Facies Models 8. Turbidites and Associated Coarse Clastic Deposits

Roger G. Walker
Department of Geology
McMaster University
Hamilton, Ontario L8S 4M1

Introduction

To the sedimentologist, the turbidity current concept is both simple and elegant. Each *turbidite* (defined as the deposit of a turbidity current) 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 allows the interpretation of thousands of graded sandstone beds, alternating with shales, as the result of a series of similar events, and it can safely be stated that no similar volume of clastic rock can be interpreted so simply.

In this review, I will begin by studying the "classical" turbidite, and will then gradually broaden the scale to encompass turbidites and related coarse clastic rocks in their typical depositional environments - deep sea fans and abyssal plains

The concept of turbidites 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 density 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 forams in the sandstones, yet bathyal or abyssal benthonic forams in interbedded shales. Low density currents were known in lakes and reservoirs, and they appeared to be competent to transport sediment for fairly long distances. Many of these different lines of evidence were pulled together by Kuenen and Migliorini in 1950 when they published their experimental results 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).

After its introduction in 1950, the turbidity current interpretation 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) Sandstone beds had abrupt, sharp bases, and tended to grade upward into finer sand, silt and mud. Some of the mud was introduced into the basin by the turbidity current (it contained shallow benthonic forams), but the uppermost very fine mud contained bathyal or abyssal benthonic forams and represented the constant slow rain of mud onto the ocean floor.
2) On the undersurface (sole) of the sandstones there were abundant markings, now classified into three types: tool marks, carved into the underlying mud by rigid tools (sticks, stones) in the turbidity current; scour marks, cut into the underlying mud by fluid scour; and organic markings - trails and burrows - filled in by the turbidity current and thus preserved on the sole. The tool and scour markings give an accurate indication of local flow directions of the turbidity currents, and by now, many thousands have been measured and used to reconstruct paleoflow patterns in hundreds of turbidite basins.
3) Within the graded sandstone beds, many different sedimentary structures were recorded. By the late 1950s, some authors were proposing turbidite models, or ideal turbidites, based upon a generalization of these sedimentary structures and the sequence in which they occurred. This generalization is akin to the distillation process discussed in the first paper, and the final distillation and publication of the presently accepted model was done by Arnold Bouma in 1962. A version of the Bouma model is shown in Figure 1.

The Bouma Turbidite Facies Model

The Bouma sequence, or model (Figs. 1,2) can be considered as a very simple facies model that effectively carries out all of the four functions of facies models discussed in the first paper in this volume. I will examine these in turn, both to shed light upon turbidites in general, and to use turbidites as an illustration of a facies model in operation. I have described the model as very simple because it contains relatively few descriptive elements, and because it is narrowly focussed upon sandy and silty turbidites *only*. I shall later refer to these as "classical" turbidites.

1. The Bouma model as a NORM. The model (Fig. 1) as defined by Bouma consists of five divisions, A-E, which occur in a fixed sequence. Bouma did not give normalized thicknesses for the divisions, and this type of information is still unavailable. In Figure 3, I have sketched three individual turbidites which clearly contain some of the elements of the Bouma model, yet which obviously differ from the norm. They can be characterized as AE, BCE and CE beds. Without the model, we could ask no more questions about these three turbidites, but with the norm, we can ask *why* certain divisions of the sequence are missing. I will try and answer this rhetorical question later.

2. The Bouma model as a framework and guide for description. The model has served as the basis for description in a large number of studies, particularly in Canada, U.S.A. and Italy. With the framework provided by the model, one can quickly log a sequence of turbidites as AE/BCE/CE etc. (as in the three turbidites of Fig. 3), and then add to the

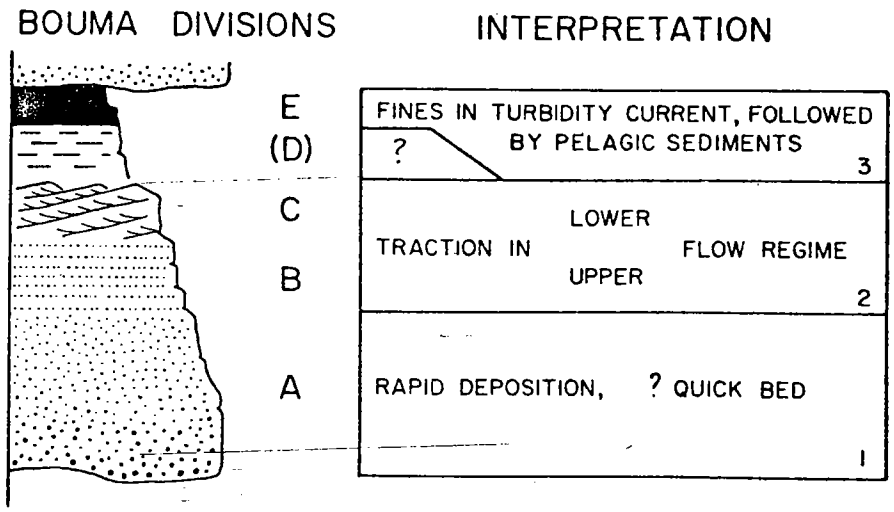

Figure 1
Five divisions of the Bouma model for turbidites: A—graded or massive sandstone; B—parallel laminated sandstone; C—ripple cross-laminated fine sandstone; D—faint parallel laminations of silt and mud, bracketed to emphasize that in weathered or tectonized outcrops it cannot be separated from E—pelitic division, partly deposited by the turbidity current, partly hemipelagic. Interpretations of depositional process are grouped into three main phases, see text.

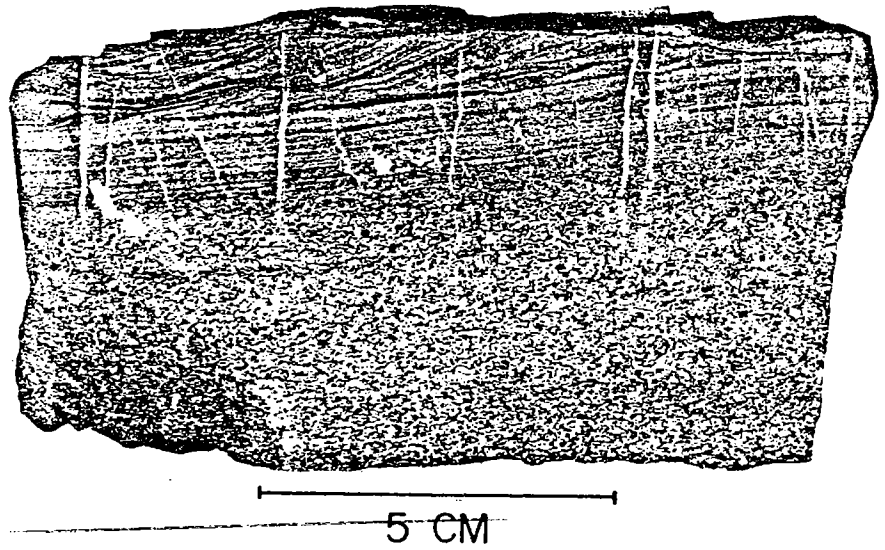

Figure 2
Complete "Bouma" turbidite (see Fig. 1), showing pelitic division E of lower bed (bottom left); graded division A, parallel laminated division B and ripple cross laminated division C. Divisions (D) and E were broken off this specimen, which is from the Côte Fréchette road cut, Lévis Formation (Cambrian), Quebec.

basic description any other features of note. With the model as a framework, one is not only aware of the features presented by any bed, but is also aware of any features embodied in the model but missing in a particular bed.

3. The model as a basis for hydrodynamic interpretation. The existence of the bouma model enables us to make one integrated interpretation of classical turbidites, rather than having to propose different origins for each different type of bed. In Figure 1, the interpretation is considered in three parts. Division A contains no sedimentary structures except graded bedding. It represents very rapid settling of grains from suspension, possibly in such quantities and at such a rate that water is forcibly expelled upward, and momentarily, the grain/water mixture becomes fluidized (or "quick"). The fluidization would destroy any possible sedimentary structures. The second phase of deposition involves traction of grains on the bed. Flow velocities are lower, and the rate of deposition from suspension is much lower. By direct comparison with many experimental studies, division B represents the upper flow regime plane bed, and division C, the lower flow regime rippled bed. The third phase of deposition involves slow deposition of fines from the tail of the current. The origin of the delicate laminations in division (D) is not understood, and I prefer to place division (D) in brackets, implying that in all but the cleanest outcrops, (D) cannot be separated from E. In the uppermost part of division E, there may be some true pelagic mudstone with a deep water (bathyal or abyssal) benthonic fauna (forams in Tertiary and younger rocks).

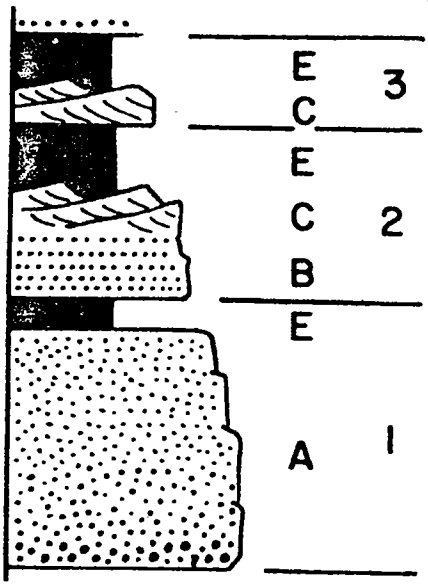

Figure 3
Hypothetical sequence of three turbidites, described as AE, BCE and CE in the Bouma model. See text.

4. The Bouma model as a predictor. Here, I shall show how the hydrodynamic interpretation of the model, together with departures from the norm, can be used on a predictive basis. Turbidite 1 (Fig. 3) begins with a thick sandy division (A), and was deposited from a high velocity current. Turbidite 2 (Fig. 3), by comparison with the norm, does not contain division A. It begins with Bouma division B, and was presumably deposited from a slower current. Turbidite 3 (Fig. 3) lacks divisions A and B, and presumably was deposited from an even slower current.

In a cautious way, we can now make some predictions based upon comparison with the norm, and upon the hydrodynamic interpretations. A sequence of many tens of turbidites in which all of the beds are thick and begin with division A (Fig. 4, and, for example, the Cambrian Charny Sandstones in the St. Romuald road cut near Levis, Quebec) probably represents an environment where all of the turbidity currents were fast-flowing during deposition. Such an environment was probably close to the source of the turbidity currents (proximal). By contrast (Fig. 5), a sequence of many tens of beds in which all the turbidites begin either with division B or C (Ordovician Cloridorme formation at Grande Vallee, Quebec) was deposited in an environment where all of the turbidity currents were flowing slowly during deposition. Such an environment was probably a long way from the source of the currents (distal). This conclusion will be slightly modified below.

This ideal proximal to distal scheme applies only to "classical" turbidites. In nature, variations in the size, sediment load, and velocity of individual currents will blur the proximal to distal distinctions, which is why I suggest taking the combined characteristics of a large number of beds before making environmental predictions. For example, if out of 250 beds, 70 per cent began with division A, the environment could be characterized as relatively proximal.

It follows from this application of the model that if one can work out the environment of deposition of a relatively large group of turbidites (let's say 300 beds - and a distal envrionment is indicated), and one knows the general paleoflow direction, one can make predictions as to what the same stratigraphic interval will look like closer to source and in a specific geographic direction. The reader is now referred to "A review of the geometry and facies organization of turbidites and turbidite-bearing basins" (Walker, 1970), and, if you are interested in the intimate details of lateral variability in classical turbidites, to an excellent paper by Enos (1965) on the Ordovician Cloridome Formation in Quebec.

It should be emphasized that for classical turbidites, the *descriptive* terminology is now *thick-bedded* and

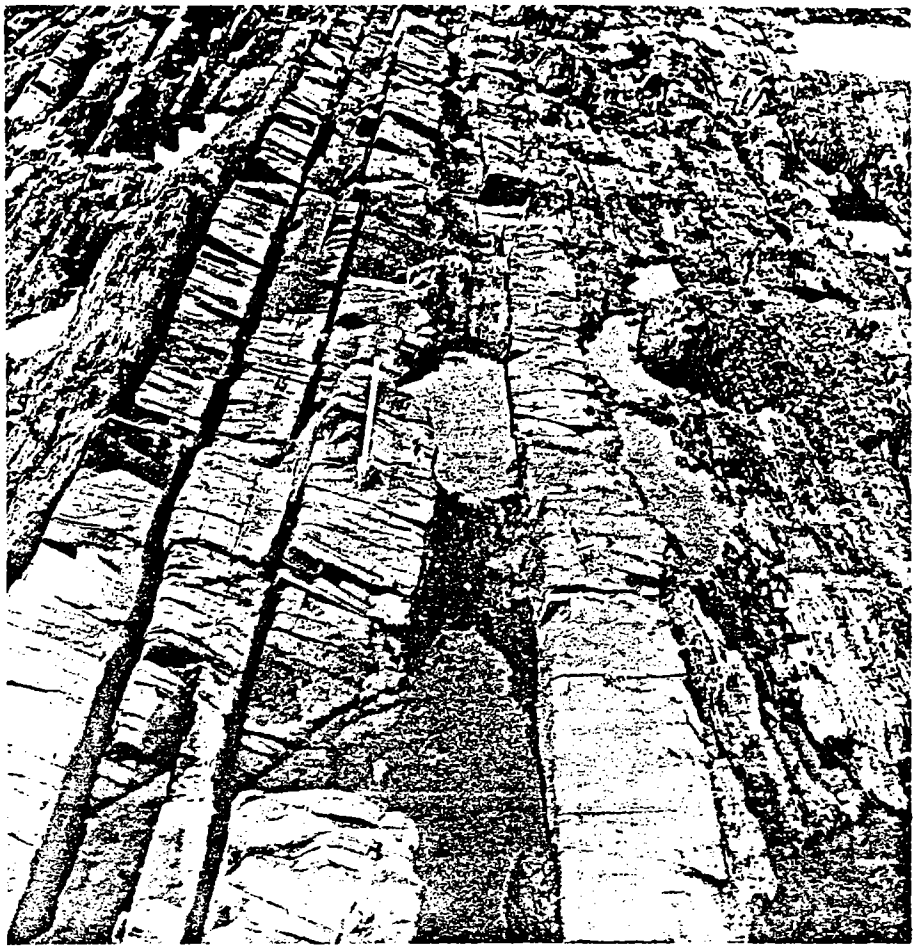

Figure 4
Group of four parallel sided turbidites, AE, AE, AE and AE, suggesting that the beds are close to their source (proximal). Beds slightly overturned, top to right; Ordovician Cloridorme Formation at Grande Vallée, Quebec.

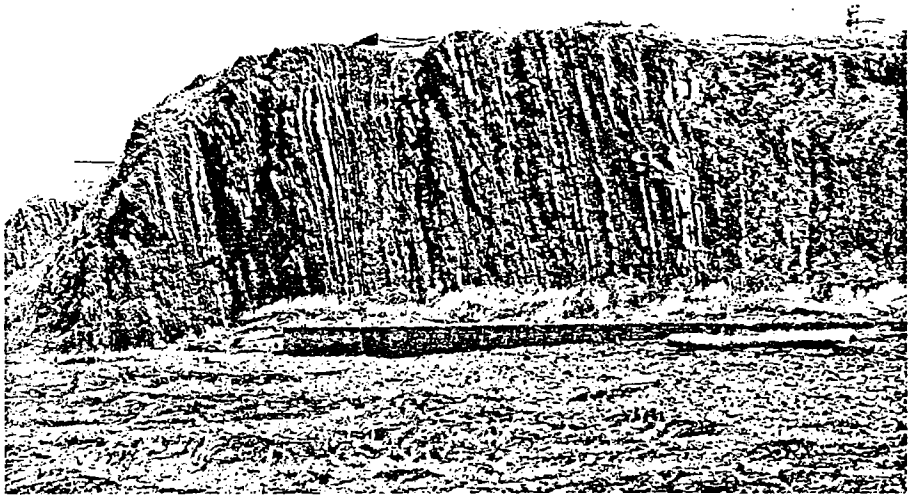

Figure 5
Very thin turbidite sandstones with thicker interbedded shales. Beds begin with Bouma divisions B and C, and suggest deposition far from their source (distal). Contrast with Figure 4. Ordivician Cloridorme Formation, Grande Vallée (near fish cannery), Quebec; stratigraphic top to left.

thin-bedded; the terms proximal and distal should only be used in an interpretive sense (see Walker, 1978).

Environments of Turbidite Deposition

Because a turbidite is simply the deposit of a turbidity current, turbidites can be found in any environment where turbidity or density currents operate. These environments include lakes and reservoirs, delta fronts, continental shelves, and most importantly, the deeper ocean basins. However, to be *preserved* and *recognized* as a turbidite, the features imposed on the bed by the current (ideally; sharp base with sole marks, graded bedding, Bouma divisions) must *not* be reworked by other types of currents. Small turbidites have been preserved in quiet water glacial lakes; thin prodeltaic turbidites can flow into water deep enough that agitation of the bottom by storms is very rare (say, less than one storm in 500 years), but to preserve a thick (hundreds or thousands of metres) turbidite sequence, the most likely environment is one that is consistently deep and quiet. Using present day morphological terms, these environments would include the continental rise (made up of coalescing submarine fans) and abyssal plains. It is important to emphasize that any sudden surge of sediment laden water can deposit a bed with all the characteristics of a classical turbidite. A levee break in a river, and a storm current transporting sediment out across the continental shelf (see paper 7 in this volume) would be two examples of this. Graded beds might be preserved in either situation, but the two environments would be characterized by the dominance of fluvial and shelf features, respectively. The presence of rare "turbidites" would indicate the possibility of density current activity, and would not condemn the entire sequences to deposition in great depths of water.

Other Facies Commonly Associated with Classical Turbidites

Classical turbidites can be characterized by three main features; first, the beds tend to be laterally extensive (hundreds of metres); second, they tend to be parallel sided and vary little in thickness laterally (hundreds of metres); and third, it is reasonable to use the Bouma model for this description and interpretation. However, along with classical turbidites there are other coarse clastic facies also known to have been transported into very deep water (as defined by bathyal and abyssal benthonic forams in interbedded shales). These facies can be listed as:

1) massive sandstones
2) pebbly sanostones
3) clast supported conglomerates
4) chaotic matrix-supported pebbly sandstones and conglomerates.

This facies list stems initially from work of Emiliano Mutti and his colleagues in Italy, and an English language version is available (Walker and Mutti, 1973). I now believe that the classification of facies published by Walker and Mutti is unnecessarily subdivided (my opinion, not necessarily Mutti's), so I will stick to the simpler list above.

Massive sandstones. This facies (Fig. 6) consists of thick sandstone beds in which graded bedding is normally poorly developed. Most of the divisions of the Bouma sequence are missing, and interbedded shales tend to be very thin or absent. 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 misapplication of the model, because its function as a norm, predictor, framework and basis for hydrodynamic 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 (Fig. 7), and is indicative of abundant fluid escape during deposition of the sandstone. 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.

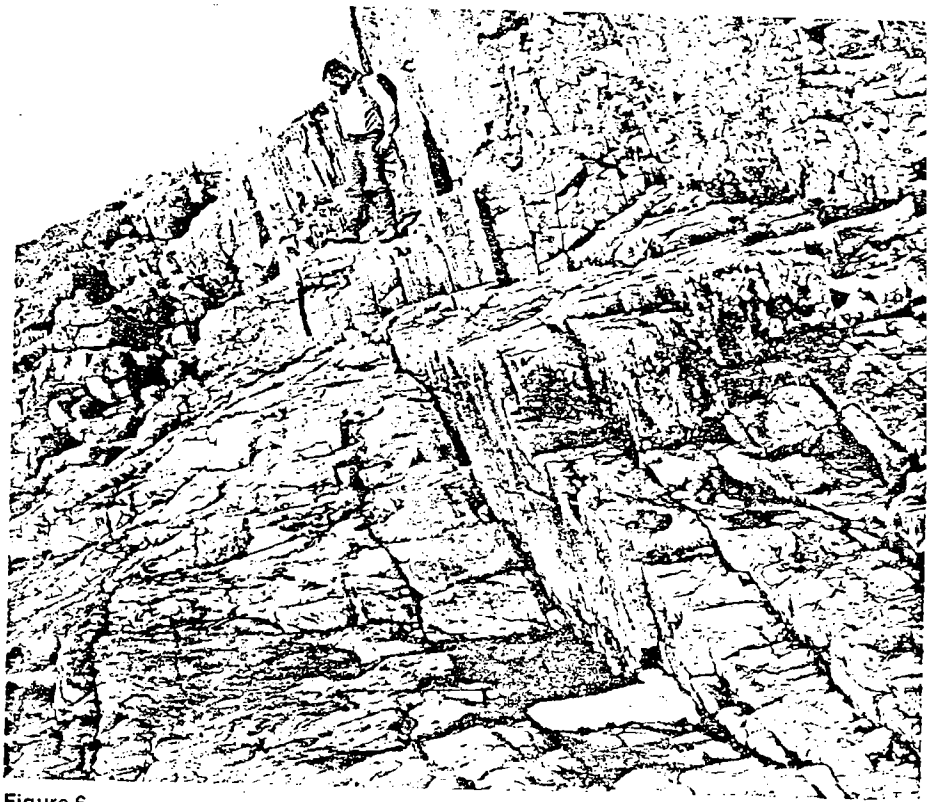

Figure 6
Massive sandstone facies. Note thickness of beds and absence of pelitic division of Bouma model. Stratigraphic top to left. Cambro-Ordovician Cap Enragé Formation near St-Simon, Quebec.

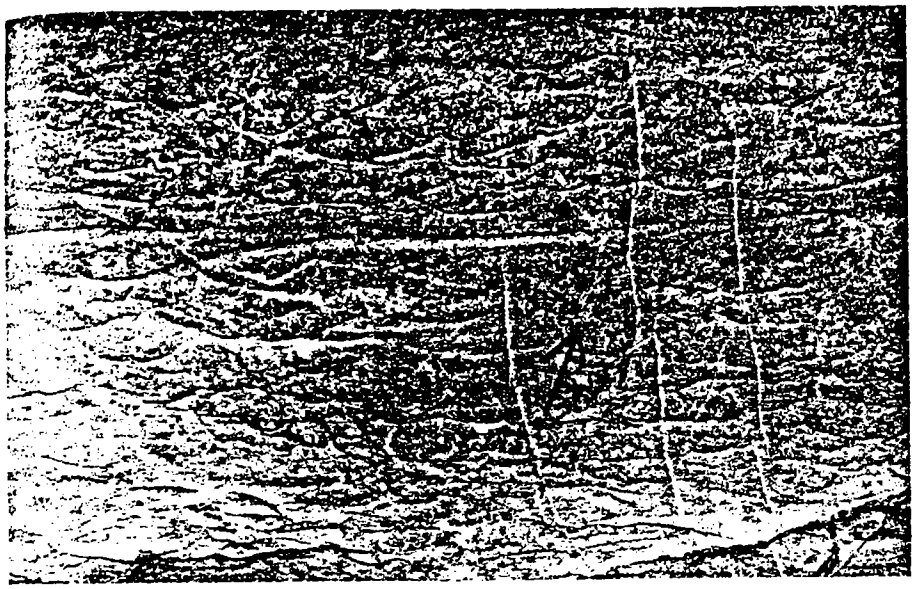

Figure 7
"Dish" structures, formed by rapid dewatering of a massive sandstone. Some of the dish edges curve upward into vertical dewatering pipes (arrow on photo). Ordovician Cap Enragé Formation, near St-Simon, Quebec.

Figure 8
Graded bed of pebbly sandstone, followed abruptly by a second bed without a pelitic division. St-Damase Formation (Ordovician) near Kamouraska, Quebec.

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 Quebec City and Lévis, and dish structures in massive sandstones are common in the Cambro-Ordovician Cap Enragé Formation near Rimouski, Quebec (Fig. 7).

Pebbly sandstones. The pebbly sandstone facies (Figs. 8, 9) 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. 8), 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 (Fig. 9) type. 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. 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

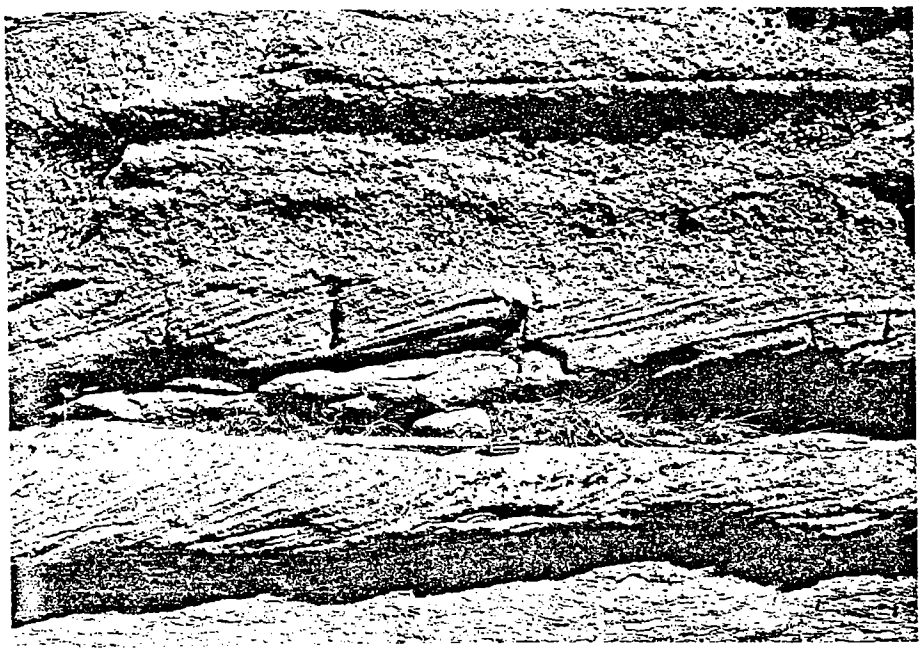

Figure 9
Pebbly sandstone facies, showing medium scale cross bedding. In isolation, this photograph could easily be confused with a photograph of fluvial gravels, but in fact is from the Cambro-Ordovician Cap Enragé Formation (near St-Simon, Quebec), and is interbedded with turbidites and graded pebbly sandstones.

in pebbly sandstones, this facies could easily be confused with a coarse fluvial facies. 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 at St. Simon (near Rimouski, Quebec), where grading, stratification and cross bedding are prominent. The facies is also abundant in the Cambrian St. Damase Formation near Kamouraska, Quebec, and in the Cambrian St. Roch Formation at L'Islet Wharf (near St-Jean-Port-Joli, Quebec).

Clast supported conglomerates. Although volumetrically less abundant than classical turbidites, conglomerates are an important facies in deep water environments. They are abundant in California and Oregon, and are particularly well exposed at many localities in the Gaspé Peninsula. 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 recently proposed some generalized "Bouma-like" models for conglomerates (Walker, 1975), but because the models are based upon less than thirty studies, they lack the universality and authority of the Bouma model for classical turbidites. The paper (Walker, 1975) discusses the models, their relationships, and how they were established. In Figure 10, it can be seen that the descriptors include the type of grading (normal (Fig. 11) or inverse), stratification (Fig. 11), 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.

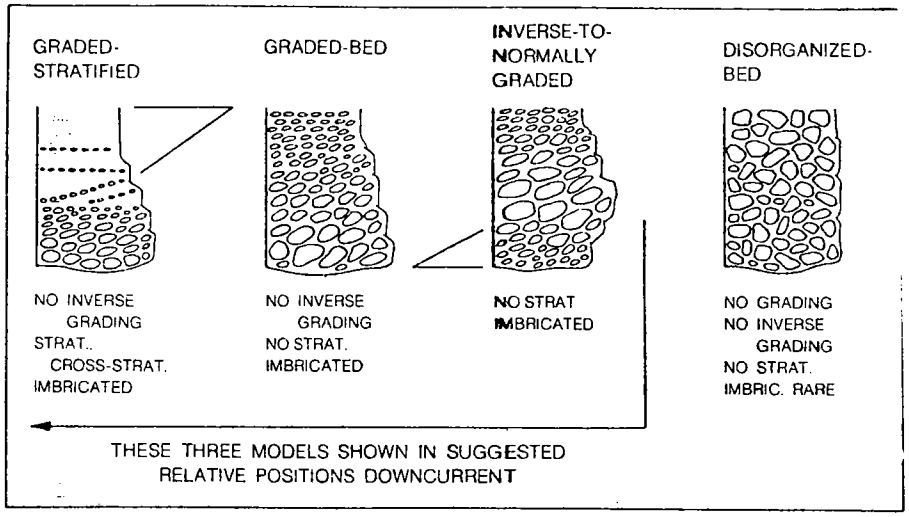

Figure 10
Four models for resedimented (deep water) conglomerates. The graded-stratified, graded-bed, and inverse-to-normally graded models are probably intergradational.

Figure 11
Graded-stratified conglomerate, Cambro-Ordovician Cap Enragé Formation at Bic, Quebec. Basal conglomerate grades up into stratified conglomerate, very coarse sandstone with crude "dish" structure (centre of photo) and finally into massive structureless sandstone (top left).

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 direction, 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. 12). 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

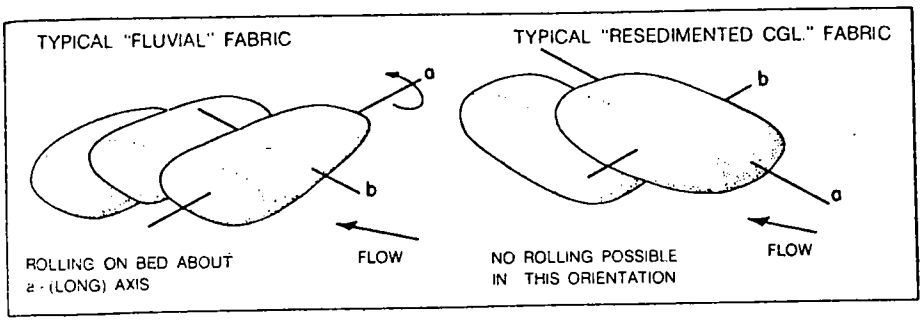

Figure 12
Contrast between conglomerate fabric produced by rolling clasts on the bed (long axis transverse to flow) with typical fabric in resedimented conglomerates (no rolling, long axis parallel to flow).

a turbulent flow. The support mechanism may have been partly fluid turbulence, and partly clast collisions. Upon deposition, the clasts immediatedly 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 10 will be of the type indicated in the figure.

Clast supported conglomerates are abundant in the Ordovician Grosses Roches Formation and Cambro-Ordovician Cap Enragé Formation, Gaspé Peninsula, Quebec, and also make up part of the Cambrian St. Roch Formation east of Rivière-du-loup, Quebec.

Chaotic matrix-supported pebbly sandstones and conglomerates. This facies includes two different types of deposit. First, there are conglomerates and pebbly sandstones that have abundant muddy matrix, and possibly show basal inverse grading and preferred clast alignment. They represent the deposits of subaqueous debris flows. Because the larger clasts in a debris flow are maintained above the bed by the strength of the debris flow 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, the second type of deposit commonly shows evidence of slumping, and represents 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 depostion of coarse sediment on top of wet, poorly consolidated clays. The latter process gives rise to the classical pebbly mudstones.

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, or in the Inner Fan environment. 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.*, Srivastava *et al.*, 1972).

An Integrated Facies Model for Turbidites and Associated Coarse Clastic Rocks

The models discussed so far apply to relatively closely defined facies, and do not consider depositional environments. Volumetrically, the turbidites and associated clastics are most abundant in large submarine fans, which in many areas have coalesced to form the continental rise. Information on modern fans is limited to short (1-5 m) cores, surveys of surface morphology, and relatively little subsurface geophysical information. Ancient fans have been proposed on the basis of paleocurrent evidence, abundance of channels, and distribution of facies. Two studies are outstandingly important - Normark's geophysical work and proposition of a fan growth model based exclusively upon recent sediment work, and Mutti and Ghibaudo's fan model based exclusively on ancient sediments. These two studies have been integrated into the review by Walker and Mutti (1973). Here, I will simply present the submarine fan - abyssal plain model as it is currently understood (Fig. 13), fit the various facies into the various morphological parts of the fan, and examine the stratigraphic consequences of fan progradation.

Because of their generally parallel-sided nature, the *classical turbidites* can be assigned to the smooth areas of the fan - the outer suprafan lobes and the outer fan. The trend from proximal to distal will develop most characteristically after the turbidites have flowed beyond the confines of the braided suprafan channels. The *massive sandstones* and *pebbly sandstones* are less regularly bedded, and the common presence of channelling suggests that they be assigned to the braided suprafan channels. As the channels become plugged, and shift in position, a sand body is gradually built up that consists of coalesced channels but no overbank deposits. In the absence of levees on the suprafan, and with the lateral channel shifting, any overbank fines that are deposited are rapidly eroded again. In nature, the gradual termination of the suprafan channels is likely to result in a very gradual facies change across the suprafan lobes - some classical turbidites might be preserved in wide, shallow channels, and some unusually large pebbly sandstone flows may spill out onto the smooth area of the suprafan.

Similarly, there is likely to be a similar facies change toward the feeder channel, from pebbly sandstones into *conglomerates* (assuming that such coarse clasts were available in the source area). Conglomerates are probably restricted to channels, mainly the inner fan channel, but also as coarse lags in

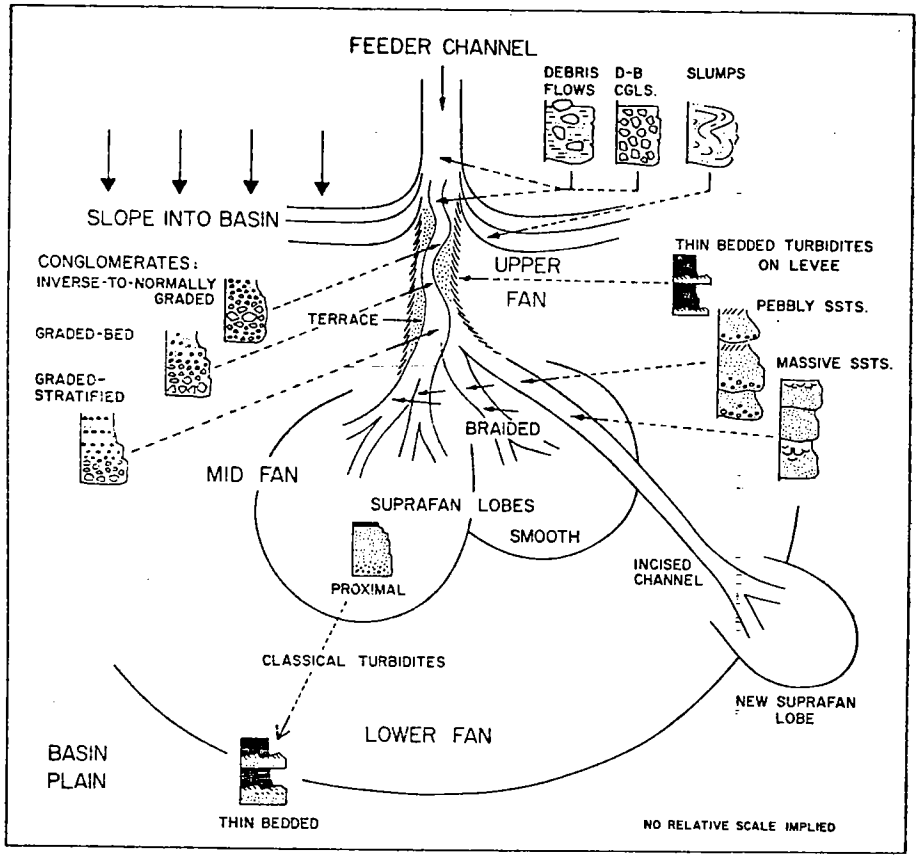

Figure 13
Submarine fan environmental model. See text for full discussion. D-B is disorganized-bed conglomerate model.

the bottoms of some suprafan channels. The gradual downfan change from inverse-to-normally graded types to graded-stratified types is suggested in Figure 13, but this change is tentative and is indicated only by theory, not by direct observation. The bottom of the feeder channel and the foot of the slope are the most likely environments for slumping and debris flows because of the steeper gradients. The disorganized-bed (D-B in Fig. 13) conglomerates might also be assigned here.

The inner fan levees are built up by flows which fill the channel and spill onto the levees and the area behind the levees. Sediment consists only of the finest suspended material (silt and clay) but there may be sufficient current strength to ripple the silt and produce a turbidite that would be described as CE in the Bouma model. Hence although a thick sequence of CE, BCE and C(D)E beds may define a distal environment, silty CE beds could also indicate levee or back-levee environments on the inner fan (a *proximal* environment by any definition). Again, I emphasize that one cannot use a checklist to define environments - in this case, the abundance of CE beds and their facies relationships (with conglomerates, or with basin plain muds) must be considered before an interpretation can be made. Problems of thin-bedded turbidites have been discussed by Mutti (1977) and Nelson *et al* (1977).

Stratigraphic Aspects of Fan Progradation

By comparison with a deltaic situation, we can reasonably assume that submarine fan progradation would result in a stratigraphic sequence passing from outer fan, through mid fan, into inner fan deposits upwards in the succession (Fig. 14). Progradation in the outer fan area would result in the deposition of a sequence classical turbidites that became more proximal in aspect upwards. This type of sequence is now termed "thickening- and coarsening-upward".

The progradation of individual suprafan lobes might also be expected to result in thickening- and coarsening-upward sequences, but these may not be restricted to classical turbidites. The smooth, outer suprafan lobes would be represented by classical turbidites, but these would pass upward into massive and pebbly sandstones as the braided portion of the suprafan prograded. The stratigraphically higher suprafan lobe sequences might therefore contain more massive and pebbly sandstones, and fewer classical turbidites.

The result of steady fan progradation so far would be one thickening- and coarsening-upward sequence of classical turbidites (outer fan), overlain by several thickening- and coarsening-upward sequences of classical turbidites, massive, and pebbly sandstones, representing several superimposed suprafan lobes that shifted laterally and built on top of each other during mid-fan progradation. The inner fan deposits would probably consist of one deep channel fill (Fig. 15), conglomeratic if coarse material were available at the source, and laterally equivalent to mudstones deposited on the channel levees and in the low areas behind the levees. It is possible during progradation, even in a generally aggrading situation, that the inner fan channel could cut into one of the braided suprafan lobes.

Channel fill sequences, both in the inner fan and braided suprafan channels, may consist of "thinning- and fining-upward sequences" (Fig. 16). Mutti and his Italian colleagues have suggested that these sequences result from progressive channel abandonment, depositing thinner and finer beds from smaller and smaller flows in the channels. Thus an inner fan channel might have a conglomeratic basal fill, and pass upward into finer conglomerates, and massive and pebbly sandstones (see Walker, 1977).

There are at least two alternative stratigraphic records of submarine fans other than the steady progradation discussed above. First, if supply for the fan is cut off at source (or diverted elsewhere), the fan will be abandoned, and will be covered by a rather uniform layer of hemipelagic mud. The previously active channels will also be mud-filled Abandoned mud-filled channels are known in the stratigraphic record, and include the Mississippi submarine channel (abandoned by post-Pleistocene rise of sea level), the Rosedale Channel (Late Miocene, Great Valley of Califor-

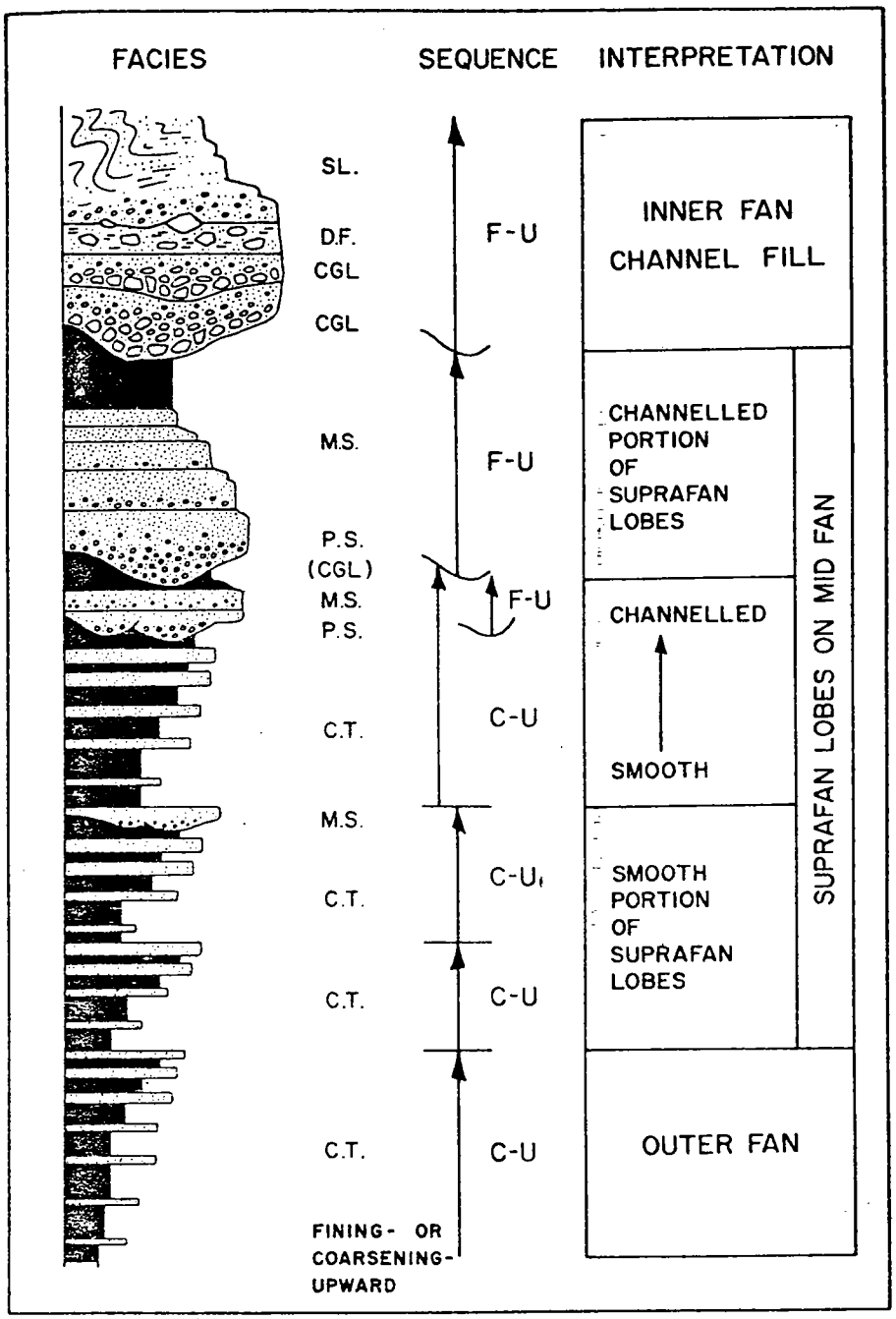

Figure 14
Hypothetical submarine fan stratigraphic sequence produced by fan progradation. C.T., classical turbidite; M.S., massive sandstone; P.S., pebbly sandstone; D.F., debris flow. Arrows show thickening- and coarsening-upward sequences (C-U) and thinning- and fining-upward sequences (F-U). See text for details.

nia) and the Yoakum Channel (Middle Eocene, Texas Gulf Coast).

Second, if the sediment supply increases considerably, or the gradient of the slope into the basin increases (tectonically?), the fan channel may be incised across the entire fan, and all sediment transported much farther into the basin. This is the situation in the modern La Jolla Fan (California), which has been entirely by-passed, with most of the coarser sediment (sand and coarser) being transported much farther into the San Diego Trough. A possible ancient example is the Cambrian St. Roch Formation at L'Islet Wharf (near St-Jean-Port-Joli), Quebec, where a thinning- and fining-upwards sequence of conglomerates and pebbly sandstones rests in a channel (Fig. 17). The channel cuts into a thick sequence of relatively thinly bedded turbidites (beds commonly begin with Bouma B and C divisions) that appear more distal than proximal. The juxtaposition of conglomerates in a channel, cutting into relatively distal turbidites, suggests an envrionment such as that labelled "incised channel" in Figure 13.

Limitations of the Fan Model

The fan model presented here is based upon data from geophysical surveys of relatively small modern fans such as La Jolla, San Lucas, and the many other fans of the Southern California Borderland. The model may not apply so well to some larger fans (Monterey and Astoria, off northern California-Oregon-Washington; the Bengal Fan) because they are characterized by major channels which cross the entire length of the fan - in the case of the Bengal Fan, the channels are over 1000 km long.

However, the fan model as presented seems to be a useful framework for considering many small to medium scale ancient basins. It cannot be applied to the long (hundreds of km) exogeosynclinal troughs in which the paleoflow pattern is dominantly parallel to the tectonic strike. Examples of turbidites in such troughs include the M. 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.

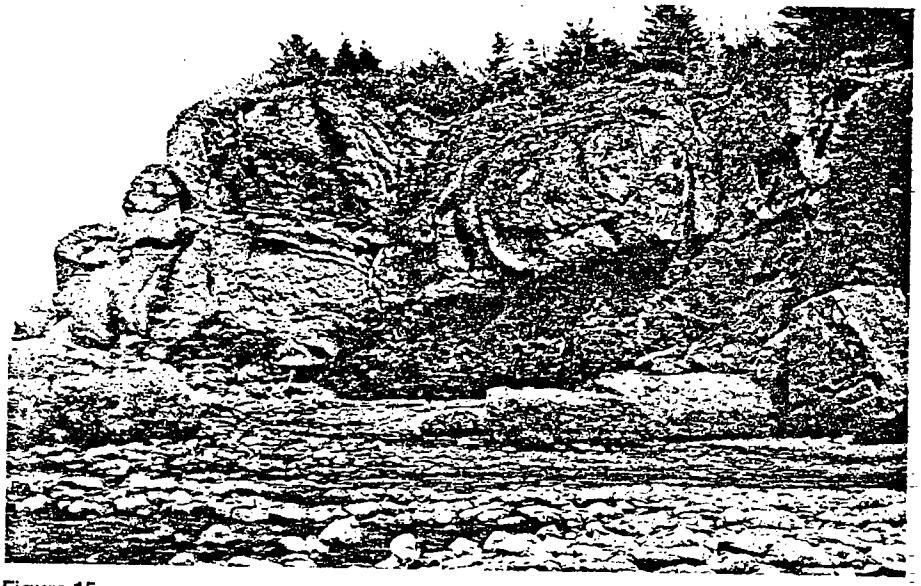

Figure 15
Portion of large channel cutting into shales. Channel fill consists of disorganized-bed conglomerates and lenticular sandstones, with an overall thinning - and fining-upward sequence. Ordovician Grosses Roches, Quebec. Appalachians. Figure far left for scale.

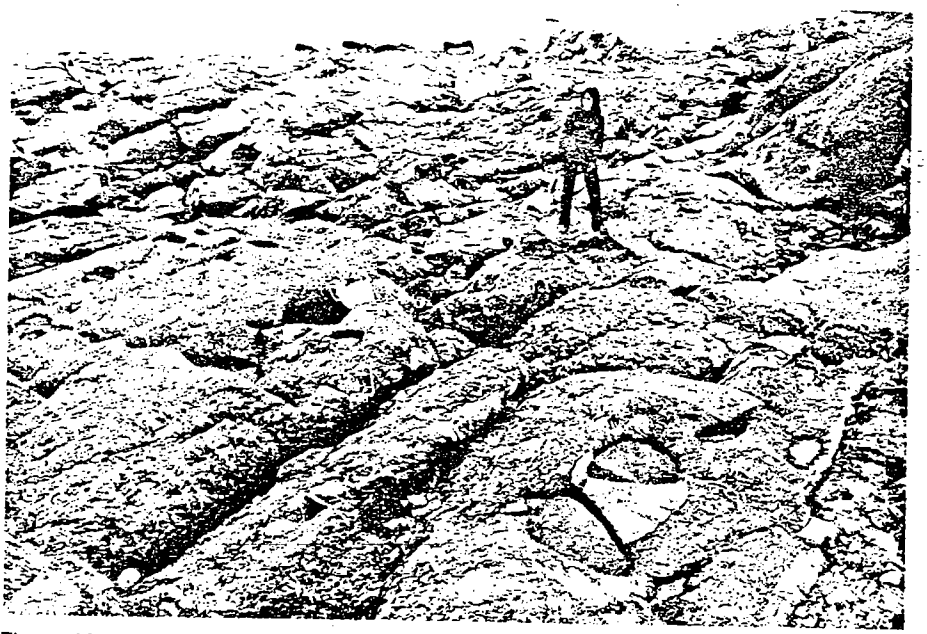

Figure 16
Example of a thinning- and fining-upward sequence (see Figure 14) from the Cambro-Ordovician Cap Enragé Formation near St-Simon. The conglomerate (lower right) contains large boulders which die out upward (toward top left). Centre of sequence is a pebble conglomerate, passing into pebbly sandstones (centre left) and finally into massive sandstones (near water's edge).

Examples of Turbidites and Associated Coarse Clastics

The papers listed below do *not* constitute a general set of readings with respect to an introduction to the turbidite concept. Rather, they are significant contributions mostly to Canadian geology, either because they discuss turbidites and their importance to specific problems or regional geology, or because they are important contributions to a general understanding of turbidites.

1. Precambrian turbidites

Walker, R.G. and F.J. Pettijohn, 1971, Archean sedimentation: analysis of the Minnitaki Basin, northwestern Ontario, Canada: Geol. Soc. Am. Bull., v. 82, p. 2099-2130.

Henderson, J.B., 1972, Sedimentolog Archean turbidites at Yellowknife, Northwest Territories: Can. Jour. Eart Sci., v. 9, p. 882-902.

Turner, C.C. and R.G. Walker, 1973, Sedimentology, stratigraphy and crus evolution of the Archean greenstone b near Sioux Lookout, Ontario: Can. Jou Earth Sci., v. 10, p. 817-845.

Rousell, D.H., 1972, The Chelmsford Formation of the Sudbury Basin - a Precambrian turbidite; *in* J.V. Guy-Bra ed., New Developments in Sudbury Geology: Geol. Assoc. Can. Spec. Pap 10, p. 79-91.

Cantin, R. and R.G. Walker, 1972, Was the Sudbury Basin circular during deposition of the Chelmsford Formation?, *in* J.V. Guy-Bray, ed., New Deve opments in Sudbury Geology: Geol. Assoc. can. Spec. Paper 10, p. 93-101.

2. Appalachian area

Enos, P., 1969, Anatomy of a flysch: Jo Sed. Petrol., v. 39, p. 680-723. (Note: th is the classic paper on the Cloridorme Formation.)

Parkash, B., 1970, Downcurrent changes in sedimentary structures in Ordovician turbidite greywackes: Jour Sed. Petrol., v. 40, p. 572-590.

Parkash, B. and G.V. Middleton, 1970, Downcurrent textural changes in Ordo vician turbidite greywackes: Sedimentology, v. 14, p. 259-293. (Note: these two papers by Parkash are detailed studies of the Cloridorme Formation.)

Skipper, K., 1971, Antidune cross-stratification in a turbidite sequence. Cloridorme Formation, Gaspé, Quebec Sedimentology, v. 17, p. 51-68. (See als discussion of this paper, Sedimentolog v. 18, p. 135-138.)

Skipper, K. and G.V. Middleton, 1975, The sedimentary structures and depos tional mechanics of certain Ordovician turbidites, Cloridorme Formation, Gaspe, Quebec: Can. Jour. Earth Sci., v. 12, p. 1934-1952.

Hubert, C., J. Lajoie and M.A. Leonard, 1970, Deep sea sediments in the Lowe Paleozoic Quebec Supergroup, *in* J. Lajoie, ed., Flysch Sdimentology in Nort America: Geol. Assoc. Can. Spec. Pape 7, p. 103-125. (Note: the main areas discussed in the paper are L'Islet Whar and the Cap Enragé Formation in the Bi

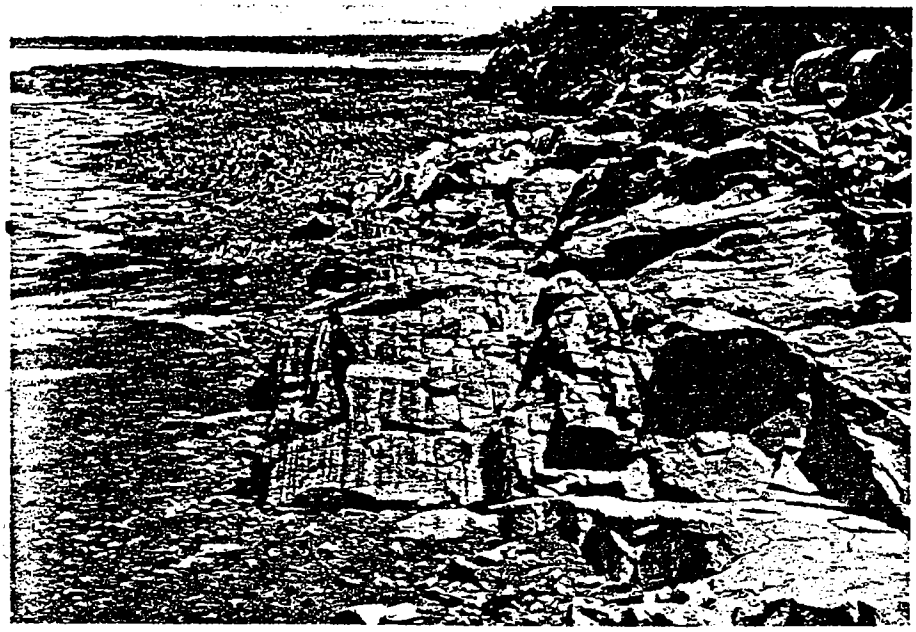

Figure 17
Channel in Cambrian St. Roch Formation at L'Islet Wharf, Quebec. Stratigraphic top to right. Channel cuts into classical turbidites, and consists of at least two main portions—foreground (with geologist for scale), and cliff at top right. Note the graded-stratified conglomerate filling lower part of channel, and passing up into massive sandstone (lower right).

- St. Fabien area. See also Rocheleau and Lajoie, and Davies and Walker, below.)

Rocheleau, M. and J. Lajoie, 1974, Sedimentary structures in resedimented conglomerate of the Cambrian flysch, L'Islet, Quebec Appalachians: Jour. Sed. Petrol., v. 44, p. 826-836.

Davies, I.C. and R.G. Walker, 1974, Transport and deposition of resedimented conglomerates: the Cap Enragé Formation, Cambro-Ordovician, Gaspé, Quebec: Jour. Sed. Petrol., v. 44, p. 1200-1216.

Hendry, H.E., 1973, Sedimentation of deep water conglomerates in Lower Ordovician rocks of Quebec - composite bedding produced by progressive liquefaction of sediment?: Jour. Sed. Petrol., v. 43, p. 125-136.

Schenk, P.E., 1970, Regional variation of the flysch-like Meguma Group (Lower Paleozoic) of Nova Scotia, compared to recent sedimentation off the Scotian Shelf, *in* J. Lajoie, ed., Flysch Sedimentology in North America: Geol. Assoc. Can. Spec. Paper 7, p. 127-153.

Stevens, R.K., 1970, Cambro-Ordovician flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a Proto-Atlantic ocean, *in* J. Lajoie, ed., Flysch Sedimentology in North America: Geol. Assoc. Can. Spec. Paper 7, p. 165-177.

Horné, G.S. and J. Helwig, 1969, Ordovician stratigraphy of Notre Dame Bay, Newfoundland *in* M. Kay, ed., North Atlantic - Geology and Continental Drift: Am. Assoc. Petrol. Geol. Mem. 12, p. 388-407.

Osborne, F., 1956, Geology near Quebec City: Nat. Can., v. 83, p. 157-223.

Hiscott, R.N., 1979, Clastic sills and dykes associated with deep-water sandstones, Tourelle Formation, Ordovician, Quebec: Jour. Sed. Petrol., v. 49, p. 1-9.
Emphasizes the importance of clastic sills in turbidites sequences, and shows how easily they can be misinterpreted as turbidites.

3. Campus, University of Montreal
Lajoie, J., 1972, Slump fold axis orientations: an indication of paleoslope?: Jour.: Sed. Petrol., v. 42, p. 584-586.

4. Canadian Arctic
Trettin, H.P., 1970, Ordovician-Silurian flysch sedimentation in the axial trough of the Franklinian geosyncline, northeastern Ellesmere Island, Arctic Canada, *in* J. Lajoie, ed., Flysch Sedimentology in North America: Geol. Assoc. Can. Spec. Paper 7, p. 13-35.

5. Western Canada
Danner, W.R., 1970, Western Cordilleran flysch sedimentation, southwestern British Columbia, Canada, and northwestern Washington and central Oregon, U.S.A., *in* J. Lajoie, Flysch Sedimentology in North America: Geol. Assoc. Can. Spec. Paper 7, p. 37-51.

Cook, H.E., P.N. McDaniel, E. Mountjoy and L.C. Pray, 1972, Allochthonous carbonate debris flows at Devonian bank ("reef") margins, Alberta, Canada: Bull. Can. Petrol. Geol., v. 20, p. 439-497.

Srivastava, P., C.W. Stearn, and E.W. Mountjoy, 1972, A Devonian megabreccia at the margin of the Ancient Wall carbonate complex, Alberta: Bull. Can. Petrol. Geol., v. 20, p. 412-438.

6. Field Guidebooks
Hubert, C.M., 1969, ed., Flysch sediments in parts of the Cambro-Ordovician sequence of the Quebec Appalachians: Geol. Assoc. Can., Guidebook for field trip 1, Montreal, 38 p.

Riva, J., 1972, Geology of the environs of Quebec City: Montreal, Internatl. Geol. Cong., Guidebook B-19, 53 p.

St. Julien, P., C. Hubert, W.B. Skidmore and J. Beland, 1972, Appalachian structure and stratigraphy, Quebec: Montreal, Internatl. Geol. Cong., Guidebook A-56, 99 p.

Harris, I.M., ed., 1975, Ancient sediments of Nova Scotia, Eastern Section, Soc. Econ. Paleont. Min., Guidebook. Also *in* Maritime Sediments, v. 11, numbers 1, 2 and 3.

Poole, W.H. and J. Rodgers, 1972, Appalachian geotectonic elements of the Atlantic Provinces and southern Quebec: Montreal, Internatl. Geol. Congr., Guidebook A-63, 200p.

7. Turbidite Reservoirs
A list of papers discussing oil and gas in turbidite reservoirs is given by Walker, 1978. For the reader who wishes to consult a few papers, I suggest the following:

MacPherson, B.A., 1978, Sedimentation and trapping mechanism in Upper Miocene Stevens and older turbidite fans of Southeastern San Joaquin Valley, California: Amer. Assoc. Petrol. Geol. Bull. v. 62, p. 2243-2274.
A comprehensive paper that is particularly valuable for the discussion of the larger scale geometry of turbidite sands.

Also important is the discussion of lateral wedging out, and the superposition of sand bodies (controlled by interbedded shales).

Dickas, A.B., and J.L. Payne, 1967, Upper Paleocene buried channel in Sacramento Valley, California: Amer. Assoc. Petrol. Geol. Bull., v. 51, p. 873-882.
Discusses a large, deep abandoned submarine channel filled with fines. The fines act as an up-dip seal for gas in surrounding rocks. See Walker (1978) for further discussion of large mud-filled channels.

Weagant, F.E., 1972, Grimes gas field, Sacramento Valley, California: *in* Stratigraphic Oil and Gas Fields: Amer. Assoc. Petrol. Geol., Memoir 16, p. 428-439.
The gas is trapped in small turbidite lobes separated by thick shale blankets. The paper contains good isopach maps of lobes, and a cross-section showing the overall superposition of lobes.

Hsu, K.J., 1977, Studies of Ventura field, California, 1: facies geometry and genesis of lower Pliocene turbidites. Amer. Assoc. Petrol. Geol. Bull., v. 61, p. 137-168.
The first release of information of Shell Oil Company work in the Ventura Basin in the 1950's. The paper contains good descriptions of the rocks, and very interesting E-log correlations and isopach maps. No modern interpretation was suggested in terms of submarine fan models (although Walker, 1978, attempted to read the data in terms of submarine fans). Hsu himself prefers to emphasive longitudinal sediment transport in the basin, downplaying fans.

Selected References - Basic Reading
This list is intentionally very brief. It is intended to serve as basic reading for those wishing to read further in various aspects of turbidites and associated coarse clastics in their basinal setting.

1. Turbidites in basins - facies and facies associations
Walker, R.G., 1970, Review of the geometry and facies organization of turbidites and turbidite-bearing basins, *in* J. Lajoie, ed., Flysch Sedimentology in North America: Geol. Assoc. Can. Spec. Paper 7, p. 219-251.
This paper discusses at length the various turbidite and associated facies, but predates the Normark-Mutti fan model. It contains an extensive reference list.

Walker, R.G. and E. Mutti, 1973, Turbidite facies and facies associations, *in* G.V. Middleton and A.H. Bouma, eds., Turbidites and deep water sedimentation: Pacific Section, Soc. Econ. Paleont. Min., Short Course Notes (Los Angeles), p. 119-157.
An extended discussion of the facies and models discussed in the present article.

Walker, R.G., 1978, Deep-water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps: Amer. Assoc. Petrol. Geol. Bull., v. 62, p. 932-966.
A review of the submarine fan model, emphasizing the separation of individual lobes by mud blankets, and suggesting how the model can be used for exploration.

2. Modern submarine fans
Normark, W. R.. 1974, Submarine canyons and fan valleys: factors affecting growth patterns of deep sea fans, *in* R.H. Dott, Jr. and R.H. Shaver, eds., Modern and Ancient Geosynclinal Sedimentation: Soc. Econ. Paleont. Min. Spec. Publ. 19, p. 56-68.
An updated version of Normark's original (1970) discussion of fan growth.

Nelson, C.H. and L.D. Kulm, 1973, Submarine fans and deep-sea channels, *in* G.V. Middleton and A.H. Bouma, eds., Turbidites and Deep Water Sedimentation: Pacific Section, Soc. Econ. Paleont. Min. Short Course Notes (Los Angeles), p. 39-78.
Although emphasizing the N.W. Pacific, this review paper, with abundant references, is a good overall summary of fan morphology and sedimentation.

Normark. W.R., 1978, Fan valleys, channels and depositional lobes on modern submarine fans: characters for recognition of sandy turbidite environments: Amer. Assoc. Petrol. Geol. Bull., v. 62, p. 912-931.
Normark's most recent and comprehensive discussion of modern submarine fans.

3. Modern and Ancient fans - comparison
Nelson, C.H. and T.H. Nilsen, 1974, Depositional trends of modern and ancient deep sea fans, *in* R.H. Dott, Jr. and R.H. Shaver, eds., Modern and Ancient Geosynclinal Sedimentation: Soc. Econ. Paleont. Min. Spec. Paper 1, p. 69-91.
Good comparison of modern and ancient fans, showing how information from both sources can be dovetailed ("distilled") together.

4. Processes - turbidity currents and associated sediment gravity flows
Middleton, G.V. and M.A. Hampton, 1976, Subaqueous sediment transport and deposition by sediment gravity flows, *in* D.J. Stanley and D.J.P. Swift, eds., Marine Sediment Transport and Environmental Management: New York Wiley Interscience.
All you need to know about turbidity currents, and associated processes. Non-mathematical.

5. History and philosophy of the turbidity current concept
Walker, R.G., 1973. Mopping-up the turbidite mess, *in* R. N. Ginsburg, ed., Evolving Concepts in Sedimentology: Baltimore, Johns Hopkins Press, p. 1-37
Detailed history, with philosophical commentary, on the evolution of the turbidity current concept. This paper will not help you find oil, however!

Other references cited in this article
Bouma, A.H., 1962, Sedimentology of Some Flysch Deposits: Amsterdam, Elsevier Publ. Co., 168 p. Cited only as the first documentation of the now-accepted turbidite model.

Kuenen, P.H. and C.I. Migliorini, 1950, Turbidity currents as a cause of gradec bedding: Jour. Geol., v. 58, p. 91-127.
Cited for historical reasons, as the first paper that directed geologists' attention to the possibility of high densit turbidity current deposits in the geological record. This paper represents one of the most important foundation stones of modern (post World War II) sedimentology.

Mutti, E., 1977, Distinctive thin-bedded turbidite facies and related depositiona environments in the Eocene Hecho Group (South-central Pyrenees, Spain) Sedimentology, v. 24, p. 107-131.
A general discussion of thin-bedded turbidites emphasizing a variety of possible depositional environments, with examples from the Hecho Group in Spain.

ıal Sedimentati
Min. Spec. Pap

ıf modern and
how informatic
can be dovetail
r.

idity currents
nt gravity flow
M.A. Hampton
sediment trans
ediment gravity
y and D.J.P. Sw
ent Transport a
agement: New

v about turbidit
iated processe

osophy of the
oncept
Mopping-up th
N. Ginsburg, e
n Sedimentolo
pkins Press, p.
n philosophical
evolution of th
cept. This pap
however!

ited in this art
Sedimentology
its: Amsterdam
68 p. Cited only
ion of the now-
nodel.

I. Migliorini, 19
s a cause of gr
, v. 58, p. 91-12
easons, as the
geologists'
ibility of high de
osits in the geo
er represents
ortant foundati
ost World War

nctive thin-bed
elated deposit
Eocene Hecho
al Pyrenees, Sp
l, p. 107-131.
n of thin-bedde
ng a variety of
l environments
the Hecho Gro

, C.H., E. Mutti, and F. Ricci-
1977, Upper Cretaceous resedi-
d conglomerates at Wheeler
California: description and field
a discussion: Jour. Sediment.
v. 47, p. 926-928.
ussion of a paper by Walker with
t to thin-bedded turbidites. I have
quently looked at these rocks
ry, 1979) and now suggest that
bidites *below* the conglomerates
tal, but that the turbidites *above*
nglomerates represent a thin-
d facies in some other environ-
possibly levee as suggested by
n *et al.* This discussion emphas-
e problems of interpreting the thin-
d facies.

r, R.G., 1977, Deposition of upper
zoic resedimented conglomerates
ssociated turbidites in southwest-
egon: Geol. Soc. Amer. Bull., v. 88,
-285.
ption and interpretation of thick
d conglomerates in thinning- and
upward sequences

tt, R.N., 1979, Clastic sills and
associated with deep-water
tones, Tourelle Formation, Ordovi-
Quebec: Jour. Sed. Petrol., v. 49,

asizes the importance of clastic
turbidites sequences, and shows
asily they can be misinterpreted as
ites

r, R.G., 1975, Generalized facies
s for resedimented conglomer-
of turbidite association: Geol. Soc.
ull., v. 86, p. 737-748.
s the most recent paper on
imented conglomerates - it shows
Bouma-like models were set up for
ent types of conglomerates.

g, J., 1970, Slump folds and early
tures, northeastern Newfoundland
lachians: Jour. Geol., v. 78,
2-187.

eceived November 24, 1975.
ed April, 1979.
inted from Geoscience Canada,
, No.1, p. 25-36.