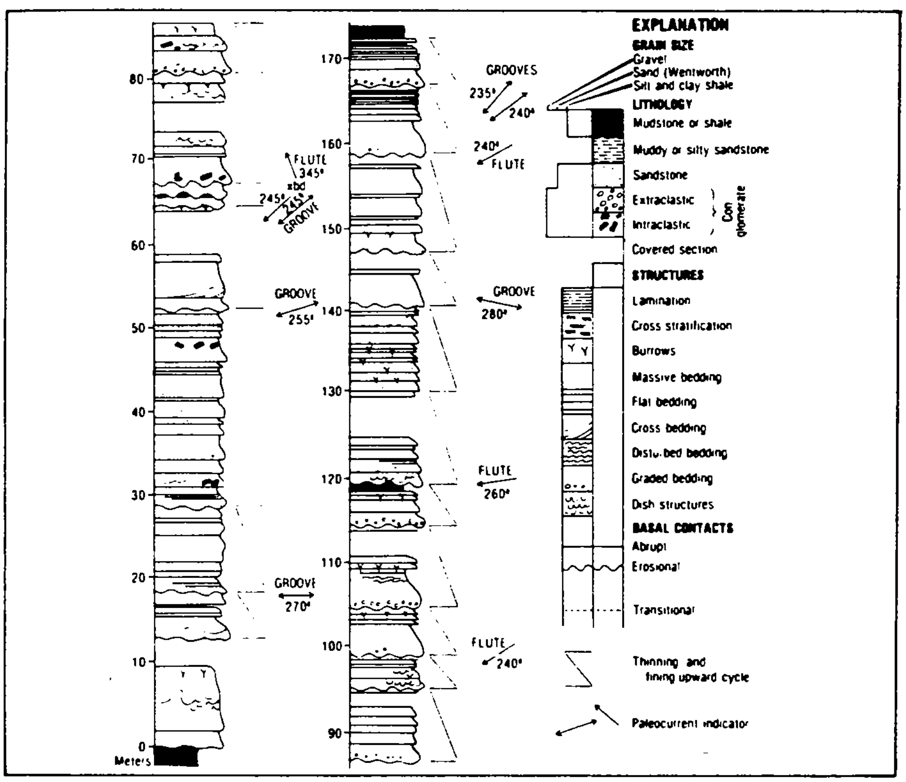

Figure 23
Measured section of The Rocks Sandstone (Eocene) in the Santa Lucia Range, California. Note the "thinning- and fining-upward cycles"; some are based on very few beds, or only show very weakly the proposed trends. Others seen well established with erosional (or channelled) bases. From Link and Nilsen, 1980.

sion (Damuth *et al.*, 1983a, 1983b), but in other fans (possibly the Indus is a good example) the channel appears to migrate progressively laterally, eroding into its older levee deposits as the whole system aggrades.

In the geological record the only well described candidate for a channel-levee complex is Frigg Fan in the Paleocene-Lower Eocene section of the North Sea (Heritier *et al.*, 1979). The fan is composed of four radiating sandy fingers apparently without well defined depositional lobes at the end. The topographically highest fingers are 2 to 4 km wide, and about 600 m thick. Within the fingers, there are interbedded channel turbidites, sandy levee deposits, and back-levee or interchannel shales. A second possible candidate is an Upper Cretaceous conglomerate channel complex

...er Gorge, California (Walker, ... in press), where the conglo... are overlain by several ...-upward sequences of thin-... turbidites with abundant slump ... The vertical succession of ...nerates to thin-bedded turbi... slumps suggests the migra... conglomerate-filled channels ... the area, with the slumped ...ded turbidites representing ... deposits of (? nearby) higher ...erate-filled channels.

...IONS OF FAN MODELS

...when the "turbidite facies ...st appeared in Geoscience ... was one of the better defined ...many published studies in the ... years have described systems ... considerably from that model ...iency fans, channel-levee ...), and descriptions of mod... show variations from the sum... of Normark (1978). I believe ...efinitely premature to propose ...erent types of fan models - ...ase for each proposed type is ... It seems better to regard the ... model" (Fig. 14 is but one ... as a norm, hence identifying ...iciency fans as different from ... is thus a fixed point for the ... of many different fans, and ...dified to suppress the deposi...es, and emphasize the chan...annel-levee complexes, as ... Once modified, it should ...sible to use the model in a ... way, understanding how the ... of the model will affect ...d lobe distributions, sand ...etry, etc.

...nted, the fan model seems to ... framework for the investiga... to medium scale ancient ...ingle points of input (single ...nnels) into the basin. The ... much of its power if two ...ns overlap, because facies ... may no longer be controlled ...ocesses (e.g., lobe progra... may be the result of irregu...ing of beds from multiple ...

...odel may also lose some ... applied to long (hundreds ...w "exogeosynclinal" ...which the paleoflow pattern ...y parallel to tectonic strike. ... turbidites in such troughs include the Middle Ordovician Cloridorme Formation (Gaspé Peninsula) and its time equivalent in the Central Appalachians, the Martinsburg Formation. The deposits consist dominantly of classical turbidites hundreds of metres thick, but showing no consistent proximal to distal change along the length of the trough in the downflow direction. It is commonly suggested that turbidity currents flowed downslope toward the trough axis, perhaps constructing fans at the trough margin. However, at the trough axis the flows turned and continued to flow parallel to the trough axis. The marginal fans were presumably destroyed by subsequent tectonics, and the absence of consistent proximal to distal changes along the trough axis is probably due to input from a whole series of fans along the trough margin. Thus any consistent changes developing from one source would be masked by input from adjacent sources up and down the trough. At present, there is no facies model that acts as a good predictor in this type of turbidite basin.

Even in short narrow elongate troughs, the fan models (Figs. 14 and 15) may be inapplicable. Hsu *et al.* (1980) have criticized the use of fan models in the Ventura Basin (California), and instead, they have emphasized the data for longitudinal flow along the axis of the basin. It follows that "the presence of most reservoir-sand beds [is] in the deepest part of the trough, not in a canyon or a fan environment on the basin flank" (Hsu *et al.*, 1980, p. 1050). This work combined with studies of small, tectonically active modern basins in the California Borderlands (e.g., Normark *et al.*, 1979; Field and Edwards, 1980; Underwood *et al.*, 1980; Graham and Bachman, 1983) emphasizes that basin geometry may greatly modify the way in which fans build into basins, adding another limitation to the use of fan facies relationships as predictors.

Recently, studies emphasizing facies and thickness sequences have been made of part of the Middle Ordovician Cloridorme Formation of Québec (Beeden, 1983). It was shown that thickening-upward sequences of classical turbidites (mostly relatively thin bedded) were present, and could be interpreted in terms of prograding lobe-fringe environments. In the same Middle Ordovician elongate trough between the rising Taconic Orogen and the craton, Belt and Bussieres (1981) have also described submarine fan facies (see their Fig. 8) in the area northeast of Québec City. Thus it may be that further studies of long narrow basins using techniques such as thickness sequence analysis will reveal more evidence of submarine fan environments.

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SOURCES OF INFORMATION

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A very lucid discussion of the problems of identifying sequences in turbidites.

Howell, D.G., and Normark, W.R., 1982. Sedimentology of submarine fans. *In* Scholle, P.A., and Spearing, D.R., eds., Sandstone depositional environments. American Association of Petroleum Geologists, Memoir 31, p. 365-404.

A very useful review of all important aspects of fans, with many colour illustrations. The next paper to consult after reading this one.

Kelts, K., and Arthur, M.A., 1981. Turbidites

at Wheeler Gorge, California (Walker, 1975b and in press), where the conglomerates are overlain by several thinning-upward sequences of thin-bedded turbidites with abundant slump features. The vertical succession of conglomerates to thin-bedded turbidites with slumps suggests the migration of conglomerate-filled channels away from the area, with the slumped thin-bedded turbidites representing back-levee deposits of (? nearby) higher conglomerate-filled channels.

LIMITATIONS OF FAN MODELS

In 1976, when the "turbidite facies model" first appeared in Geoscience Canada, it was one of the better defined models. Many published studies in the last eight years have described systems that vary considerably from that model (low efficiency fans, channel-levee complexes), and descriptions of modern fans show variations from the summary model of Normark (1978). I believe that it is definitely premature to propose several different types of fan models - the data base for each proposed type is too scanty. It seems better to regard the "basic fan model" (Fig. 14 is but one example) as a norm, hence identifying, say, low efficiency fans as different from the norm. It is thus a fixed point for the comparison of many different fans, and can be modified to suppress the depositional lobes, and emphasize the channels, or channel-levee complexes, as appropriate. Once modified, it should still be possible to use the model in a predictive way, understanding how the modification of the model will affect channel and lobe distributions, sand body geometry, etc.

As presented, the fan model seems to be a useful framework for the investigation of small to medium scale ancient fans, with single points of input (single feeder channels) into the basin. The model loses much of its power if two separate fans overlap, because facies sequences may no longer be controlled by single processes (e.g., lobe progradation), but may be the result of irregular interbedding of beds from multiple sources.

The fan model may also lose some power when applied to long (hundreds of km) narrow "exogeosynclinal" troughs in which the paleoflow pattern is dominantly parallel to tectonic strike. Examples of turbidites in such troughs include the Middle Ordovician Cloridorme Formation (Gaspé Peninsula) and its time equivalent in the Central Appalachians, the Martinsburg Formation. The deposits consist dominantly of classical turbidites hundreds of metres thick, but showing no consistent proximal to distal change along the length of the trough in the downflow direction. It is commonly suggested that turbidity currents flowed downslope toward the trough axis, perhaps constructing fans at the trough margin. However, at the trough axis the flows turned and continued to flow parallel to the trough axis. The marginal fans were presumably destroyed by subsequent tectonics, and the absence of consistent proximal to distal changes along the trough axis is probably due to input from a whole series of fans along the trough margin. Thus any consistent changes developing from one source would be masked by input from adjacent sources up and down the trough. At present, there is no facies model that acts as a good predictor in this type of turbidite basin.

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Hiscott, R.N., 1981. Deep sea fan deposits in the Macigno Formation (Middle-Upper Oligocene) of the Gordana Valley, Northern Appennines, Italy: Discussion. Journal of Sedimentary Petrology, v. 51, p. 1015-1021.
A very lucid discussion of the problems of identifying sequences in turbidites.

Howell, D.G., and Normark, W.R., 1982. Sedimentology of submarine fans. *In* Scholle, P.A., and Spearing, D.R., eds., Sandstone depositional environments. American Association of Petroleum Geologists, Memoir 31, p. 365-404.
A very useful review of all important aspects of fans, with many colour illustrations. The next paper to consult after reading this one.

Kelts, K., and Arthur, M.A., 1981. Turbidites

after ten years of deep-sea drilling - wringing out the mop? *In* Warme, J.E., Douglas, R.G., and Winterer, E.L., eds., The deep sea drilling project: a decade of progress. Society of Economic Paleontologists and Mineralogists, Special Publication 32, p. 91-127.
This is the only coherent source of information on the DSDP findings with respect to turbidites and submarine fans. It forms an invaluable entry into the vast library of DSDP reports. Read Walker (1973) to understand the significance of the title.

Kuenen, P.H., and Migliorini, C., 1950. Turbidity currents as a cause of graded bedding. Journal of Geology, v. 58, p. 91-127.
This paper established the turbidite concept, and is one of the most important papers in sedimentology this century. Required reading, not only for historical reasons.

Lowe, D.R., 1975. Water escape structures in coarse grained sediments. Sedimentology, v. 22, p. 157-204.
A thorough and very abundantly illustrated discussion of these structures, which are common in many turbidite facies.

Menard, H.W., 1964. Marine geology of the Pacific. New York, McGraw Hill, 271 p.
Chapter 9 on turbidity currents is still a useful review, and contains important quantitative data.

Mutti, E., 1979. Turbidites et cones sous-marins profonds. *In* Homewood, P., ed., Sedimentation detritique (fluviatile, littorale et marine). Institut de Geologie de l'University de Fribourg, Short Course 1979, p. 353-419.
Excellent review (in French) of submarine fan facies, facies sequences and facies models. Full discussion of channel mouth bars and by-passing, and introduces the idea of fans of "low and high transport efficiency". Required reading - a different point of view from Walker (1978).

Mutti, E., and Ghibaudo, G., 1972. Un esempio di torbiditi di conoide sottomarina esterna: le Arenarie di San Salvatore (Formazione di Bobbio, Miocene) nell'Appennino de Piacenza. Memorie dell'Accademia delle Scienze di Torino, Classe di Scienze Fisiche, Matematiche e Naturali, Series 4, No. 16, 40 p.
As well as describing the facies, this paper emphasizes facies sequences, and for the first time compares turbidite fining-up sequences with delta channels, and coarsening-up sequences with prograding deltaic lobes. Suggests a fan model with lobes at the ends of channels (see Mutti and Ricci Lucchi, 1972, below).

Mutti, E. and Ricci Lucchi, F., 1972. Le torbiditi dell'Appennino settentrionale: introduzione all'analisi di facies. Memorie dell Societa Geologica Italiana, v. 11, p. 161-199. An extremely important and influential paper that established a widely-used facies classification, grouped the facies into associations, and related the associations to fan depositional environments. Did not discuss sequences in as much detail as Mutti and Ghibaudo (1972), above, and proposed a fan model with channels but no lobes.
REQUIRED READING - fortunately, there is an English translation by T.H. Nilsen, 1978. Turbidites of the northern Appennines: introduction to facies analysis. International Geology Review, v. 20, p. 125-166.

Mutti, E., and Ricci Lucchi, F., 1975. Examples of turbidite facies and facies associations from selected formations of the northern Appennines. Nice, France, 9th International Congress of Sedimentology, Guidebook to Field Trip A 11 (Mutti, E., *et al.*, eds.), 120 p.

Nilsen, T.H., 1980. Modern and ancient submarine fans: discussion of papers by R.G. Walker and W.R. Normark. American Association of Petroleum Geologists, Bulletin, v. 64, p. 1094-1101.
Discussion of Walker (1978) and Normark (1978). An important paper which establishes many of the current topics of research and disagreement.

Normark, W.R., 1970. Growth patterns of deep sea fans. American Association of Petroleum Geologists, Bulletin, v. 54, p. 2170-2195.
This is the first generalization about fan morphology and growth patterns, now superceded by Normark, 1978.

Normark, W.R., 1978. Fan-valleys, channels and depositional lobes on modern submarine fans: characters for the recognition of sandy turbidite environments. American Association of Petroluem Geologists, Bulletin, v. 61, p. 912-931.
Summary of growth patterns of many modern fans, and still the best general summary. See discussion by Nilsen (1980) and Normark's reply (1980).

Normark, W.R., 1980. Modern and ancient submarine fans: reply. American Association of Petroleum Geologists, Bulletin, v. 64, p. 1108-1112.
Here, Normark replies to the discussion of his 1978 paper by Nilsen (above).

Tillman, R.W., and Ali, S.A., 1982. Deep water canyons, fans and facies: models for stratigraphic trap exploration. American Association of Petroleum Geologists, Reprint Series 26, 596 p.
A very useful collection of papers from the AAPG Bulletin. Pages 1-100 usefully group the papers by Walker and Normark, with Nilsen's discussion and authors' replies.

Walker, R.G., 1967. Turbidite sedimentary structures and their relationship to proximal and distal depositional environments. Journal of Sedimentary Petrology, v. 37, p. 25-43.
Uses the Bouma sequence as starting point for an investigation of turbidite variablility. The proximal/distal ideas show how the sequence can be used as a predictor, but being "pre-fan", the predictions are now out of date.

Walker, R.G., 1973. Mopping-up the turbidite mess. *In* Ginsburg, R.N., ed., Evolving concepts in sedimentology. Baltimore, The John Hopkins University Press, p. 1-37.
A philosophical history of the turbidite concept, based on the ideas of Thomas H. Kuhn. Read the paper to understand the title!

Walker, R.G., 1975a. Generalized facies models for resedimented conglomerates of turbidite association. Geological Society of America, Bulletin, v. 86, p. 737-748.
Established four "Bouma-like" sequences for conglomerates - the scheme has been little-modified during the last 10 years but still has a rather slim data base.

Walker, R.G., 1978. Deep water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps. American Association of Petroleum Geologists, Bulletin, v. 62, p. 932-966.
Review of facies, facies sequences and facies models. A very useful source of references, and ideas current to 1978. There is now a greater variety of modern fans and ancient rock studies that need to be blended or distilled into a general model.

Walker, R.G., 1980. Modern and ancient submarine fans: reply. American Association of Petroleum Geologists, v. 64, p. 1101-1108.
Reply to Nilsen's (1980) discussion of Walker (1978).

Walker, R.G. and Mutti, E., 1973. Turbidite facies and facies associations. *In* Middleton, G.V., and Bouma, A.H. eds., Turbidites and deep water sedimentation. Pacific Section, Society of Economic Paleontologists and Mineralogists, Short Course (Anaheim, 1973), p. 119-157.
This is the first attempt to blend modern fan studies (Normark, 1970) and ancient rock studies (Mutti and Ricci Lucchi, 1972) into a combined recent/ancient fan model. The evolution of this model has been discussed by Walker (1980).

RECENT SEDIMENTS

Colella, A., *et al.*, 1981. The Crati submarine fan, Ionian Sea. A preliminary report. International Association of Sedimentologists, Second European Meeting, Bologna, Abstracts, p. 34-39
Brief description of a complex of channels

and levees, passing basinward into elongate lobes and interlobe areas.

Damuth, J.E., and Embley, R.W., 1981. Mass-transport processes on Amazon Cone. Western Equatorial Atlantic. American Association of Petroleum Geologists, Bulletin, v. 65, p. 629-643.
General description of the Amazon Cone, emphasizing three huge slump/debris flow deposits.

Damuth, J.E. *et al.*, 1983a. Distributary channel meandering and bifurcation patterns on the Amazon deep sea fan as revealed by long-range side-scan sonar (GLORIA). Geology, v. 11, p. 94-98.
Beautiful and amazing side-scan sonar pictures of extremely sinuous channels within channel-levee complexes.

Damuth, J.E., *et al.*, 1983b. Age relationship of distributary channels on Amazon deep sea fan: implications for fan growth pattern. Geology, v. 11, p. 470-473.
Detailed description of the evolution of western and eastern channel-levee complexes.

Elmore, R.D., Pilkey, O.H., Cleary, W.J., and Curran, H.A., 1979. Black Shell turbidite, Hatteras abyssal plain, western Atlantic Ocean. Geological Society of America, Bulletin, v. 90, p 1165-1176.
Detailed description of the world's largest known turbidite, and its relationship to other Hatteras abyssal plain sediments.

Field, M.E., and Edwards, B.D., 1980. Slopes of the southern California continental borderland: a regime of mass transport. *In* Field, M.E., *et al.*, eds., Quaternary depositional environments of the Pacific coast. Pacific Coast Paleogeography Symposium 4, Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 169-184.
Shows the influence of basin topography on the way in which basins are filled.

Graham, S.A. and Bachman, S.B., 1983. Structural controls on submarine fan geometry and internal architecture: upper La Jolla Fan system, offshore southern California. American Association of Petroleum Geologists, Bulletin, v. 676, p. 83-96.
Shows the La Jolla Fan feeder channels (Newport, La Jolla, Loma) and the structural control of their evolution. Channel-levee complexes are well developed in the Newport system.

Heezen, B.C., 1956. Corrientes de turbidez del Rio Magdalena. Societa Geografica de Colombia, Boll., v. 52-2, p. 135-143.
This paper, quoted by Menard (1964), is apparently the data source for the Magdalena turbidity current of 1935. See Menard (1964) and Kolla *et al.* (1984).

Heezen, B.C., Menzies, R.J., Schneider, E.D., Ewing, W.M., and Granelli, N.C.L., 1964. Congo submarine canyon. American Association of Petroleum Geologists, Bulletin, v. 48, p. 1126-1149.
An important paper that establishes a direct relationship between turbidity current generation (cable breaking) and the behaviour of the Congo river - specifically *months* of high discharge and *years* when the river is establishing a new path through its estuarine sand bars. The paper is reprinted in Tillman and Ali (1982).

Horn, D.R., Ewing, J.I., and Ewing, M., 1972. Graded bed sequences emplaced by turbidity currents north of 20° N in the Pacific, Atlantic and Mediterranean. Sedimentology, v. 18, p. 247-275.
Describes abyssal plains, their sediments and sediment thicknesses, and points of input into the basins.

Kolla, V., Buffler, R.T., and Ladd, J.W., 1984. Seismic stratigraphy and sedimentation of Magdalena Fan, southern Colombia Basin, Caribbean Sea. American Association of Petroleum Geologists, Bulletin, v. 68, p. 316-332.
Establishes six seismic sequences, and models channellized and overbank turbidity current flow (upper fan) and unchannellized flow (down fan). A possible modern example of a "high efficiency" fan (see Mutti, 1979).

Kolla, V., Kostecki, J.A., Henderson, L., and Hess, L., 1980. Morphology and Quaternary sedimentation of the Mozambique Fan and environs, southwestern Indian Ocean. Sedimentology, v. 27, p. 357-378.
General description of Mozambique Fan.

Normark, W.R., Piper, D.J.W., and Hess, G.R., 1979. Distributary channels, sand lobes and mesotopography of Navy submarine fan, California Borderlands, with applications to ancient fan sediments. Sedimentology, v. 26, p. 749-774.
Establishes in detail the pattern of lobe/channel switching and sediment distribution. Contributes an important data base to fan models of the Normark type.

Normark, W.R., Piper, D.J.W., and Stow, D.A.V., 1983. Quaternary development of channels, levees and lobes on middle Laurentian Fan. American Association of Petroleum Geologists, Bulletin, v. 67, p. 1400-1409.
Establishes a pattern of channel switching and levee growth.

Pilkey, O.H., Locker, S.D., and Cleary, W.J., 1980. Comparison of sand-layer geometry on flat floors of 10 modern depositional basins. American Association of Petroleum Geologists, Bulletin, v. 64, p. 841-856.
Important and useful comparison of turbidite geometries on Atlantic and Caribbean abyssal plains (plus Santa Monica basin).

Piper, D.J.W., and Normark, W.R., 1982. Acoustic interpretation of Quaternary sedimentation and erosion on the channelled upper Laurentian fan, Atlantic margin of Canada. Canadian Journal of Earth Sciences, v. 19, p. 1974-1984.
Shows that previously suggested large slumps are in fact absent, but establishes a channel switching pattern.

Piper, D.J.W., and Normark, W.R., 1983. Turbidite depositional patterns and flow characteristics, Navy submarine fan, California Borderlands. Sedimentology, v. 30, p. 681-694.
Correlates beds on the fan, and introduces the concept of "flow stripping", whereby most of a flow can overtop a levee at a channel bend.

Stevenson, A.J., Scholl, D.W., and Vallier, T.L., 1983. Tectonic and geologic implications of the Zodiac Fan, Aleutian Abyssal Plain, northeast Pacific. Geological Society of America, Bulletin, v. 94, p. 259-273.
A large fan that differs from many others in that the channels continue essentially to the margins of the fan. Well developed channel-levee complexes.

Stow, D.A.V., 1981. Laurentian Fan: morphology, sediments, processes and growth patterns. American Association of Petroleum Geologists, Bulletin, v. 65, p. 375-393.
A good general description and discussion of all of the above topics.

Uchupi, E., and Austin, J.A., 1979. The stratigraphy and structure of the Laurentian Cone region. Canadian Journal of Earth Sciences, v. 16, p. 1726-1752.
Seismic reflection profiling shows two fan megasequences. Re-survey of the fan gives better definition of channel patterns, and allowed re-calculation of Grand Bands turbidity current velocities.

Underwood, M.B., Bachman, S.B., and Schweller, W.J., 1980. Sedimentary processes and facies associations within trench and trench-slope settings. *In* Field, M.E., *et al.*, eds., Quaternary depositional environments of the Pacific Coast. Pacific Coast Paleogeography Symposium 4. Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 211-229.
Describes and models the tectonic control of turbidite facies and channels in trench settings.

Whitmarsh, R.B., *et al.*, 1974. Initial reports of the Deep Sea Drilling Project, Volume 23. Washington, D.C., U.S. Government Printing Office, p. 211-289.
Documents DSDP Site 222, with comments on rates of sedimentation for this site (on the western margin of the Indus Cone).

ANCIENT ROCKS

Beeden, D.R., 1983. Sedimentology of some turbidites and related rocks from the Cloridorme Group, Ordovician, Québec. Hamilton, Ontario, McMaster University, M.Sc. Thesis. 256 p.
Documents sequences in turbidites, the turbidites occurring in a long narrow trough with all paleocurrent directions parallel to regional strike. Possible submarine fan facies in a long narrow trough.

Belt, E.S. and Bussieres, L., 1981. Upper Middle Ordovician submarine fans and associated facies, northeast of Québec City. Canadian Journal of Earth Sciences, v. 18, p. 981-994.
Documents submarine fans in a very long narrow basin between the Taconic Orogen and the Craton. Possibly a similar situation to that of Beeden (1983).

Chan, M.A. and Dott, R.H. Jr., 1983. Shelf and deep sea sedimentation in Eocene forearc basin, western Oregon - fan or non-fan? American Association of Petroleum Geologists, Bulletin, v. 67, p. 2100-2116.
Proposes a sand-rich (or "poorly efficient") fan interpretation for the Eocene Tyee Formation.

Clari, P. and Ghibaudo, G., 1979. Multiple slump scars in the Tortonian type area (Piedmont Basin, northwestern Italy). Sedimentology, v. 26, p. 719-730.
Excellent documentation of large slump scars, interpreted to have formed near the shelf-slope break.

Cook, H.E., McDaniel, P.N., Mountjoy, E., and Pray, L.C., 1972. Allochthonous carbonate debris flows at Devonian bank ("reef") margins, Alberta, Canada. Bulletin of Canadian Petroleum Geology, v. 20, p. 439-497.
Well documented example of huge debris flows.

Crowell, J.C., 1957. Origin of pebbly mudstones. Geological Society of America, Bulletin, v. 68, p. 993-1009.
The title says it all. For the Pigeon Point examples, see also Howell and Joyce (1981).

Davies, I.C. and Walker, R.G., 1974. Transport and depostion of resedimented conglomerates: the Cap Enragé Formation, Cambro-Ordovocian, Gaspe, Québec. Journal of Sedimentary Petrology, v. 44, p. 1200-1216.
Establishes conglomerate fabric types and uses the results to document paleoflow directions.

Gregory, M.R., 1969. Sedimentary features and penecontemporaneous slumping in the Waitemata Group, Whangaparaoa Peninsula, north Auckland, New Zealand. New Zealand Journal of Geology and Geophysics, v. 12, p. 248-282
Contains excellent illustrations of some of the largest sedimentary slumps ever described.

Hein, F.J., 1982. Depositional mechanisms of deep sea coarse clastic sediments, Cap Enragé Formation, Québec. Canadian Journal of Earth Sciences, v. 19, p. 267-287.
Describes internal structures and structure sequences for massive and pebbly sandstones.

Hein, F.J., and Walker R.G., 1982. The Cambro-Ordovician Cap Enragé Formation, Québec, Canada: conglomeratic deposits of a braided submarine channel with terraces. Sedimentology, v. 29, p. 309-329.
Conglomerate facies sequences, both lateral and vertical, establish the nature of this deep water braided channel.

Helwig, J., 1970. Slump folds and early structures, northeastern Newfoundland, Appalachians. Journal of Geology, v. 78, p. 172-187.

Hendry, H.E., 1978. Cap des Rosiers Formation at Grosses Roches, Québec - deposits of the mid-fan region on an Ordovician submarine fan. Canadian Journal of Earth Sciences, v. 15, p. 1472-1488
Conglomerate-to-sandstone fining-upward sequences interpreted as backfilling a channel mouth in the mid-fan region.

Heritier, F.E., Lossel, P., and Wathne, E., 1979. Frigg Field - large submarine-fan trap in lower Eocene rocks of North Sea. American Association of Petroleum Geologists, Bulletin, v. 63, p. 1999-2020.
Subsurface data seems to indicate a fan made up of channel levee complexes without prominent smooth depositonal lobes. The authors supply little of their own fan interpretation, however. Reprinted in Tillman and Ali, 1982.

Howell, D.G., and Joyce, J.M., 1981. Field guide to the Upper Cretatceous Pigeon Point Formation. *In* Frizzell, V., ed., Upper Cretaceous and Paleocene turbidites, central California Coast. Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 61-70
Describes the classic section where Crowell (1957) first studied and illustrated pebbly mudstones.

Hsu, K.J., Kelts, K., and Valentine, J.W., 1980. Resedimented facies in Ventura Basin, California, and model of longitudinal transport of turbidity currents. American Association of Petroleum Geologists, Bulletin, v. 64, p. 1034-1051.

Johnson, B.A., and Walker, R.G., 1979. Paleocurrents and depositional environments of deep water conglomerates in the Cambro-Orodovician Cap Enragé Formation, Québec Appalachians. Canadian Journal of Earth Sciences, v. 16, p. 1375-1387.
Establishes facies relationships among different types of conglomerate, and suggests initial channel model - see Hein and Walker, 1982.

Link, M.H., Squires, R.L., and Colburn, I.P., eds., 1981. Simi Hills Cretaceous turbidites, southern California. Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, Field Trip Guide Book, 134 p.
Extremely useful guide book to a superbly exposed and very interesting group of turbidites, and massive and pebbly sandstones.

Link, M.H., and Nilsen, T.H., 1980. The Rocks Sandstone, an Eocene sand-rich deep-sea fan deposit, northern Santa Lucia Range, California. Journal of Sedimentary Petrology, v. 50, p. 583-601.
Sand-rich (channellized) fan based on abundant thinning- and fining-upward sequences.

Link, M.H., and Welton, J.E., 1982. Sedimentology and reservoir potential of Matilija Sandstone: an Eocene sand-rich deep-sea fan and shallow marine complex, southern California. American Association of Petroleum Geologists, Bulletin, v. 66, p. 1514-1534.
Well-documented example of a very sandy fan. Slope facies between fan and shallow marine parts of the section are very enigmatic.

Martin, B.D., 1963. Rosedale Channel - evidence for late Miocene submarine erosion in Great Valley of California. American Association of Petroleum Geologists, Bulletin, v. 47, p. 441-456.
Subsurface example of a partly sand-filled canyon. Reprinted in Tillman and Ali (1982).

Nilsen, T.H., and Abbott, P.L., 1981. Paleogeography and sedimentology of Upper Cretaceous turbidites, San Diego, California. American Association of Petroleum Geologists, Bulletin, v. 65, p. 1256-1284.
Well described and abundantly illustrated forearc basin fan deposits.

Piper, D.J.W., Normark, W.R., and Ingle, J.R., Jr., 1976. The Rio Dell Formation: a Plio-Pleistocene basin slope deposit in northern California. Sedimentology, v. 23, p. 309-328.
Describes slope deposits, with sketches (but no photos) of slumps.

Srivastava, P., Stearn, C.W., and Mountjoy, E.W., 1972. A Devonian megabreccia at the margin of the Ancient Wall carbonate complex, Alberta. Bulletin of Canadian

Petroleum Geology. v. 20, p. 412-438.
Good descriptions of debris flow/rockfall? megabreccias.

Stevens, R.K., 1970. Cambro-Orodovician flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a Proto-Atlantic ocean. *In* Lajoie, J., ed., Flysh sedimentology in North America. Geological Association of Canada, Special Paper 7, p. 165-177.
Some sedimentological description, but the thrust of the paper is concerned with allochthonous flysch complexes.

Sullwold, H.H., 1960. Tarzana Fan, deep submarine fan of late Miocene age, Los Angeles County, California. American Association of Petroleum Geologists, Bulletin, v. 44, p. 433-457.
I believe this is the first interpretation of a turbidite sequence in terms of submarine fans. It is based on a radial spread of flow directions which, if traced upslope, converge at the suggested foot of a canyon. See next paper.

Walker, R.G., 1966. Shale Grit and Grindslow Shales: transition from turbidite to shallow water sediments in the Upper Carboniferous of northern England. Journal of Sedimentary Petrology, v. 36, p. 90-114.
A submarine fan interpretation based on variability of flow directions, facies relationships and, particularly, the abundance of channels. Interpretive block diagram redrawn in Walker (1978).

Walker R.G., 1975a. Generalized facies models for resedimented conglomerates of turbidite association. Geological Society of America, Bulletin, v. 86, p. 737-748.
Four "Bouma-like" models are established, with comments on transport mechanisms and proximal-distal implications.

Walker, R.G., 1975b. Upper Cretaceous resedimented conglomerates at Wheeler Gorge, California: description and field guide. Journal of Sedimentary Petrology, v. 45, p. 105-112.
Establishes three major thinning-upward sequences. This study is put in context by Walker (in press).

Walker, R.G., 1977. Deposition of upper Mesozoic resedimented conglomerates and associated turbidites in south western Oregon. Geological Society of America, Bulletin, v. 88, p. 273-285.
Establishes a series of thinning-upward sequences, and proposes a mechanism for channel blocking leading to channel fill.

Walker, R.G., 1979. Stop 1. L'Islet Wharf: an early Cambrian submarine channel complex. *In* Middleton, G.V., *et al.*, eds., Cambro-Ordovician submarine channels and fans, L'Islet to Sainte-Anne-des-Monts, Québec. Geological Association of Canada, Guidebook to Field Trip A-6 (Québec, 1979), p. 4-7.
Preliminary interpretation of a superbly exposed deep submarine fan channel.

Walker, R.G., in press. Mudstones and thin bedded turbidites associated with the Upper Cretaceous Wheeler Gorge conglomerates, California: a possible channel-levee complex. Journal of Sedimentary Petrology.
Interprets mudstones below conglomerates as basin plain, and mudstones with turbidites above the conglomerates as levee.