

50 years of the turbidite paradigm (1950s–1990s): deep-water processes and facies models—a critical perspective

G. Shanmugam*

Mobil Technology Company, PO Box 650232, Dallas, TX 75265-0232, USA

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Abstract

Under the prevailing turbidite paradigm, the term ‘turbidite’ (i.e., deposits of turbidity currents with Newtonian rheology and turbulent state) is used very loosely and is commonly applied to deposits of debris flows with plastic rheology and laminar state. For example, because ‘high-density turbidity currents’ are defined on the basis of three different concepts (i.e., flow density, grain size, and driving force), there are no consistent criteria for recognition of their deposits. As a result, deep-water massive sands of debris-flow origin are routinely misinterpreted as high-density turbidites. The concept of waxing flow as a type of turbidity current is problematic because waxing flows are defined on the basis of velocity, not on fluid rheology and flow state. The waxing-flow concept allows inversely graded sands to be misinterpreted as turbidites. Perhaps, the most problematic issue is the use of alluvial channel traction bed forms observed in flume experiments as the analog for the five divisions of the Bouma Sequence (i.e., classic turbidites deposited from suspension). This is because flume experiments were conducted under equilibrium flow conditions, whereas natural turbidity currents deposit sediment under disequilibrium waning flow conditions. This and other problems of deep-water processes and facies models are addressed in this paper from the author’s personal perspective. Classification of sediment-gravity flows into *Newtonian flows* (e.g., turbidity currents) and *plastic flows* (e.g., debris flows), based on fluid rheology and flow state, is a meaningful and practical approach. Although popular deep-water facies models are based on transport mechanisms, there are no standard criteria in the depositional record to reliably interpret transport mechanisms. According to existing turbidite-facies models, an ideal turbidite bed, which has normal grading, with gravel- to mud-size particles should contain a total of 16 divisions. However, no one has ever documented a complete turbidite bed with 16 divisions in modern or ancient deposits. Recognition of units deposited by deep-water bottom currents (also referred to as contour currents) is difficult. Traction structures are good indicators of bottom-current reworking, but distinguishing deposits of bottom currents from deposits of overbanking turbidity currents is difficult even though it has important implications for developing depositional models for hydrocarbon exploration and production. I consider sandy debris flows to be the dominant process responsible for transporting and depositing sands in the deep sea. Experiments on sandy debris flows suggest that low clay content (as little as 1%) is sufficient to provide the strength necessary for sandy debris flows. Deposits of experimental sandy debris flows are characterized by massive sand, sharp upper contacts, floating clasts, inverse grading, normal grading with clasts, and water-escape structures. As a counterpart to turbidite-dominated fan models suited for basinal settings, a slope model is proposed that is a debris-flow dominated setting with both non-channelized and channelized systems. Contrary to popular belief, deposits of sandy debris flows can be thick, areally extensive, clean (i.e., mud poor), and excellent reservoirs. High-frequency flows tend to develop amalgamated debris-flow deposits with lateral connectivity and sheet-like geometry. Submarine-fan models with turbidite channels and lobes have controlled our thinking for nearly 35 years, but I consider that these models are obsolete. The suprafan lobe concept was influential in both sedimentologic and sequence-stratigraphic circles because it provided a basis for constructing a general fan model and for linking mounded seismic facies with sheet-like turbidite sandstones. However, this concept recently was abandoned by its proponent, which has left the popular sequence-stratigraphic fan models with a shaky foundation. A paradigm shift is in order in the 21st century. This shift should involve the realization that thick deep-water massive sands are deposits of debris flows, not ‘high-density turbidites’. However, there are no standard vertical facies models that can be applied universally for either turbidites, contourites, or sandy debris flows. Science is a journey, whereas facies models terminate that journey and become the final destination. © 2000 Elsevier Science Ltd. All rights reserved.

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* Tel.: +1-214-951-3109; fax: +1-214-905-7058.

E-mail address: shan_shanmugam@email.mobil.com

1. Introduction

The underlying theme of the turbidite paradigm is that turbidity currents and their deposits (i.e., turbidites) are the fundamental building blocks of deep-water depositional systems. The turbidite paradigm, which is manifested in the form of various turbidite facies models (e.g., Bouma, 1962; Mutti & Ricci Lucchi, 1972, 1975; Walker, 1978; Stow & Shanmugam, 1980; Lowe, 1982), has been the single most influential factor in directing our thinking on deep-water research during the past 50 years. This skewed emphasis on turbidites has left us with many basic problems that are important not only to our basic scientific need to understand deep-water processes and products, but also in exploring and producing deep-water reservoirs, targets that are becoming increasingly important as we approach the 21st century.

The current trend in both academia and the petroleum industry is to study the reservoir architecture of deep-water sands without paying much attention to the depositional processes that emplaced these sands. This is an unhealthy trend because reservoir architecture is largely the product of depositional processes. Thus, reservoir architecture (large scale) cannot be understood without understanding the processes (small scale) that created that architecture. In addition, a clear understanding of depositional processes is the key to (1) constructing a meaningful depositional model, and (2) establishing sand distribution. The primary purpose of the following critical review is to highlight the problems associated with concepts of deep-water processes and related facies models. Specific objectives are the following:

1. To reflect on the history of deep-water research during the past 50 years.
2. To stress the value of rheologic classification of sediment-gravity flows.
3. To discuss theoretical and experimental aspects of sandy debris flows.
4. To evaluate the importance of bottom currents created by processes other than downslope gravity-induced flows.
5. To assess the validity of the concepts of 'high-density turbidity currents' and 'traction carpets'.
6. To critique turbidite and contourite facies models.
7. To review the status of submarine-fan models.
8. To show the link between suprafan-lobe model and basin-floor fan model.
9. To discuss the validity of seismic facies and geometries of deep-water systems for interpreting deep-water processes.
10. To emphasize the current crisis that involves questioning of the very foundation of the turbidite paradigm (e.g., Shanmugam, 1996a, 1997a), and abandonment of popular fan models (Normark, 1991; Walker, 1992a).

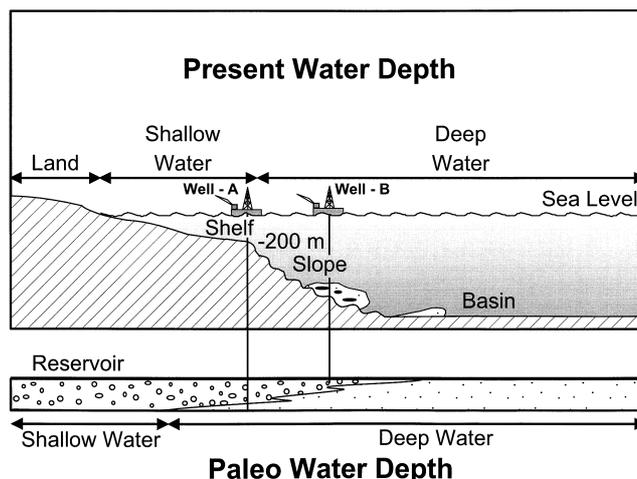


Fig. 1. The term 'deep-water' is used in this paper to refer to bathyal water-depth environments (>200 m) occurring seaward of the continental shelf break on the slope, and basin where sediment-gravity processes (slides, slumps, debris flows, and turbidity currents), and bottom currents are the dominant depositional mechanisms. In petroleum exploration and production, the term 'deep-water' is used with two different meanings. (1) To denote the deep-water depositional origin of the reservoir, even if the drilling for this reservoir commences from the shelf (e.g., Well A), and (2) to denote the deep-water drilling depths (e.g., Well B), even if the target reservoir is of shallow-water origin. Gravel symbol = reservoirs of shallow-water origin. Sand symbol = reservoirs of deep-water origin.

11. To assess the problem of mud matrix in deposits of turbidity currents and debris flows.
12. Finally, to present a depositional model for debris-flow dominated slope systems.

By design, this article is a cumulative expression of my personal views, observations and research based largely on my papers I have published since the 1970s (e.g., Shanmugam & Benedict, 1978; Shanmugam, 1980, 1990, 1996a, 1997a). Although I have cited too many of my own papers, this superfluity is necessary to keep track of my evolutionary thought process during the past 25 years. By choice, this paper is a blend of advocacy, autobiography, bibliography, history, personal odyssey, philosophy, psychology, rheology, and a lot of deep-water geology.

The term 'deep-water' is used here to refer to bathyal water-depth environments (>200 m) occurring seaward of the continental shelf break on the continental slope, rise, and basin where sediment-gravity processes (slides, slumps, debris flows, and turbidity currents), and bottom currents are the dominant depositional mechanisms. In petroleum exploration and production, the term 'deep-water' is used to convey two different meanings. (1) Most geologists would use the term 'deep water' to convey the deep-water depositional origin of the buried reservoir, even if the drilling for this reservoir commences from the shelf (e.g., Fig. 1, Well A). (2) Drilling engineers would

use the term to denote the deep-water drilling depths, even if the buried reservoir is of shallow-water origin (Fig. 1, Well B).

2. Progress in science

The conventional view is that science progresses in a continuous and cumulative manner. However, Kuhn (1970) argued that science does not proceed in a continuous and cumulative manner, but rather by periods of scientific revolutions (times when old ideas are rejected) followed by periods of normal science (times when new ideas are introduced and adopted). Kuhn's stages of scientific development are: (1) early random observations, (2) first paradigm, (3) crisis, (4) revolution, and (5) mopping-up operations or normal science. Turbidite facies models may be considered to represent the normal science stage of Kuhn. Once this final stage or normal science is achieved (i.e., the paradigm), scientists enjoy a sense of confidence as well as comfort. This comfort often leads to complacency. In this regard, Kuhn (1970) has argued that:

1. The paradigm forces scientists to force-fit nature into preconceived models of the paradigm.
2. The paradigm encourages scientists to ignore data that do not fit the paradigm.
3. The paradigm discourages scientists from inventing new theories.
4. The paradigm makes scientists intolerant of new theories invented by others.

I agree with Kuhn's (1970) views based on my own experience in deep-water research during the past 25 years. For example, I, in collaboration with several co-workers (Shanmugam et al., 1995a), have recently reinterpreted several deep-water massive sand reservoirs in the North Sea as the deposits of sandy debris flows. These deposits were previously interpreted as turbidites by other workers (e.g., Newman, Leeder, Woodruff & Hatton, 1993). Shanmugam et al. (1995a) have also shown how sequence-stratigraphic models influenced geoscientists to force-fit geologic data into preconceived basin-floor fan models. In line with Kuhn's (1970) concept (see item #4 above), Hiscott et al. (1997) were intolerant of our new theories and stated that "We therefore reject the paradigm of Shanmugam et al. (1995) . . ." In response, Shanmugam, Bloch, Damuth and Hodgkinson (1997) pointed out that Hiscott et al. (1997) presented no evidence that they had examined the cores interpreted by us and thus they had no first hand information about the data set used in our study. Because of this we believe that their critique should not be given any credence.

Throughout history, the geologic community has been known for its intolerance of new observations and theor-

ies. A well known example is the long-standing objection to the concept of long runout landslides (the term 'landslide' includes debris flows, liquefied flows, grain flows, and other mass movements in both subaerial and subaqueous environments). This objection was based on the conventional wisdom that the runout distance of a landslide equals its vertical fall distance. Although there are many documented cases of landslides (e.g., submarine slides in Hawaii with more than 200 km of runout distances—see Hampton, Lee and Locat (1996); the 1881 Elm slide in Switzerland; the 1903 Frank slide in Canada; the 1970 Earthquake generated debris flows in Peru; and the 1985 volcanic mud flows in Colombia that killed 24,000 people) with long runout distances (up to 100 times their vertical fall) and high speeds (up to 320 km/h), the geologic community opposed such concepts because there were no known mechanisms to explain why these landslides traveled so far and so fast (The Learning Channel, 1997). There are at least 20 documented theories that attempt to explain this mechanical paradox, such as, cushion of compressed air beneath the slide (Shreve, 1968), shearing of granular flows (Campbell, 1990), hydroplaning of subaqueous debris flows (Mohrig, Whipple, Hondzo, Ellis & Parker, 1998), and the acoustic fluidization theory proposed by Melosh (see The Learning Channel, 1997). A major turning point on this issue had occurred on 18 May, 1980 when the eruption of Mount St. Helens in the US generated impressive long runout landslides that were captured on videotapes (see The Learning Channel, 1997). The lesson here is that we should not simply reject a new observation or theory because of a lack of precedents. New observations and theories cannot have precedents. In an observational science like geology, new observations should be encouraged, not discouraged.

Perhaps, the best known example is the rejection of Alfred Wegener's theory of 'continental drift' by the geologic community in the 1920s and 1930s because there were no established mechanisms to explain the 'drifting continents'. Bullard (1975) offered the most insightful answer to the question, "why the geologic community rejected Wegener's theory for so long?" "It is easy to see", Bullard (1975) explained, "why there was such strong opposition to Wegener in the 1920s and 1930s. If weak or fallacious arguments are mixed with strong ones, it is natural for opponents to refute the former and to believe that the whole position has been refuted. There is always a strong inclination for a body of professionals to oppose an unorthodox view. Such a group has a considerable investment in orthodoxy: they have learned to interpret a large body of data in terms of the old view, and they have prepared lectures and perhaps written books with the old background. To think the whole subject through again when one is no longer young is not easy and involves admitting a partial misspent youth. Further, if one endeavors to change one's views in mid-

career, one may be wrong and be shown to have adopted a specious novelty and tried to overthrow a well-founded view that one has oneself helped to build up. Clearly it is more prudent to keep quiet, to be a moderate defender of orthodoxy, or to maintain that all is doubtful, sit on the fence, and wait in statesmanlike ambiguity for more data (my own line till 1959).“

The geologic community did reverse its position on this issue when paleomagnetic evidence derived from polar-wandering studies (Runcorn, 1962) and sea-floor magnetic anomalies (Vine and Mathews, 1963) began to provide irrefutable evidence of continental drift and ‘sea-floor spreading’.

Bullard’s (1975) humorous analysis is quite fitting to the issues of the turbidite paradigm today. Considering the monumental efforts that went into promoting turbidite systems and submarine fans in the form of journal articles, books, research symposiums, short courses, core workshops, and field trips, it is no surprise that many in the geologic community, especially in industry, are vehemently opposing any critique of the turbidite paradigm. However, I believe that once the initial rage of emotions over the critique subsides, the intellect will prevail.

Throughout the 1980s and 1990s, I have been hammering away at the negative influences of the turbidite paradigm on deep-water research (e.g., Shanmugam, 1990, 1996a, 1996b, 1997a; Shanmugam and Moiola, 1985, 1988, 1991, 1994, 1995, 1997; Shanmugam, Damuth & Moiola, 1985a; Shanmugam, Moiola & Damuth, 1985b; Shanmugam et al., 1995a, 1996, 1997). Finally, the geologic community appears to be responding to my criticism of the turbidite paradigm as the *American Association of Petroleum Geologists Bulletin* (1997, vol. 81, p. 449–491, 662–672) published a total of six discussions and replies on my papers and at the 1997 *American Association of Petroleum Geologists Annual Convention* in Dallas, a formal debate was held to address many of the issues of deep-water processes and facies models (moderator: H. E. Clifton; panelists: A. H. Bouma, D. R. Lowe, J. E. Damuth, G. Parker & G. Shanmugam).

In its 1997 *Geoscience Highlights* issue, *Geotimes* observed, “Turbidites hit the fan after Shanmugam and colleagues reinterpreted most of them as sandy debris flows because reversely graded or ungraded bases in ‘most’ turbidites imply settling hindered by yield strength. This yield strength supposedly implies laminar plastic flow, whereas turbulent flow should cause unhindered settling and normal grading. ‘High-density turbidity current’ becomes an oxymoron, and ‘turbidite’ would be as overextended as ‘greywacke’.” (Wells, 1998).

In responding to my critique of the ‘Bouma Sequence’ (Shanmugam, 1997a), Miall (1999) commented, “But it is precisely because we have in our minds a good concept of what a ‘true’ Bouma turbidite should look like, that

we can readily appreciate how far off the track many sedimentological descriptions and interpretations have strayed, when someone like Shanmugam comes along and brings us up short with different observations. It turns out that many deep-marine sands may not be turbidites at all.”

Hopefully, this debate will continue and will result in a better understanding of deep-water processes and depositional systems.

3. Fifty years of the turbidite paradigm

At this point I believe it is useful to reflect on the past 50 years of the turbidite paradigm to capture what we have learned, and to determine what have we missed, and what needs to be done in the future. A philosophical history of the turbidite concept from 1880 to 1973 is given by Walker (1973). Historical development of the main concepts in the study of deep-water clastic sediments from 1872 to 1985 is discussed by Stow (1985). Benchmark papers on deep-marine sedimentation from 1950 to 1970 are listed by Pickering, Hiscott and Hein (1989). Sanders and Friedman (1997) provided a thoughtful review of petroleum exploration in deep-water deposits with special emphasis on historical perspective, process sedimentology, and the importance of mud in turbidites.

The year 1948 may be considered to mark the advent of the turbidite paradigm. At the 18th International Geological Congress (held in London, UK) in 1948, Migliorini discussed the origins of graded bedding by density currents, Shepard showed underwater photographs of steep, massive walls of submarine canyons, and Kuenen discussed the erosive potential of high-density currents in creating submarine canyons (see Friedman & Sanders, 1997, for a historical review). Prior to 1948, the geologic community was very skeptical of the importance of density currents (i.e., turbidity currents) in eroding submarine canyons and depositing graded beds in the deep sea. Until 1950 when Kuenen and Migliorini (1950) published their classic paper ‘Turbidity currents as a cause of graded bedding’, the geologic community generally believed that the deep sea was a tranquil realm free of current activity where only mud slowly accumulated from pelagic settling (Friedman & Sanders, 1997). However, systematic shallow coring of continental margin and abyssal-plain sediments beginning in the 1940s confirmed the existence of turbidity currents and related gravity-controlled deposition of sediment in the deep sea. Since then the occurrence of turbidite sands in deep-water strata has gained global acceptance. Today, however, the turbidite paradigm has gone to the other extreme in some circles of the geologic community; which now routinely rely on model-driven interpretations that envision nearly all deep-water sands as true turbidites deposited on submarine fans. I find it remarkable that during a period of

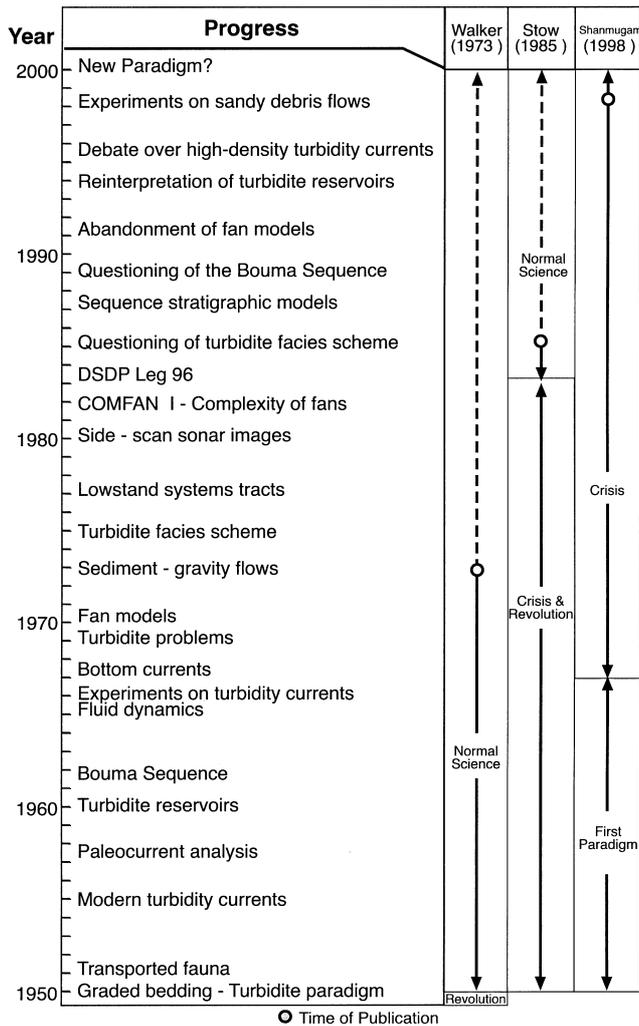


Fig. 2. Important contributions to deep-water research made during the past 50 years. An expanded list is given in the text. Note differences between Walker (1973), Stow (1985), and Shanmugam (1998b) in perspectives on the advent of the normal science stage. See text for detailed discussion.

just 50 years, geologists went from a state of caution to a state of complacency regarding turbidity currents and their deposits. In this paper, I have attempted to capture the general trend of deep-water research during the past 50 years (Fig. 2). The following is an expanded list of pioneering studies, milestones, selected contributions, and events along that general trend, but is by no means a comprehensive bibliography:

3.1. Pre-1950s

- First description of density currents in Swiss Lakes reported (Forel, 1887)
- Tranquil deep-sea realm receiving only pelagic clays perceived (Murray & Renard, 1891)
- Cable breaks by submarine avalanches along the submarine canyon axis recognized (Milne, 1897)
- First sequence of structures, which would later become

the Bouma Sequence, recognized in the US (Sheldon, 1928)

- Sequence of structures with five divisions, which would later become the Bouma Sequence, recognized in Italy (Signorini, 1936)
- In a pioneering study, the possibility of occurrence of deep bottom currents in the Atlantic Ocean suggested (Wust, 1936)
- Deep-water origin of 'graded facies' first proposed (Bailey, 1936)
- Origin of submarine canyons through erosion by density currents advocated (Daly, 1936)
- Currents in submarine canyons first noted (Stetson, 1936; Shepard, Revelle & Dietz, 1939)
- First experiments on density currents to test Daly's hypothesis conducted (Kuenen, 1937)
- Density currents in Lake Mead observed (Grover & Howard, 1938)
- The term *turbidity current* introduced (Johnson, 1938)
- Graded sand from deep-sea cores described (Bramlette & Bradley, 1940)
- Density currents as agents for transporting sediments recognized (Bell, 1942)

3.2. 1950s

- First experiments on turbidity currents of high density conducted (Kuenen, 1950)
- Turbidity current origin of graded bedding, which formed the foundation of the turbidite paradigm, proposed (Kuenen & Migliorini, 1950)
- Criteria for recognition of slope deposits proposed (Rich, 1950)
- Transported shallow water fauna in deep-water sequences recognized (Natland & Kuenen, 1951)
- Mass movements in heads of modern submarine canyons documented (Shepard, 1951)
- Association of ancient debris flows and slides with turbidites recognized (Doreen, 1951)
- Cable breaks by Grand Banks slump suggested (Heezen & Ewing, 1952; Heezen & Drake, 1964)
- Turbidites from modern oceans recovered (Heezen & Ewing, 1952; Ericson, Ewing & Heezen, 1952)
- Existence of dispersive pressure by colliding grains in high-concentration dispersions, which would later be termed 'grain flows', proposed (Bagnold, 1954)
- First detailed account of modern submarine fans off California reported (Menard, 1955)
- The term *turbidite* for the deposit of a turbidity current introduced (Kuenen, 1957)
- Importance of detrital mud matrix in turbidite sandstone reported (Pettijohn, 1957)
- Debris-flow origin of pebbly mudstone proposed (Crowell, 1957)
- Classification for landslide types and processes proposed (Varnes, 1958)

- The term ‘fluxoturbidites’ for deposits of transitional flows between slumping and turbidity currents introduced (Kuenen, 1958; Dzulynski, Ksiazkiewicz & Kuenen, 1959)
- Canyon-fan systems vs slope-apron systems described (Gorsline & Emery, 1959)
- Concept of turbidity currents critiqued (Ten Haaf, 1959)
- Tectonic control of deep-sea sedimentation in continental margins discussed (Drake, Ewing & Sutton, 1959)
- High-concentration granular wedge at the base of a depositing turbidity current, which would later be termed ‘traction carpet’, proposed (Hsu, 1959)

3.3. 1960s

- High silt and clay content (13.5–34.5%) of turbidite sandstone recognized (Sullwold, 1960)
- Hydrocarbon reservoirs of ‘turbidite’ origin emphasized (Sullwold, 1961)
- The first vertical facies model of turbidites, which has become known as the ‘Bouma Sequence’ formulated from the Annot Sandstone outcrops in SE France (Bouma, 1962)
- In a pioneering study, a clear distinction between along-slope bottom currents and down-slope turbidity currents made (Murphy & Schlanger, 1962)
- Outcrops of the Martinsburg flysch, central Appalachians described (McBride, 1962)
- The term ‘traction carpet’ for flowing-grain layers at the base of a depositing turbidity current introduced (Dzulynski & Sanders, 1962)
- Auto-suspension of transported sediment in turbidity currents proposed (Bagnold, 1962)
- Diagenetic origin of mud matrix in greywacke suggested (Cummins, 1962)
- First classification of sediment-gravity flows based on fluid rheology proposed (Dott, 1963)
- Interpretation of fluid mechanics from sedimentary structures discussed (Sanders, 1963)
- The importance of slumps, debris flows, grain flows, and liquefied flows in the origin of the Annot Sandstone, SE France, discussed (Stanley, 1963)
- First collection of papers on turbidite research published (Bouma & Brouwer, 1964)
- Importance of non-gravity-driven bottom currents in redistributing sediments in modern oceans discussed (Hubert, 1964)
- Modern Congo submarine canyon, west Africa studied (Heezen, Menzies, Schneider, Ewing & Granelli, 1964)
- A book on sedimentary features of flysch published (Dzulynski & Walton, 1965)
- Hydrodynamic interpretation of the ‘Bouma Sequence’, based on comparison with traction structures produced in experimental alluvial channels, proposed (Harms & Fahnstock, 1965; Walker, 1965)
- The meaning of turbidity currents as opposed to other gravity-driven processes discussed (Sanders, 1965)
- Importance of non-gravity driven bottom currents in the Ouachita flysch, Pennsylvanian, Arkansas and Oklahoma discussed (Klein, 1966)
- First flume experiments in understanding body and head dynamics of turbidity currents conducted (Middleton, 1966)
- Worldwide examples of modern submarine canyons and valleys compiled (Shepard & Dill, 1966)
- The importance of parallel-to-slope thermohaline and wind-driven currents (i.e., bottom currents) in the deep sea recognized and the term *contour current* introduced (Heezen, Hollister & Ruddiman, 1966; Hollister, 1967)
- For the first time, the term *contourite* for the deposit of a contour current introduced (Hollister, 1967)
- Sequence of structures in turbidites studied (Walton, 1967)
- Paleocurrent patterns in the Ouachita flysch, Pennsylvanian, Oklahoma documented (Briggs & Cline, 1967)
- Grain flow deposits, California discussed (Stauffer, 1967)
- Details of a mid-sized modern submarine fan off Oregon studied (Nelson, 1968)
- Detailed outcrop description of a flysch, Canada discussed (Enos, 1969)
- Problems associated with turbidity current concepts discussed (Van der Lingen, 1969)

3.4. 1970s

- First model for modern submarine fan including suprafan-lobe concept introduced (Normark, 1970)
- The Pennsylvanian Ouachita flysch, Oklahoma studied (Cline, 1970)
- Large mass-transport deposits (e.g., slumps) on the modern Mississippi Fan, Gulf of Mexico recognized (Walker & Massingill, 1970)
- Trace fossils in the Ouachita flysch, Pennsylvanian, Oklahoma discussed (Chamberlain, 1971)
- Deep-sea processes revealed by sea-floor photographs published (Heezen & Hollister, 1971)
- First detailed seismic study of the architecture, growth patterns, and sedimentation processes of a large modern deep-sea fan—Bengal Fan, Bay of Bengal—discussed (Curry & Moore, 1971)
- Hydraulic jumps in turbidity currents discussed (Komar, 1971)
- Criteria for recognition of deposits of coarse-grained high-concentration fluids developed (Fisher, 1971)
- Modern slumps on continental slopes of 1–4° reported (Lewis, 1971)
- First model of depositional lobe for ancient submarine fans introduced (Mutti & Ghibaudo, 1972)

- First channel-lobe submarine-fan model based on outcrop studies in Italy and Spain introduced (Mutti & Ricci Lucchi, 1972)
 - Turbidite origin of laminated mudstone discussed (Piper, 1972)
 - Sedimentation processes, architecture, and growth pattern of a small modern deep-sea fan—Navy Fan—on an active continental margin based on seismic and sediment cores discussed (Normark & Piper, 1972)
 - First major experiments on subaqueous debris flows conducted (Hampton, 1972)
 - Liquefaction to account for the structureless appearance of deep-water conglomerates invoked (Hendry, 1973)
 - Historical account of the turbidite paradigm reviewed (Walker, 1973)
 - An important collection of papers on deep-water processes and facies models published (Middleton & Bouma, 1973)
 - First classification of sediment-gravity flows based on sediment-support mechanisms proposed (Middleton & Hampton, 1973)
 - Properties of submarine canyons compiled (Whitaker, 1974)
 - Turbiditic and non-turbiditic mudstone distinguished (Hesse, 1975)
 - For the first time, the concept of ‘sandy debris flows’ with low clay content discussed (Hampton, 1975)
 - A classification of laminar-mass flow into *grain flow* with water as interstitial fluid and *slurry flow* with water-mud slurry as interstitial fluid proposed (Carter, 1975)
 - Detailed seismic study of the architecture, growth patterns, and sedimentation processes of a large modern deep-sea fan—Amazon fan—discussed (Damuth & Kumar, 1975)
 - First turbidite facies scheme for interpreting deposits of submarine fans proposed (Mutti & Ricci Lucchi, 1975)
 - Detached lobe concept for submarine fans introduced (Mutti & Ricci Lucchi, 1975)
 - The use of modern Bengal Fan as an analog for the Pennsylvanian Ouachita flysch proposed (Graham, Dickinson & Ingersoll, 1975)
 - Depositional cycles in turbidites discussed (Ricci Lucchi, 1975)
 - Classification of very high-resolution (3.5 kHz sonar) seismic facies to study deep-sea sedimentation processes proposed (Damuth, 1975)
 - Distribution of large slides and debris flows on modern continental margins reported (Jacobi, 1976; Embley, 1976)
 - Glacio-eustatic control of turbidite, hemipelagic and other terigenous sediment deposition on continental margins proposed (Damuth, 1977)
 - Facies geometry of turbidite reservoirs, lower Pliocene, Ventura Field, California discussed (Hsu, 1977)
 - First seismic stratigraphic models for sedimentation on passive continental margins introduced (Vail, Mitchum & Thompson, 1977)
 - First side-scan sonar surveys of modern submarine canyons, channels, and slope features reported (Belderson & Kenyon, 1976; Coleman & Garrison, 1977)
 - Characteristics of a large submarine slump, SE Africa described (Dingle, 1977)
 - A general submarine-fan model with an emphasis on stratigraphic traps for hydrocarbon exploration proposed (Walker, 1978)
 - A collection of papers on submarine canyons, fans, and trenches published (Stanley & Kelling, 1978)
 - Fine-grained turbidites discussed (Piper, 1978)
 - Detailed seismic study of the architecture, growth patterns, and sedimentation processes of a large modern deep-sea fan—Mississippi Fan—discussed (Moore, Starke, Bonham & Woodbury, 1978)
 - A model for fine-grained debris flows, Ordovician, Tennessee introduced (Shanmugam & Benedict, 1978)
 - Tectonic significance of distal turbidites discussed (Shanmugam & Walker, 1978)
 - Up- and down-bottom currents in submarine canyons, induced by tidal forces, documented (Shepard & Marshall, 1978; Shepard, 1979)
 - Petrology of the modern Bengal Fan, Bay of Bengal studied (Ingersoll & Suczek, 1979)
 - Dipmeter and log motifs of submarine channels and lobes introduced (Selley, 1979)
 - Fine-grained turbidites and contourites distinguished (Stow, 1979)
 - Modern and ancient contourites reviewed (Stow & Lovell, 1979)
 - A classification of sediment-gravity flows based on rheology and sediment-support mechanism introduced (Lowe, 1979)
 - Mounded seismic geometry of the Frigg fan, lower Eocene, Frigg Field, North Sea discussed (Heritier, Lossel & Wathne, 1979)
 - Mass movement processes reviewed (Nardin, Hein, Gorsline & Edwards, 1979)
 - Mass movements on carbonate slopes discussed (Cook, 1979)
 - Sizes of submarine slides documented (Woodcock, 1979)
- 3.5. 1980s
- Rhythms in fine-grained turbidites, Ordovician, Tennessee studied (Shanmugam, 1980)
 - Sand-layer geometry of modern basin-floor turbidites compared (Pilkey, Locker & Cleary, 1980)
 - A vertical facies model for fine-grained turbidites introduced (Stow & Shanmugam, 1980)
 - Submarine-fan concepts debated (Nilsen, 1980)
 - DSDP (Deep Sea Drilling Project) results summarized (Warne, Douglas & Winterer, 1981)

- Turbidites from DSDP compiled (Kelts & Arthur, 1981)
 - Existence and importance of very large mass-transport deposits on the modern Amazon Fan, Equatorial Atlantic discussed (Damuth & Embley, 1981)
 - GLORIA (Geological Long Range Inclined Asdic) side-scan sonar survey reviewed (Laughton, 1981)
 - Petroleum source beds of deep-marine origin discussed (Kvenvolden, 1981)
 - Data in support of eustatic control of turbidites and winnowed turbidites compiled (Shanmugam & Moiola, 1982)
 - A collection of papers on deep-water models for stratigraphic traps published (Tillman & Ali, 1982)
 - First remote acoustic detection of a modern 'turbidity current', Rupert Inlet, British Columbia claimed (Hay, Burling & Murray, 1982)
 - Deep-water facies in subduction complexes discussed (Underwood & Bachman, 1982)
 - A theoretical model for deposits of 'high-density turbidity currents' proposed (Lowe, 1982)
 - Four types of flow transformations in sediment-gravity flows proposed (Fisher, 1983)
 - A collection of papers on the shelfbreak processes and facies published (Stanley & Moore, 1983)
 - Hydrocarbon-bearing sands of depositional lobe origin, lower Pliocene, Italy discussed (Casnedi, 1983)
 - Modern Storegga Slide, offshore Norway discussed (Bugge, 1983)
 - The use of manganese distribution in recognizing ancient deep-water lithofacies documented (Shanmugam & Benedict, 1983)
 - Highly meandering distributary channels on modern deep-sea fans during GLORIA side-scan sonar survey of the Amazon Fan, Equatorial Atlantic discovered (Damuth et al., 1983; Damuth, Flood, Kowsmann, Gorini & Belderson, 1988)
 - First COMFAN (COMmittee on FANs) Meeting (Pittsburgh, Pennsylvania, 1982)—realization of complexity of modern and ancient submarine fans and that no general model is applicable to describe all fans—convened (Bouma, 1983)
 - Spectrum of processes between cohesive and cohesionless debris flows discussed (Shultz, 1984)
 - Debris-flow dynamics in subaerial environments discussed (Costa & Williams, 1984)
 - Debris flows reviewed (Johnson, 1984)
 - Mechanics of rapid granular flows reviewed (Savage, 1984)
 - Short course notes on modern and ancient deep-sea fan sedimentation published (Nelson & Nilsen, 1984)
 - A collection of papers on fine-grained turbidites published (Stow & Piper, 1984)
 - Data in support of eustatic control of calciclastic turbidites compiled (Shanmugam & Moiola, 1984)
 - HEBBLE (High-Energy Benthic Boundary Layer Experiment) project, North Atlantic discussed (Hollister & McCave, 1984)
 - Subaqueous slope failures in fjords documented (Syvitski, 1985)
 - DSDP Leg 96 (1983)—First modern submarine fan (Mississippi Fan), Gulf of Mexico cored (Bouma et al., 1985)
 - Three types of turbidite systems based on sea level control proposed (Mutti, 1985)
 - Provenance of modern deep-sea sands discussed (Valtoni, 1985)
 - Submarine-ramp model, an alternative to submarine-fan model, proposed (Heller & Dickinson, 1985)
 - Turbidite facies scheme for interpreting submarine-fan environments questioned (Shanmugam et al., 1985a)
 - Tectonic control of detached lobes in submarine fans proposed (Shanmugam & Moiola, 1985)
 - First model on seismic expression of submarine fans in a sequence-stratigraphic framework proposed (Mitchum, 1985)
 - A classification of deep-water facies proposed (Pickering, Stow, Watson & Hiscott, 1986)
 - A model for geometry of gully sands and related sand injections, upper Jurassic, East Greenland proposed (Surlyk, 1987)
 - Basin-floor fan and slope fan models in a sequence-stratigraphic framework proposed (Vail, 1987)
 - Modern and ancient turbidite systems compared (Mutti & Normark, 1987)
 - Mass wasting features on the continental slope, Northwest Europe documented (Kenyon, 1987)
 - Second COMFAN Meeting (Parma, Italy, 1988) convened (no formal publication)
 - Modern and ancient submarine fans reviewed (Shanmugam & Moiola, 1988)
 - Experiments on 'high-density turbidity currents' conducted (Postma, Nemeč & Kleinspehn, 1988)
 - Modern examples of sediment drifts, Argentine Basin, South Atlantic documented (Klaus & Ledbetter, 1988)
 - Mechanisms of high concentration sediment-gravity flows, based on flume study and field study of the Annot Sandstone in SE France, discussed (Oakshott, 1989)
 - A book on deep-marine environments published (Pickering et al., 1989)
 - The validity of the Bouma Sequence questioned (Hsu, 1989)
- 3.6. 1990s
- Deep-marine facies models reviewed (Shanmugam, 1990)
 - Rapid granular flows reviewed (Campbell, 1990)
 - Aspects of sediment movement on steep delta slopes discussed (Nemeč, 1990)
 - Mississippi Fan—first study of a modern fan using

- standard industry multifold seismic data and to put a modern submarine fan into a sequence-stratigraphic framework—discussed (Weimer, 1990)
- Seismic expression of submarine fans discussed (Posamentier & Erskine, 1991; Weimer & Link, 1991)
 - Submarine-fan lobe concepts critiqued (Shanmugam & Moiola, 1991)
 - Normark's (1970) suprafan lobe concept abandoned (Normark, 1991)
 - Walker's (1978) general submarine-fan model abandoned (Walker, 1992a)
 - A photographic book on turbidite sandstones issued (Mutti, 1992)
 - Dendritic channel patterns at the terminus of the Mississippi Fan, Gulf of Mexico documented (Twichell, Schwab, Nelson, Kenyon & Lee, 1992)
 - Deposition from turbidity currents reviewed (Middleton, 1993)
 - Giant ancient sandy slides, Antarctica documented (Macdonald, Moncrief & Butterworth, 1993)
 - Hydrocarbon-bearing reservoirs in bottom-current reworked sands, Plio-Pleistocene, Gulf of Mexico described (Shanmugam, Spalding & Rofheart, 1993a, 1993b, 1995c)
 - Reservoir sands of slump and debris flow origin, Norwegian North Sea documented (Shanmugam et al., 1994)
 - Turbidite fan models based on grain size and feeder system proposed (Reading & Richards, 1994)
 - A collection of papers on deformation of sediments published (Maltman, 1994)
 - A collection of papers on submarine fans and turbidite systems published (Weimer, Bouma & Perkins, 1994)
 - ODP (Ocean Drilling Program) Leg 155 (1994)—first systematic, continuous deep coring of stratigraphic and seismic units, architecture, and sediment facies of the Amazon Fan; confirmation that channel-fill (HAR units) and base of channel-levee system deposits (HARP units) are predominantly sand—documented (Flood, Piper & Shipboard Scientific Party, 1995)
 - A collection of papers on reservoir characterization of deep-water clastic systems published (Hartley & Prosser, 1995)
 - Classic 'turbidites' of Pennsylvanian Ouachita flysch, Arkansas reinterpreted as sandy debris flows (Shanmugam & Moiola, 1995)
 - Hydrocarbon-producing sands of slump and debris flow origin, lower Eocene, Frigg Field, Norwegian North Sea discussed (Shanmugam et al., 1995a)
 - Hydrocarbon-producing sands of slump and debris flow origin, Pliocene, Edop Field, offshore Nigeria reported (Shanmugam, Hermance, Olaifa & Odior, 1995b)
 - Basin-floor fans in a sequence-stratigraphic framework critiqued (Shanmugam et al., 1995a, 1996)
 - Atlas of architectural style in turbidite systems published (Pickering, Hiscott, Kenyon, Ricci Lucchi & Smith, 1995)
 - A book on submarine channels published (Clark & Pickering, 1996)
 - US Continental slopes documented (Pratson & Haxby, 1996)
 - The concept of 'high-density turbidity currents' questioned and a theoretical model for sandy debris flows presented (Shanmugam, 1996a)
 - Perception vs. reality in deep-water exploration discussed (Shanmugam, 1996b)
 - Long runout distances of modern submarine slides documented (Hampton et al., 1996)
 - Debris-flow deposits classified (Coussot & Meunier, 1996)
 - Reinterpretation of classic 'turbidites' as sandy debris flows debated (Shanmugam & Moiola, 1997; Shanmugam et al., 1997)
 - The Bouma Sequence and the turbidite mind set critiqued (Shanmugam, 1997a)
 - History behind dispelling the myth of sea-floor tranquility reviewed (Friedman & Sanders, 1997)
 - Petroleum exploration in deep-water deposits reviewed (Sanders & Friedman, 1997)
 - Physics of debris flows reviewed (Iverson, 1997)
 - Finger-like debris flows on the glaciated Norwegian-Barents Sea continental margin documented (Elverhoi et al., 1997)
 - First experiments on subaqueous sandy debris flows with low clay content conducted (Marr, Harff, Shanmugam & Parker, 1997)
 - Conceptual models and their uncertainties in deep-water exploration discussed (Shanmugam, 1997c)
 - First experiments demonstrating hydroplaning of subaqueous debris flows conducted (Mohrig et al., 1998)
 - Modern tidal rhythmites in a deep-water estuary documented (Cowan, Cai, Powell, Seramur & Spurgeon, 1998)
 - Fossil contourites reviewed (Stow, Faugeres, Viana & Gonthier, 1998)
 - Fossil contourites exposed in China documented (Zhenzhong et al., 1998)
 - Slope and base-of-slope systems reviewed (Galloway, 1998)
 - A book on turbidite systems of SE France published (Pickering & Hilton, 1998)
 - A book on dimensions and geometries of deep-water systems issued (Shanmugam, 1998a)
 - A keynote talk on '50 years of the turbidite paradigm' delivered (This paper, Shanmugam, 1998b)
 - Turbidite facies models defended (Miall, 1999)
 - International Geological Correlation Programme (IGCP) Project 432 (1998)—Contourite Watch—to facilitate research on contourites and bottom currents established (Stow, 1999)

- Sandy debris flow contributing to a long runout distance of over 400 km downslope of the Canary Islands on slopes that decrease to as little as 0.05° documented (Gee, Masson, Watts & Allen, 1999)

In summary, the 1950s, 1960s, and 1970s were periods of model building for the deposits of turbidity currents; however, the definition and meaning of ‘turbidity currents’ has been debated since the mid 1960s (Sanders, 1965). In the 1980s, fundamental questions were raised regarding the Bouma Sequence, fan models, and turbidite facies scheme. Furthermore, results of COMFAN I (Bouma, 1983) revealed that modern and ancient fan systems are much more complex than we had envisioned. In spite of these problems, fan models with channels and lobes continued to dominate deep-water sedimentology and sequence stratigraphy. The 1990s have been a period of re-evaluation and abandonment of fan models, reinterpretation of deep-water massive ‘turbidite’ sands as deposits of sandy debris flows, debate over high-density turbidity currents, experiments on sandy debris flows, and contemplation of the meaning of seismic geometries in terms of depositional facies.

3.7. Differing perspectives on the turbidite paradigm

Differing scientific perspectives exist over the timing of onset of the final science stage (i.e., mopping-up operations, Kuhn, 1970) of the turbidite paradigm. For example, Walker (1973) suggested that the normal science stage of the turbidite paradigm began in 1950 (Fig. 2). However, Stow (1985) suggested that the ‘age of order’ (i.e., normal science stage) began in 1983. From my perspective, the turbidite paradigm has always been in a crisis mode, and the normal science stage has never been achieved (see Fig. 2). We are still in the process of learning the fundamentals of deep-water processes and products, and we are far from solving many fundamental problems. We can never achieve a normal science stage until we clearly establish the basic principles of a scientific paradigm. A possible reason that Walker (1973) and Stow (1985) expressed different perspectives is because many of the problems that came to light during the past few years were not fully realized when they published their papers. Our perspectives tend to change with time.

3.8. Science vs time

Just over 50 years ago, geologists thought that the deep-sea floor was a tranquil environment, which received only pelagic sediment (see review by Friedman & Sanders, 1997). We now know that in the deep sea, the entire water column is a highly dynamic environment and that coarse sediment can be transported hundreds of kilometers downslope from the continental shelf edge by gravity-controlled mass-transport processes. In addition,

deep thermohaline-induced bottom currents redistribute enormous volumes of sediment along the continental slope, rise and basin plains. Although science is dynamic, changes in scientific concepts are not always swift. For example, just over 500 years ago, it was still believed that the Earth was at the center of the universe as proposed by Ptolemy in the second century A.D. It took nearly 1500 years to prove that the Earth was not at the center of the universe by the works of Copernicus, Galileo, and Newton. Hopefully, we can resolve the remaining deep-water problems in a shorter time span!

4. Deep-water processes

An understanding of mechanics of deep-water processes is of critical importance in understanding the nature of transport and deposition of sand in the deep-sea. Process sedimentology serves as the fundamental underpinning for building depositional models. Sediment gravity plays an important role in transporting and depositing sediments in deep-water environments. Major sediment-gravity processes include slides, slumps, debris flows, and turbidity currents. In addition, bottom currents (contour currents) are important in reworking deep-water deposits. Numerous schemes are in use for classifying sediment-gravity processes based on rheology (e.g., Dott, 1963), sediment-support mechanisms (e.g., Middleton & Hampton, 1973), or both (Lowe, 1979, 1982). There are inherent problems with classifications based on sediment-support mechanisms alone because: (1) these classifications deal only with end-member types, whereas in natural flows more than one support mechanism may be involved, (2) these classifications deal with sediment-support mechanisms only during the time of transport, whereas deposits reflect sediment-support mechanisms during the time of deposition, and (3) at present, there are no criteria to recognize transport mechanisms from the depositional record. For these reasons, I find classifying sediment-gravity flows into two broad groups, namely (1) *Newtonian flows* and (2) *plastic flows*, based on rheology (Fig. 3), is the most useful for interpreting the origin of deep-water sands. This classification is analogous to the one originally proposed by Dott (1963).

4.1. Newtonian flows

The rheology of fluids can be expressed as a relationship between applied shear stress and rate of shear strain (Fig. 3). Newtonian fluids (i.e., fluids with no inherent strength), like water, will begin to deform the moment shear stress is applied, and the deformation is linear. For Newtonian fluids, the criterion for initiation of turbulence is the *Reynolds Number*, Re (ratio between inertia and viscous forces), which is greater than 2000 (Fig. 3).

In deep-water environments, turbidity currents rep-

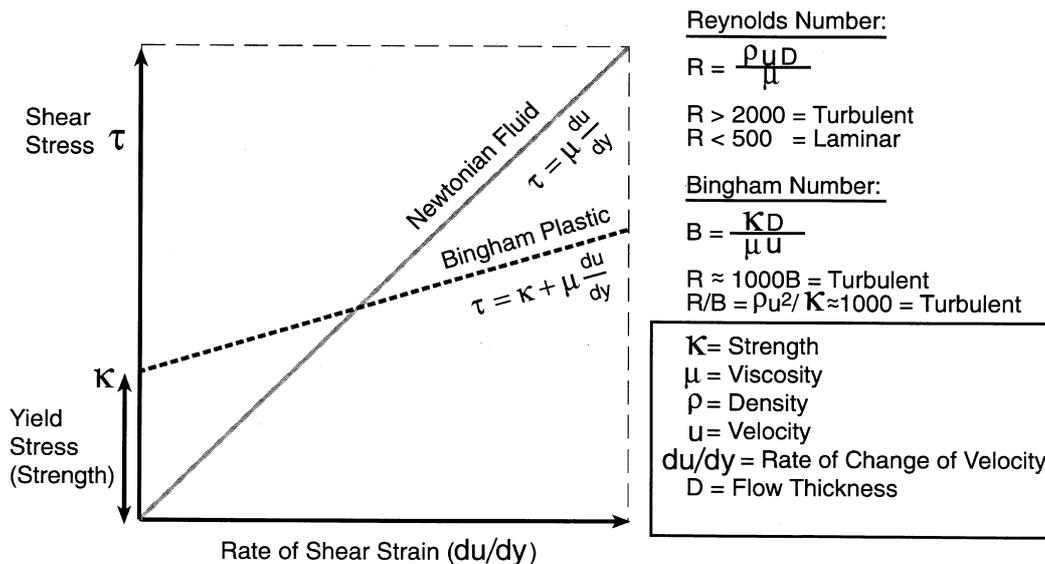


Fig. 3. Rheology (stress-strain relationships) of Newtonian fluids (e.g., turbidity currents) and Bingham plastics (e.g., debris flows), compiled from several sources (Dott, 1963; Enos, 1977; Pierson and Costa, 1987; Phillips and Davies, 1991; Middleton and Wilcock, 1994). This graph shows that a fundamental rheological difference between debris flows (Bingham plastics) and turbidity currents (Newtonian fluids) is that debris flows exhibit strength, whereas turbidity currents do not. In general, turbidity currents are turbulent, and debris flows are laminar in state. From Shanmugam (1997a).

represent Newtonian flows. Newtonian rheology of turbidity currents has been addressed by many researchers (Dott, 1963; Nardin et al., 1979; Lowe, 1979, 1982; Shanmugam & Moiola, 1995). Lowe (1979) and Nardin et al. (1979) classified turbidity currents as both sediment-gravity flows and fluidal flows. According to Oakeshott (1989), this classification is confusing because sediment-gravity flows are flows in which *sediment* is moved by gravity, whereas fluidal flows are flows in which *fluid* is moved by gravity (see Middleton & Hampton, 1973). In other words, turbidity currents cannot be both sediment-gravity flows and fluidal flows. Classifying turbidity currents as Newtonian flows can eliminate this confusion.

Turbulence is characteristic of Newtonian flows, not plastic flows. According to Middleton (1993), "Turbidity currents are one type of sediment gravity flow in which the sediment is held in suspension by fluid turbulence." More importantly, if a flow is laminar or non-turbulent it can no longer be considered as a turbidity current (Middleton, 1993). *A turbidity current is a sediment-gravity flow with Newtonian rheology and turbulent state from which deposition occurs through suspension settling.*

4.2. Plastic flows

In contrast to Newtonian fluids, some naturally occurring materials (i.e., fluids with strength) will not deform until yield stress has been exceeded (Fig. 3); once the yield stress is exceeded the deformation is linear. Such materials with strength are considered to be Bingham plastic. Flows that exhibit plastic rheology are termed

here plastic flows. For Bingham plastics, the criterion for initiation of turbulence is based on both the *Reynolds Number*, Re , and the *Bingham Number*, B (Fig. 3). Although some debris flows can develop turbulence (Enos, 1977), such flows are not diagnostic of most debris flows that are laminar (i.e., no fluid mixing across streamlines). Johnson (1970) favored a Bingham plastic rheologic model for debris flows. Although the rheology is a complex parameter and is difficult to measure accurately (Phillips & Davies, 1991), it is useful in distinguishing turbidity currents from other sediment-gravity flows. *A debris flow is a sediment-gravity flow with plastic rheology and laminar state from which deposition occurs through freezing.* The term 'debris flow' is used here for both the process and the deposit of that process.

The rheology of a sediment–water mixture is governed mainly by sediment concentration and to a lesser extent by grain size and the physical and chemical properties of transported solids (Pierson & Costa, 1987). A compilation of published sediment concentration values of various flow types shows that the boundary between Newtonian and plastic flows occurs at about 20–25% by volume (Fig. 4). The one exception is the concept of 'high-density turbidity current' that has a range of values representing both Newtonian and plastic flows. Therefore, I suggest that the concept of 'high-density turbidity current' is not meaningful in this rheologic classification of flows. Although I have distinguished low-density turbidity currents (i.e., true turbidity currents) from 'high-density turbidity currents' for discussion purposes (Fig. 4), I do not consider 'high-density turbidity currents' as

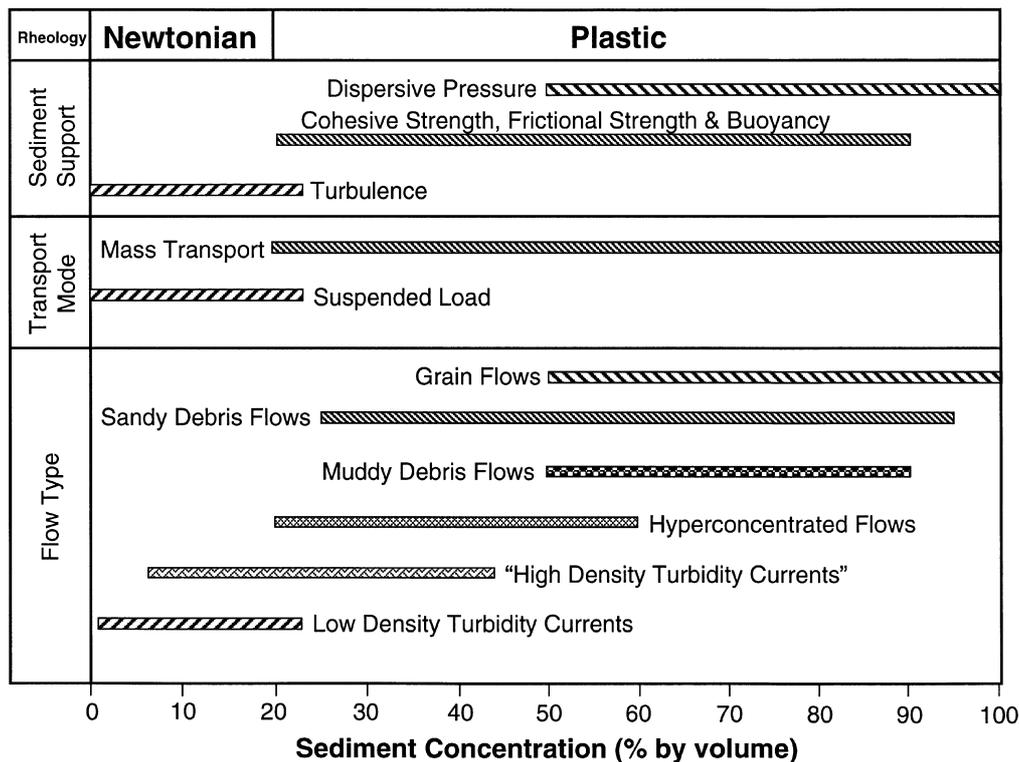


Fig. 4. A classification of subaqueous gravity flows, based on fluid rheology, showing two general types, *Newtonian* and *Plastic*. This classification is analogous to a classification originally advocated by Dott (1963). Turbidity currents are *Newtonian* flows, whereas all mass flows (muddy debris flows, sandy debris flows, and grain flows) are *Plastic* flows. Turbidity currents occur only as subaqueous flows, whereas debris flows and grain flows can occur both as subaerial and as subaqueous flows. For purposes of comparison, subaerial flows (river currents and hyperconcentrated flows) are included. Sediment concentration is the most important property in controlling fluid rheology. High-density turbidity currents are not meaningful in this rheologic classification because their sediment concentration values represent both *Newtonian* and *plastic* flows; however, I have included them here for discussion purposes. Published values of sediment concentration by volume % are: (1) river currents (1–5%; e.g., Galay, 1987), (2) low-density turbidity currents (1–23%; e.g., Middleton, 1967, 1993), (3) high-density turbidity currents (6–44%; Kuenen, 1966; Middleton, 1967), (4) hyperconcentrated flows (20–60%; Pierson and Costa, 1967), (5) muddy debris flows (50–90%; Coussot and Muenier, 1996), (6) sandy debris flows (25–95%; Shanmugam, 1997a; partly based on my reinterpretations of various processes that exhibit plastic rheology in papers by Middleton, 1966, 1967; Wallis, 1969; Lowe, 1982; Shultz, 1984;), and (7) grain flows (50–100%; partly based on Rodine and Johnson, 1976; Shultz, 1984; Pierson and Costa, 1987). Concentration values of more than 95 vol.% can be without significant particle interlocking (Rodine and Johnson, 1976), and therefore flow (i.e., deformation of material in response to applied stress) is possible at high concentration values. Two general modes of transport represent different subaqueous flow types: (1) suspended mode in turbidity currents, and (2) mass transport mode in plastic flows. Bed-load transport is meaningful only in river currents, but not in turbidity currents because sediment is held in suspension by flow turbulence during transport. Two general sediment support mechanisms represent different subaqueous flow types: (1) turbulence in turbidity currents, and (2) cohesive strength, frictional strength, and buoyancy in plastic flows. Dispersive pressure (frictional strength) can become an important sediment support mechanism at sediment concentration values of 50–100% (Rodine and Johnson, 1976).

true turbidity currents in terms of fluid rheology; I consider them to be sandy debris flows (see Shanmugam, 1996a).

Mass transport processes are dominated by plastic behavior (Nardin et al., 1979). Therefore, I restrict the use of the term 'mass flows' only to plastic flows, and I do not apply the term 'mass flows' to turbidity currents. Plastic flows comprise cohesive debris flows, liquefied flows, fluidized flows, and grain flows (see Lowe, 1979, 1982). In addition, sandy debris flows (Shanmugam, 1997a), and liquefied cohesionless coarse-particle flow (Friedman, Sanders & Kopaska-Merkel, 1992; Sanders & Friedman, 1997) belong to the family of 'sandy plastic

flows'. Synonymous terms used for these sandy types include: (1) flowing-grain layers, (2) fluidized flowing-grain layer, (3) inertia-flow layer, (4) avalanching flow (see Sanders & Friedman, 1997), (5) traction carpet, and (6) high-density turbidity current (see Shanmugam, 1996a). All these sandy flows have one important property in common, namely, plastic rheology. Therefore, the use of a general term 'sandy debris flow' for all these types may help minimize the terminology congestion in the sedimentologic literature. Also, when we are unable to distinguish the specific type of a down-slope gravity flow, a more general term 'sediment-gravity flow' is preferred.

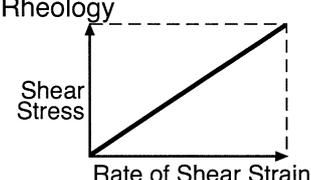
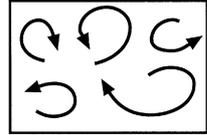
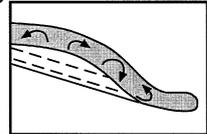
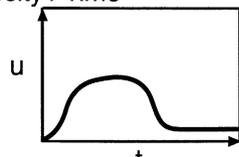
Criteria	Type	Deposit
Rheology 	Newtonian (Dott, 1963)	Evidence Preserved
Support 	Turbulent (Middleton & Hampton, 1973)	
Driving Force 	High Density (Postma et al., 1988)	Evidence Not Preserved
Velocity / Time 	Waxing / Waning (Kneller, 1995)	

Fig. 5. Four different definitions of turbidity currents based on (1) rheology of fluids, (2) sediment-support mechanism, (3) driving force, and (4) velocity/time factors. Of these four types, only the Newtonian and turbulent types are useful in interpreting the behavior of flow because evidence for fluid rheology and sediment-support mechanism is preserved in the deposit. However, evidence for driving force and waxing velocity is not always preserved.

4.3. Differing definitions of turbidity currents

In spite of the precise definition of turbidity currents discussed above, there are other definitions of turbidity currents with widely differing concepts. I have selected four types based on four different criteria (Fig. 5): (1) Newtonian flows based on rheology (Dott, 1963), (2) turbulent flows based on sediment-support mechanism (Middleton & Hampton, 1973), (3) high-density turbidity currents based on driving force (Postma et al., 1988), and (4) waxing flows based on velocity (Kneller, 1995). Of these four types, only the first two types are useful in recognizing depositional processes because evidence for rheology and sediment-support mechanism is preserved in the rock record.

In Newtonian flows (i.e., turbidity currents), the deposition occurs through unhindered settling of individual grains from suspension. Hence, normal grading, indicative of Newtonian rheology and fluid turbulence, is a characteristic feature of a turbidite. However, normal grading is not unique to turbidites; it has also been observed in dilute experimental debris flows as well (Marr et al., 1997). Normally graded beds of debris flow origin

can be distinguished from normally graded beds of turbidity current origin by associated features. For example, floating granules and clasts in a normally graded sand unit are indicative of deposition through hindered settling in a plastic debris flow rather than in a Newtonian turbidity current. I will return to this point later.

'High-density turbidity currents' are defined based on the driving force (Fig. 5). For example, the basal traction carpets (also known as inertia-flow layer) in 'high-density turbidity currents' are driven by the overriding turbidity currents (Postma, et al., 1988). In addition, 'high-density turbidity currents' are defined based on grain size (Lowe, 1982), on rapid deposition, and on flow density (Kuenen, 1950). Because of these conceptually differing flow types, there are no standard criteria to recognize deposits of high-density turbidity currents. This confusion has paved the way for interpreting deep-water massive sands of debris-flow origin as high-density turbidites. In fact, the term 'high-density turbidite' is a misnomer because the term 'high density' should refer to the density of the flow, not the density of the deposit.

The concept of 'high-density turbidity currents', based on flow density with a range of 1.5–2.0 (Kuenen, 1950),

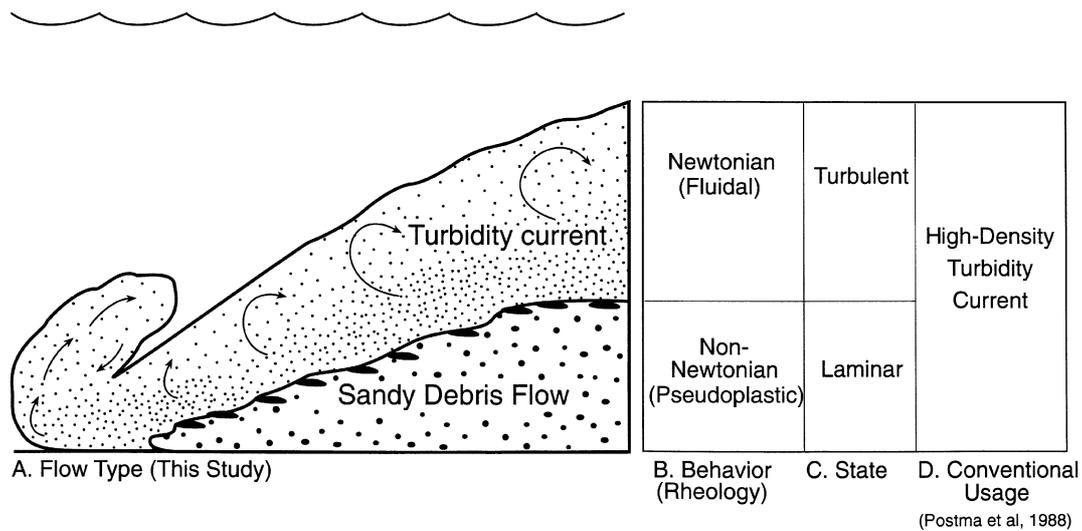


Fig. 6. (A) An experimental view of 'high-density turbidity currents' by Postma et al. (1988) who suggested that the basal high-concentration layer (labeled as sandy debris flow) was driven by the upper low-concentration layer (labeled as turbidity current). According to Postma et al. (1988), both upper and lower layers comprise the 'high-density turbidity currents'. I consider upper and lower layers as rheologically different entities and therefore separate flow processes (see Shanmugam, 1996a). (B) According to Postma et al. (1988), lower and upper layers represent non-Newtonian and Newtonian rheology, respectively. (C) According to Postma et al. (1988), lower and upper layers represent laminar and turbulent states, respectively. The basal laminar layer (i.e., sandy debris flow) is variously termed as inertia-flow layer, traction carpet, flowing-grain layer etc. by various authors (see Shanmugam, 1996a). The basal layer with high sediment concentration promotes hindered settling, and allows development of floating mudstone clasts and quartz granules. (D) Interpretation of Postma et al. (1988). Because sediment-gravity flows are classified on the basis of rheology and sediment-support mechanism (Lowe, 1982), a single flow (i.e., high-density turbidity current) cannot be both Newtonian and non-Newtonian in rheology, and laminar and turbulent in state at the same time. This type represents gravity flow transformation of Fisher (1983). From Shanmugam (1997a).

is a highly confusing one because the density may vary dramatically through the flow. A flow density of 2.0 is not unique to high-density turbidity currents because debris flows also have a density of 2.0 (Hampton, 1972). At these high flow densities, turbulence would be damped by high sediment concentration, and flows would become non-turbulent (i.e., laminar). Without turbulence, high-density flows cannot be turbidity currents (Shanmugam, 1996a).

The other problem is that a 'high-density turbidity current', defined on the basis of driving force, is a density-stratified flow composed of a lower layer (i.e., high-concentration, plastic, laminar) and an upper layer (i.e., low-concentration, Newtonian, turbulent), in which the basal high-concentration layer (i.e., traction carpet) cannot be a turbidity current because of its plastic rheology and laminar flow state (Fig. 6). The basal layer with high sediment concentration would severely hinder settling, and would freeze mudstone clasts and quartz granules in floating positions.

Kneller (1995) observed that simple normally graded beds are rare in deep-water sequences, and that most deep-water sequences with complications (e.g., massive sandstones, disordered sequences, abrupt grain-size breaks, large-scale bedforms etc.) are difficult to interpret as turbidites. In alleviating this problem, Kneller (1995)

has redefined turbidity currents using velocity (u), distance (x), and time (t), and classified turbidity currents into five types, namely (1) depletive waning flow, (2) uniform waning flow, (3) depletive steady flow, (4) depletive waxing flow, and (5) accumulative waning flow. This classification allows room for interpreting deep-water deposits with any kind of grading (i.e., normal or inverse) as turbidites (Fig. 7). The very foundation of the turbidite paradigm, based on the relationship between turbidites and normal grading (Kuenen & Migliorini, 1950; Bouma, 1962), has been undermined by the introduction of concepts relating massive sands (Harms & Fahnstock, 1965) and inversely graded sands (Kneller, 1995) to turbidites (Fig. 7).

Unlike the conventional definition of turbidity currents based on fluid rheology and flow turbulence that take into consideration sediment concentration, velocity, thickness, and viscosity, Kneller's (1995) definition is primarily concerned with velocity. The object of redefining turbidity currents using velocity alone serves no real scientific purpose; although it does provide a psychological solace in interpreting all deep-water sands as turbidites whether they show normal grading or not. I would suggest that rarity of normally graded beds in the rock record simply means that deposits of true turbidity currents are rare in nature!

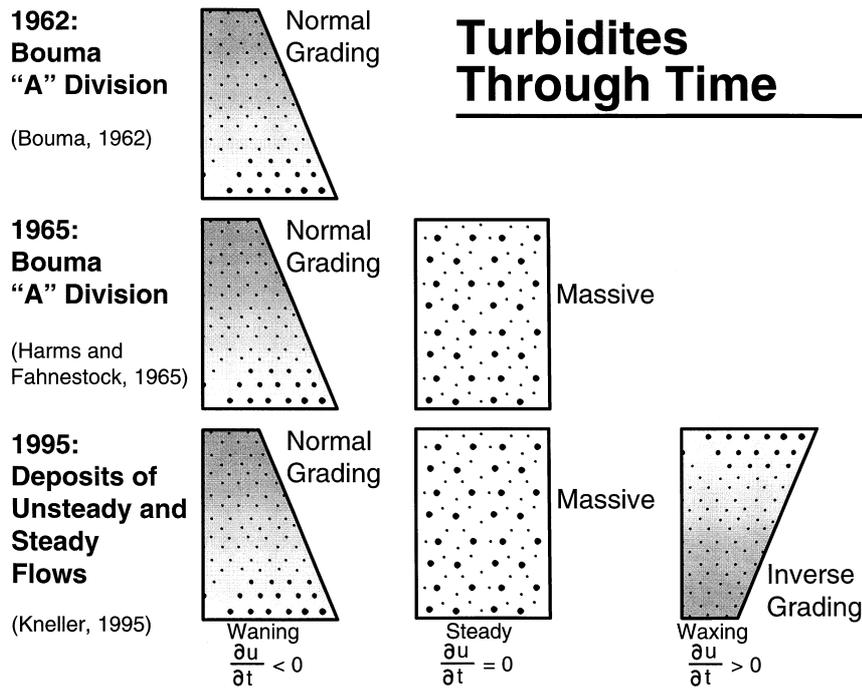


Fig. 7. Three publications showing how opinions on nature of grading in turbidites have changed through time. Top: Bouma (1962) suggested normal grading for turbidites. Middle: Harms and Fahnestock (1965) proposed normal grading and massive (i.e., no grading) for turbidites. Bottom: Kneller (1995) advocated normal grading, massive (i.e., no grading), and inverse grading for turbidites.

4.4. Inappropriate subaerial analogs for turbidity currents

A troubling practice is to compare *subaqueous* turbidity currents with *subaerial* river currents (Chikita, 1989). This comparison is ill-founded for many reasons (Table 1). River currents and turbidity currents are fundamentally different, although both are turbulent in state (Shanmugam, 1997a). River currents are low in suspended sediment (1–5% by volume; Galay, 1987), whereas turbidity currents (i.e., low-density turbidity currents) are relatively high in suspended sediment (1–23% by volume; Middleton, 1967, 1993), although both currents are considered to be Newtonian in rheology (Fig. 4). River currents are *fluid*-gravity flows, whereas turbidity currents are *sediment*-gravity flows (Middleton, 1993). In river currents, sand and gravel fractions are transported primarily by bed load (traction) mechanism, and there-

fore river deposits are characterized by dune bedforms with cross bedding. In contrast, sands in true turbidity currents (i.e., low-density turbidity currents) are transported by suspended load, and thus sandy turbidites show a general lack of cross bedding and show a characteristic normal grading.

Bouma and Coleman (1985) interpreted the deep-water Annot Sandstone, exposed in Peira Cava area in SE France, as lateral accretionary channel-fill turbidites using fluvial point-bar analogy. They used the presence of pebble nests, foreset bedding, and paleocurrent directions in support of their interpretations. However, this analogy is inappropriate for several reasons. First, the Annot Sandstone example used in the study does not show channel geometry (e.g., Bouma & Coleman, 1985, their fig. 3), but does show a sheet geometry, which is an unlikely geometry of lateral-accretion deposits by a

Table 1
Comparison of subaerial river currents and subaqueous turbidity currents. Partly based on Shanmugam (1997a)

Features	River currents	Turbidity currents
Ambient fluid	Air	Water
Rheology of fluid	Newtonian	Newtonian
Type of gravity flow	Fluid gravity flow	Sediment gravity flow
Nature of flow	Uniform, steady, and continuous	Non-uniform, unsteady, and episodic
Sediment concentration	Low (1–5 vol.%)	High (1–23 vol.%)
Dominant transport of sand and gravel	Bed load	Suspended load
Dominant structures	Cross bedding	Normally graded bedding

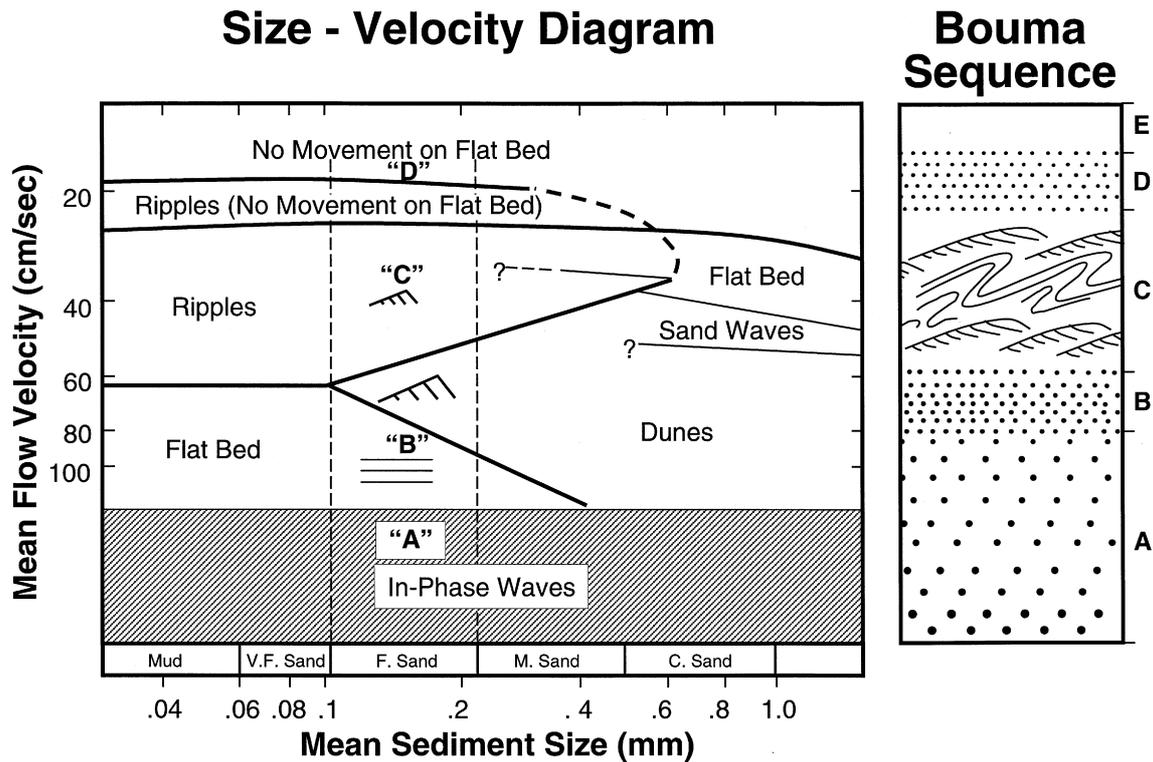


Fig. 8. Comparison of size-velocity diagram for bed forms (structures) developed in flume experiments at a flow depth of 20 cm (compiled from many sources, see Southard (1975)) with the five internal divisions (A, B, C, D, and E) of the Bouma (1962) Sequence. Bouma divisions A, B, C, and D are labeled in the size-velocity diagram for fine-grained sand for discussion purposes. Note that dunes and in-phase waves (antidunes) observed in flume experiments are absent in the Bouma Sequence. Also note that the basal normally graded division of the Bouma Sequence is absent in flume structures. Published size-velocity diagram of experimental structures by Southard (1975) is flipped vertically in order to make an easy comparison with the Bouma Sequence.

meandering channel. Second, the logged sequences of the Annot Sandstone in Peira Cava do not contain sedimentary facies in support of the lateral accretion model (Oakshott, 1989). Third, the pebble nests in the Annot Sandstone are analogous to slurried beds, and slurried beds were interpreted to be deposits of debris flows (Mutti, Nilsen & Ricci Lucchi, 1978). In addition to slurried beds, the Annot Sandstone exhibits inverse grading at the base and contains armoured mud balls (Pickering & Hilton, 1998; Stanley, Palmer & Dill, 1978). I would suggest that these features are products of debris flows, and plastic debris flows are not a viable mechanism to explain lateral accretion deposits in a meandering channel. Also, the origin of meandering channels by unsteady turbidity currents in deep-marine environments is still an unresolved issue.

Perhaps, the most problematic issue is the use of the five alluvial channel bed forms (i.e., plane bed, ripples, dunes, upper flow regime plane bed, and antidunes) observed in flume experiments (Simons, Richardson & Nordin, 1965; Southard, 1975) as the analog for the five divisions of the Bouma (1962) Sequence (see Harms & Fahnstock, 1965; Walker, 1965). Although this comparison is deeply embedded in our psyche (Fig. 8), it is not founded on sound fluid dynamic principles.

Simons et al. (1965) cautioned that sedimentary structures observed in their flume experiments are meaningful only for structures developed in subaerial alluvial channels. The obvious implication is that these experimental alluvial structures are not analogous to turbidite structures formed under subaqueous environments.

Simons et al. (1965) conducted flume experiments under equilibrium flow conditions. However, in most natural flows, changes in bed configurations tend to lag behind changes in flow conditions, and there have been almost no flume experiments on disequilibrium bed configurations (Southard 1975). Natural turbidity currents are waning flows, and waning flows may never attain equilibrium (see Allen, 1973).

On the use of experimental structures of Simons et al. (1965) as analog for turbidite structures, Walker (1965) cautioned, "... the flume experiments were conducted under conditions of non-deposition, whereas many of the sedimentary structures of turbidites are formed under conditions of net deposition."

Dunes are an integral part of bed forms produced in flume experiments of alluvial channels (Simons et al., 1965), whereas cross beds (i.e., internal structures of dune bed forms) are absent in the Bouma Sequence (Fig. 8). In fact, all structures observed in flume experiments were

formed under traction or bed load (Simons et al., 1965). The origin of traction structures requires establishment of hydrodynamic equilibrium. The duration required for establishing hydrodynamic equilibrium is greater than the time required for sedimentation (Allen, 1973). Therefore, traction structures formed in flume experiments are not appropriate analogs for interpreting structures formed by natural turbidity currents. It is worth remembering that Kuenen (1964) would use the presence of dune structures in deep-water sandy sequences as evidence against turbidite deposition.

The very last stages of sand transport by ‘dilute tail’ end of turbidity currents may form thin divisions of parallel lamination by reworking (Kuenen, 1953, 1964). However, the ‘dilute tail’ concept can be invoked only if there is evidence for turbidite deposition, independent of parallel lamination. This evidence must constitute: (1) the presence of a normally graded division beneath the division of parallel lamination, (2) the presence of a normally graded division that is thicker than the overlying division of parallel lamination, (3) the presence of a normally graded division without associated inverse grading, and (4) the presence of a normally graded division without floating mudstone clasts and floating quartz granules. In the absence of an underlying normally graded division, the origin of parallel lamination by ‘dilute tail’ end of turbidity currents cannot be invoked because the ‘dilute tail’ end of *waning* turbidity currents cannot attain *equilibrium*.

The routine interpretation of deep-water sands with thick divisions of ‘parallel lamination’ as upper flow regime flat beds of turbidity currents is not justified because thick upper flat beds have never been generated by experimental turbidity currents. On the other hand, experimental studies have shown that some horizontal layers formed by sandy debris flows may mimic ‘parallel lamination’. Also, the development of pervasive lamination has been ascribed to sediment shear during freezing of mass flows (Stauffer, 1967). Furthermore, deep bottom currents are traction currents and are quite capable of generating parallel lamination. In other words, there is no reason to assume that all laminated beds are ‘turbidites’ (Murphy & Schlanger, 1962).

Kuenen (1964) stated, “. . . a turbidity current must have carried its load of grains in suspension almost up to the point at which each particle comes to rest”. For this reason, normal grading is typical of turbidite beds, but is absent in experimental structures of alluvial channels (Fig. 8).

To date, no one has ever generated the complete Bouma Sequence, with all its five divisions, by turbidity currents with Newtonian rheology and turbulent state in flume experiments. There are no size-velocity type diagrams for turbidity currents. Clearly, there is a conceptual disconnect when we try to explain the origin of turbidites deposited from suspension using the origin of exper-

imental structures formed from traction. Therefore, the current hydrodynamic interpretation of the Bouma Sequence is tenuous. New experiments are needed in establishing the true relationship between sequence of structures, if any, in turbidites and their relationship to deposition from turbidity currents.

A common perception is that high-density turbidity currents in subaqueous environments are analogous to hyperconcentrated flows in subaerial environments (Fig. 9). According to Pierson and Costa (1987), hyperconcentrated flows are plastic flows, and therefore, ‘high-density turbidity currents’ cannot be true turbidity currents. In China (Qian, Yang, Zhao, Cheng, Zhang, & Xu, 1980), the term ‘hyperconcentrated flow’ is used for two distinctly different flow types: (1) Newtonian fluids characterized by low sediment concentration and turbulent state in which coarse and fine particles settle separately, and (2) Bingham (i.e., non-Newtonian) fluids characterized by high sediment concentration and laminar state in which coarse and fine particles are deposited together (i.e., freezing).

Analogous to the application of the term ‘hyperconcentrated flow’ for both turbulent and laminar flows in subaerial environments (Qian et al. 1980), the term ‘high-density turbidity current’ is applied to both turbulent and laminar flows in subaqueous environments (Postma et al., 1988). High-density turbidity currents are commonly perceived to occupy an intermediate position between low-density turbidity currents and debris flows (Fig. 9). Although the introduction of the ‘hyperconcentrated stream flow’ concept for conditions intermediate between ‘normal stream flow’ and ‘debris flow’ in subaerial environments appears to have resolved the problem of intermediate flows (Beverage & Culbertson, 1964), the boundaries between these flow types based on sediment concentration vary with grain size and composition (Pierson & Costa, 1987). The other problem is that both hyperconcentrated flows and debris flows are considered to be non-Newtonian fluids that exhibit plastic behavior (Fig. 9). In short, the use of subaerial river currents and hyperconcentrated flows as analogs for subaqueous turbidity currents, in my opinion, is not appropriate.

4.5. Flow transformation in sediment-gravity flows

Based on theoretical hydrodynamic considerations, Kuenen (1950) proposed downslope transformations of slumping to mud flow, and subsequently others have proposed transformations of slumping and debris flows to turbidity currents (Dott, 1963; Hampton, 1972). The transformation of one type of flow (e.g., laminar debris flow) to another (e.g., turbulent turbidity current) during transport is perhaps the most important and the least understood phenomenon in process sedimentology. An understanding of flow transformation is important

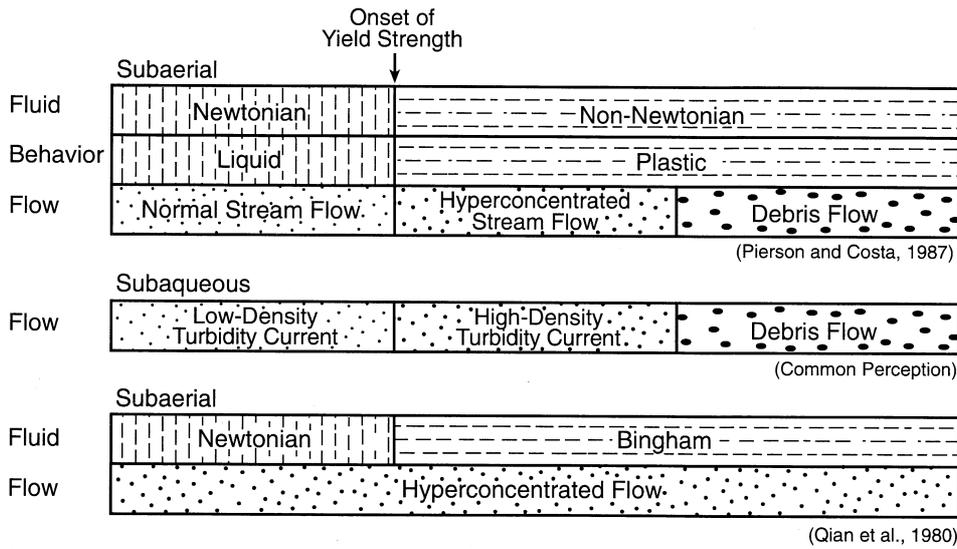


Fig. 9. Schematic diagram showing inconsistencies when comparing subaerial 'hyperconcentrated flow' with subaqueous 'high-density turbidity current'. See text for details.

because whether a flow had transported sediment in debris-flow mode or turbidity-current mode is critical in developing a geologic model. For example, Newtonian turbidity currents are more likely to spread laterally than plastic debris flows. Also, deposition of sediment by settling from turbidity currents vs by freezing from debris flows will make a difference in sandbody geometry. However, there are no established criteria for recognizing transport mechanisms in the depositional record because of flow transformations (Dott, 1963; Walton, 1967; Middleton & Hampton, 1973; Carter, 1975; Stanley et al., 1978; Lowe, 1982; Postma, 1986; Middleton, 1993; Shanmugam, 1996a). For this reason, process terms used in this review refer only to depositional mechanisms, not transport mechanisms.

Four types of transformations have been proposed for sediment-gravity flows by Fisher (1983). They include (1) body transformation, (2) gravity transformation, (3) surface transformation, and (4) elutriation transformation (Fig. 10). Experimental studies of Postma et al. (1988) have shown that turbidity currents can develop basal laminar layers (i.e., sandy debris flows) by gravity flow transformation (Fig. 6). Postma et al. (1988) called such flows as 'high-density turbidity currents'. Experimental studies have also shown that plastic debris flows can be diluted to develop Newtonian turbidity currents (Hampton, 1972; Marr et al., 1997). If a laminar debris flow generates an upper turbulent cloud (i.e., turbidity current) due to surface flow transformation (Fig. 11), then we should call it a 'low-density debris flow' if we apply the reasoning of Postma et al. (1988) for high-density turbidity current (Fig. 6). This is because these turbidity currents are derived from and initially driven by underlying debris flows. Although these turbidity cur-

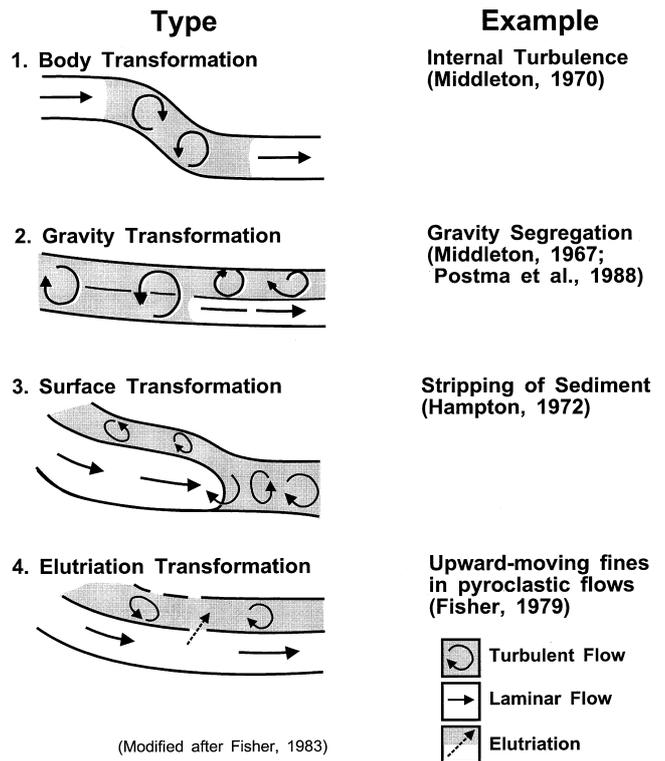


Fig. 10. Four types of flow transformations in sediment-gravity flows (modified after Fisher, 1983).

rents are generated by dilution of debris flows, these currents still possess distinct Newtonian rheology and turbulent state that are characteristics of turbidity currents. Therefore, I discourage any classification of sediment-gravity flows based on driving forces.

Phillips and Davies (1991) noted, "... although a flow

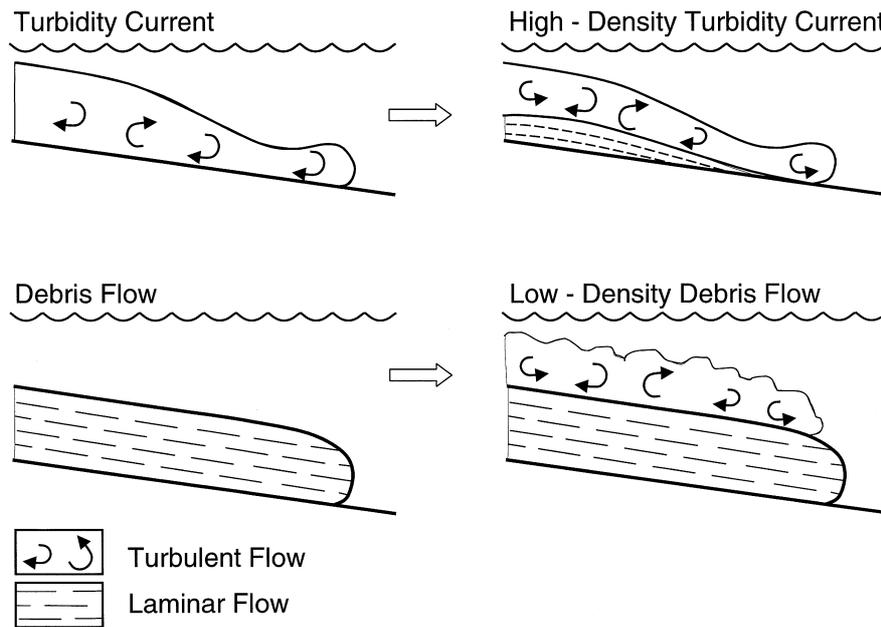


Fig. 11. Problems in classifying sediment-gravity flows based on driving forces. Top: If a turbidity current generates a basal high-concentration laminar layer due to gravity flow transformation, Postma et al. (1988) would call it a 'high-density turbidity current'. This is because the basal high-concentration layer is derived from and driven by over-riding turbidity currents. Open arrow shows direction of transport. Bottom: If a laminar debris flow generates an upper turbulent cloud (i.e., turbidity current) due to surface flow transformation through dilution (e.g., Hampton, 1972), we should call it a 'low-density debris flow' if we follow the reasoning of Postma et al. (1988) for high-density turbidity current. These weak turbidity currents are not capable of transporting sand and gravel in suspension. Open arrow shows direction of transport.

may start as a viscous plastic material it may subsequently develop grain-dispersive characteristics. Then, as shear rates are reduced, for example, by a reduction in bed slope or by jamming of coarse grains in the channel, the flow may once again exhibit plastic-viscoplastic behavior". In other words, a debris flow may transform into a grain flow, and then back to a debris flow again. Similarly, Middleton (1970) has suggested the transformation of a grain flow (laminar state) to a turbidity current (turbulent state) and returning to a grain flow (laminar state) during the last stages of deposition.

In discussing the physics of debris flows, Iverson (1997) stated, "When mass movement occurs, the sediment-water mixtures transform to a flowing, liquid-like state, but eventually they transform back to nearly rigid deposits". In other words, although these transformations do occur during transport, evidence for flow transformations cannot be inferred from the final deposit.

The challenge in interpreting the depositional record has always been how to distinguish flows that underwent flow transformation from flows that did not. Many of us use this universal constraint as a license to assume that all deep-water sands must have been transported by turbidity currents and subsequently underwent late-stage plastic deformation to resemble debris-flow deposits. This false assumption is one of the reasons why the turbidite facies models have been reigning over the debris flow facies models during the past 50 years.

4.6. Theoretical sandy debris flows

The concept of sandy debris flows was first introduced by Hampton (1975). I have expanded that concept to include the following specific parameters (Fig. 4): (1) plastic rheology, (2) multiple sediment-support mechanisms (cohesive strength, frictional strength and buoyancy), (3) mass transport mode, (4) a minimum of 25–30% sand and gravel, (5) 25–95% sediment (gravel, sand and mud) concentration by volume, and (6) variable clay content (as low as 0.5% by weight). I would suggest that rheology is more important than grain-size distribution in controlling sandy debris flows. I would also suggest that sandy debris flows can develop in slurries of any grain size (very fine sand to gravel), any sorting (poor to well), any clay content (low to high), and any modality (unimodal and bimodal). Sandy debris flows have been discussed previously in some details (Shanmugam, 1996a, 1997a).

Theoretically, grain flows (i.e., cohesionless debris flows) and muddy debris flows (i.e., cohesive debris flows) can be considered to be two end members of plastic flows (Fig. 12). Sandy debris flows are considered to represent an intermediate position between grain flows with frictional strength and muddy debris flows with cohesive strength (Shanmugam, 1997a). Therefore, multiple sediment support mechanisms, such as, cohesive strength, frictional strength and buoyancy are proposed for sandy

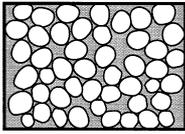
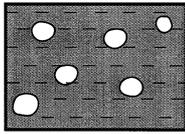
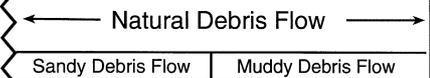
Theoretical Flow Type	Grain Flow (Bagnold, 1956) 	Not Studied	Debris Flow (Johnson, 1970) 
Support (Middleton and Hampton, 1973)	Dispersive Pressure		Mud Matrix
Rheology (Lowe, 1979)	Plastic (Frictional Strength)		Plastic (cohesive strength)
Problem (Middleton and Wilcock, 1994)	Requires high slopes (>20°)		Neglects grain collision
This Study			

Fig. 12. Theoretical vs natural debris flows. Theoretically, grain flows (i.e., cohesionless debris flows) and debris flows (i.e., cohesive debris flows) can be considered to be two end members of rheological 'debris flows' (Lowe, 1979). Following Lowe (1979), the rheologic term 'plastic' is used for both grain flows (frictional strength) and debris flows (cohesive strength). Sandy debris flows are considered to represent an intermediate position between end-member types, and therefore, multiple sediment support mechanisms are proposed for sandy debris flows. An advantage of this concept is that it requires neither the steep slopes required for grain flows nor the high matrix content necessary for cohesive debris flows. From Shanmugam (1997a).

debris flows (Fig. 4). An advantage of this concept is that it requires neither the steep slopes necessary for grain flows nor the high matrix content necessary for cohesive debris flows.

4.7. Experimental sandy debris flows

One of the main criticisms that has been leveled at the concept of sandy debris flows is the erroneous notion that all debris flows must have a high clay content in order to provide the necessary strength (e.g., D'Agostino & Jordan, 1997). Although Hampton (1975) has noted that as little as 2% clay is sufficient to provide the strength for sandy debris flows, some members of the geologic community (e.g., D'Agostino & Jordan, 1997) are still troubled by the concept of sandy debris flows with low clay content. Costa and Williams (1984) also showed a number of mud-poor debris flows in which clasts are lubricated by a mud slurry, but mud constitutes less than 1 or 2% of the debris flow.

In verifying the concept of sandy debris flows with low clay content, experiments were conducted on subaqueous sandy debris flows at St. Anthony Falls Laboratory of the University of Minnesota (Marr et al., 1997). The experimental flume used was 10 m in length, 30 cm in width, and 80 cm in depth (Fig. 13). The flume was fitted with three different slopes: 4.6, 1.1, and 0° in order to observe changes in deposition at points of slope change. Sediment slurries were composed of silica sand (120 μm size), clay (bentonite or kaolinite), coal slag (same bulk

density as silica sand: 2.6 g/cm³), and water. Coal slag of 500 μm size was used as tracer material. Sandy debris flows were generated with bentonite clay content as low as 0.5% by weight or with kaolinite clay 5% by weight. Sandy debris flows were also generated using medium-grained sand (300 μm size) with bentonite clay content as low as 1.5% by weight or kaolinite clay 5% by weight.

The following general observations can be made regarding sandy debris flows based on our experimental studies:

1. Sandy debris flows are a viable mechanism for transporting and depositing sand in subaqueous environments.
2. Sandy debris flows can travel long distances on gentle slopes (less than 1°).
3. Contrary to popular belief, sandy debris flows do not require high clay content. As low as 0.5% clay content is sufficient to generate sandy debris flows. However, without that amount of clay, debris flows will not develop. In the absence of clay, the sand-water slurry either becomes a short-lived grain flow or a short-lived turbidity current.
4. Sandy debris flows were developed from slurries of both bimodal and unimodal grain-size distribution.
5. The ratio of water to clay and types of clay determine the flow behavior. For example, by maintaining a constant amount of kaolinite at 15% by weight, and by increasing the water content, three different types of sandy debris flows (i.e., strong, moderate, and

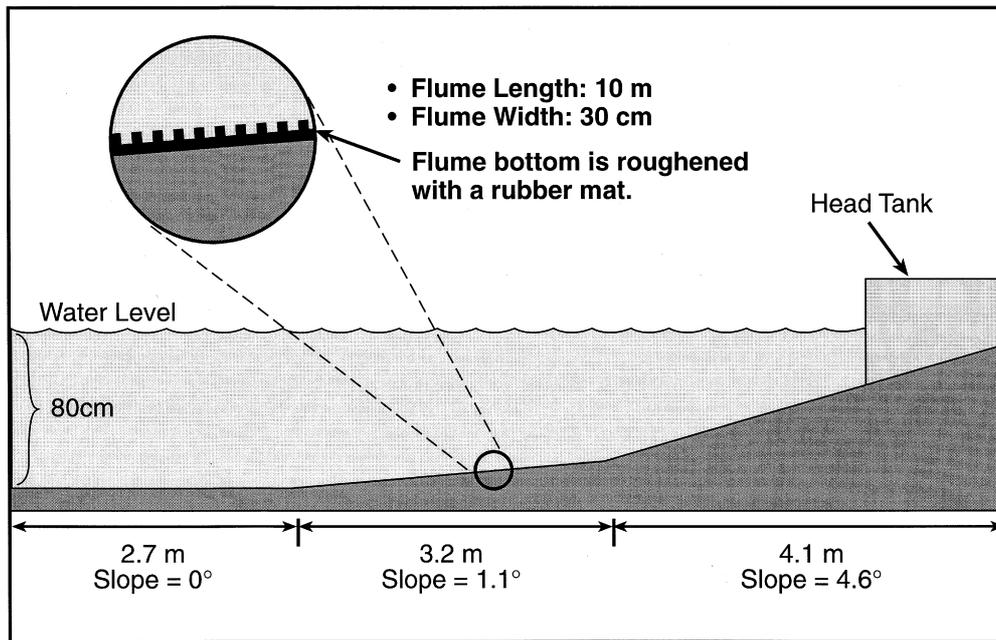


Fig. 13. Dimensions of the flume used in sandy debris flow experiments described in this paper. From Marr et al. (1997).

weak), reflecting a decrease in fluid strength, are generated at 25, 30, and 40% water by weight, respectively (Fig. 14). The significance of this observation is that the change of water content alone can make a difference in the flow behavior. More importantly, the amount of clay in the deposit is not always an

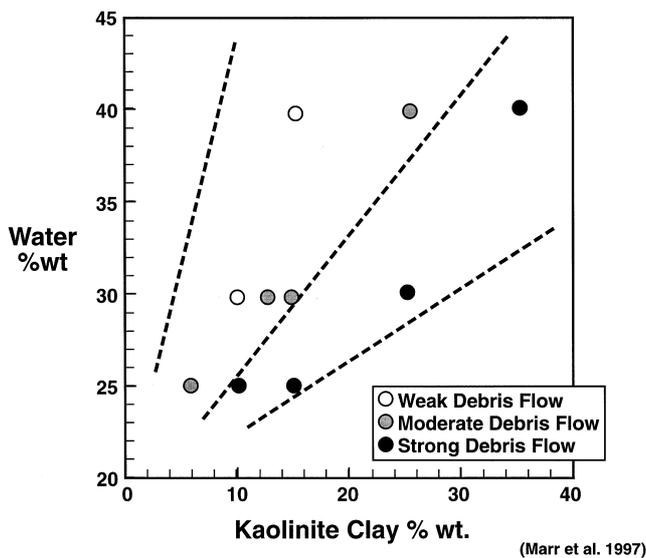


Fig. 14. Changes in flow behavior of sandy debris flows with changes in water and kaolinite clay. Note that with 40% water, debris flow types change from weak through moderate to strong at kaolinite content of 15, 25, and 35%, respectively. At 15% kaolinite, debris flow changes from weak through moderate to strong types with 40, 30, and 25% water, respectively. In other words, increasing clay content and decreasing water content result in stronger debris flows. From Marr et al. (1997).

useful criterion in interpreting the nature of flow. Primary sedimentary features are more reliable in interpreting flow behavior than clay content. Deposits of sandy debris flows with low clay content (e.g., 0.5%) are obvious candidates for misinterpretation as the deposits of other processes, such as 'high-density' turbidity currents and grain flows.

- Subaqueous debris flows tend to develop hydroplaning, whereas subaerial debris flows do not (Mohrig et al., 1998). Experimental studies of subaqueous debris flows have shown that hydroplaning can dramatically reduce the bed drag, and thus increase head velocity (Mohrig et al., 1998). This explains why subaqueous debris flows can travel faster and farther on gentle slopes than subaerial debris flows.
- In subaqueous debris flows with hydroplaning, erosion does not occur (Mohrig et al., 1998).
- Water-escape structures (dishes and pillars) have been observed in experimental sandy debris flows. Dish structures and pillars are commonly ascribed to liquefaction and fluidization (Lowe, 1975). Lowe (1975) suggested that dish structures form through the following steps: (1) when vertically escaping water meets an impermeable barrier the water is forced to move laterally until discontinuities form, (2) at discontinuities the water resumes its vertical movement resulting in the evacuation of fluid under the impermeable barrier, (3) the evacuation of water results in the formation of cavity under the impermeable barrier, and finally (4) the collapse of the cavity forms the dish structures. Lowe (1975) explain-

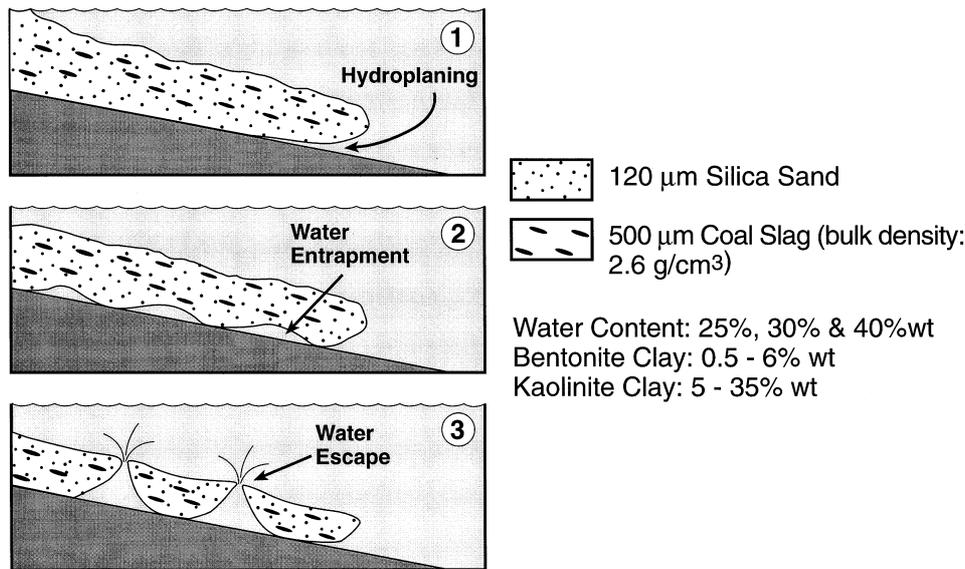


Fig. 15. Stages of development of water-escape structures in sandy debris flows: (1) hydroplaning, (2) water entrapment in cavities, and (3) water escape. Settling of debris-flow layer squeezes the water in cavities to escape upward, resulting in sand volcanoes, dish structures, and vertical pipes. This diagram is based on direct observations of experiments as well as observations made on videotapes of experiments.

ned that pillars form when horizontal flow of water is converted to vertical flow.

The dish structures in experimental sandy debris flows form in three stages, namely, (1) hydroplaning, (2) water entrapment, and (3) water escape (Fig. 15). During the hydroplaning stage, water penetrates underneath the plastic flow layer (Fig. 15, Stage 1). When the deposit begins to settle, water gets trapped in cavities underneath the bed (Fig. 16A; Fig. 15, Stage 2). Finally, further settling of sediment causes the trapped water to escape by bursting open the top of the cavity, resulting in a sand volcano. A fully developed volcano would form a dish-shaped basal surface (Fig. 15, Stage 3), which would eventually mimic dish structures along the bedding surface in the rock record. Water escape also results in vertical pipes or pillars (Fig. 17B).

Water-escape structures in deep-water sands were previously used as evidence for deposition from liquefied flows and high-density turbidity currents (Lowe, 1982). Our experiments suggest that water-escape structures are quite common in subaqueous sandy debris flows with hydroplaning. Perhaps, the presence of water-escape structures in sandy debris flows may be used as evidence for inferring hydroplaning.

9. Inverse grading is common in sandy debris flows (Fig. 16B).
10. Normal grading also develops in weak debris flows (Fig. 17A). Settling of coarser grains occurs from suspension through hindered settling after the flow stopped. This settling of grains from a non-turbulent (i.e., laminar) flow after the flow had halted is differ-

ent from settling of grains that occurs from a turbulent turbidity current during transport.

A different origin for the development of normal grading in muddy debris flows has been proposed by Vallance and Scott (1997) who stated, "if normally segregated flow stops rapidly enough, the resulting deposit will be normally graded." In short, debris flows can develop inverse grading, normal grading, or no grading, whereas turbidity currents can develop only normal grading.

Sandy debris flows with normal grading could be misinterpreted as turbidites in the rock record (Fig. 17B). Normally graded sandy debris flows can be distinguished from normally graded sandy turbidites by the associated features. For example, floating clasts and granules due to hindered settling are common in 'normally graded' debris flows. In turbidites, however, floating clasts and granules are not likely to be present because of unhindered settling.

In experiments using 300 µm size silica sand and 5 wt% kaolinite, sandy debris flows developed not only a normal grading, but also a relatively clean basal sand layer. The origin of this clean basal sand layer is speculated to be by sudden settling of sand grains coupled with upward migration of mud. This has important implications for developing alternative deep-water depositional models because the conventional wisdom dictates that only turbidites form good-quality reservoirs. Our experiments suggest that sandy debris flows are capable of forming clean, mud poor sands.

11. Massive sand emplaced by sandy debris flows exhibits a random distribution of coal slag throughout

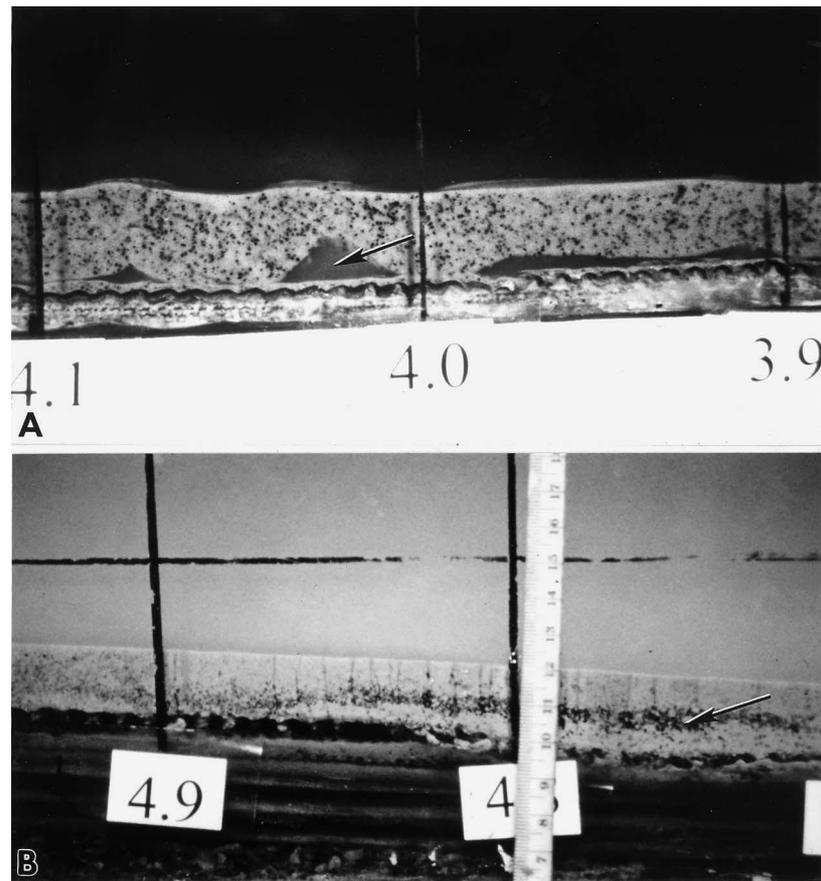


Fig. 16. (A) Side view of flume tank showing sandy debris flows with water entrapment (arrow) beneath a debris-flow layer (i.e., Stage 2 in Fig. 15). Trapped water escapes when the sandy debris flow layer begins to settle toward the flume floor, causing sand volcanoes. Horizontal distance between 4.0 and 4.1 markers is 10 cm. Flow direction from right to left. (B) Side view of flume tank showing sandy debris flows with a middle layer of coal slag (arrow) in a sandy unit (white). The sandy unit is composed of a basal inversely graded layer; an upper normally graded layer, and a middle coal slag layer. Horizontal distance between 4.8 and 4.9 markers is 10 cm. Flow direction from right to left.

the bed (Fig. 18A), which is analogous to floating granules in sandstone.

12. Internal layers in sandy debris flows develop because of post-depositional movement along failure planes (or secondary glide planes) during remobilization of flows (Fig. 18B). These layers could be misidentified as parallel lamination in the rock record, resulting in an erroneous interpretation of the depositional process.
13. Imbricate slices can develop in sandy debris flows. When the front of a flow freezes, the body of the flow breaks away from the front end and overrides the front as successive thrust slices (Fig. 18B). Imbricate slices suggest compression. Large scale compressional ridges have been reported from a modern submarine 'flow slide' in a fjord in British Columbia (Prior, Bornhold & Johns, 1984). Imbricate slices (duplex-like structures) also have been reported from the subaerial Blackhawk landslide (Shreve, 1968), and from the Pennsylvanian flysch sequences in the Ouachita Mountains in Arkansas (Shanmugam Moiola & Sales, 1988a). Duplex structures are con-

ventionally associated with tectonic activity, and therefore, it is important to know that duplex-like structures can also be formed by remobilization of sandy debris flows unrelated to tectonic activity.

14. The frontal part (snout) of sandy debris flows commonly comes to a sudden stop due to freezing. Snouts are characterized by irregular and/or sharp frontal edges (Fig. 19A).
15. During remobilization, frontal parts of sandy debris flows detach themselves from the main body and start to move ahead of the main body as isolated blocks (Fig. 19B). Such isolated blocks are evidence for tensional movement. Large bodies of isolated muddy debris flows and slumps have been reported from modern oceans (Embley, 1976, 1980; Embley & Jacobi, 1977). Recognition of similar isolated bodies of sandy debris flows in the subsurface has important implications for hydrocarbon exploration.

A summary of all the features observed in the flume experiments of sandy debris flows (Fig. 20) suggest that many of these features can easily be mistaken for other

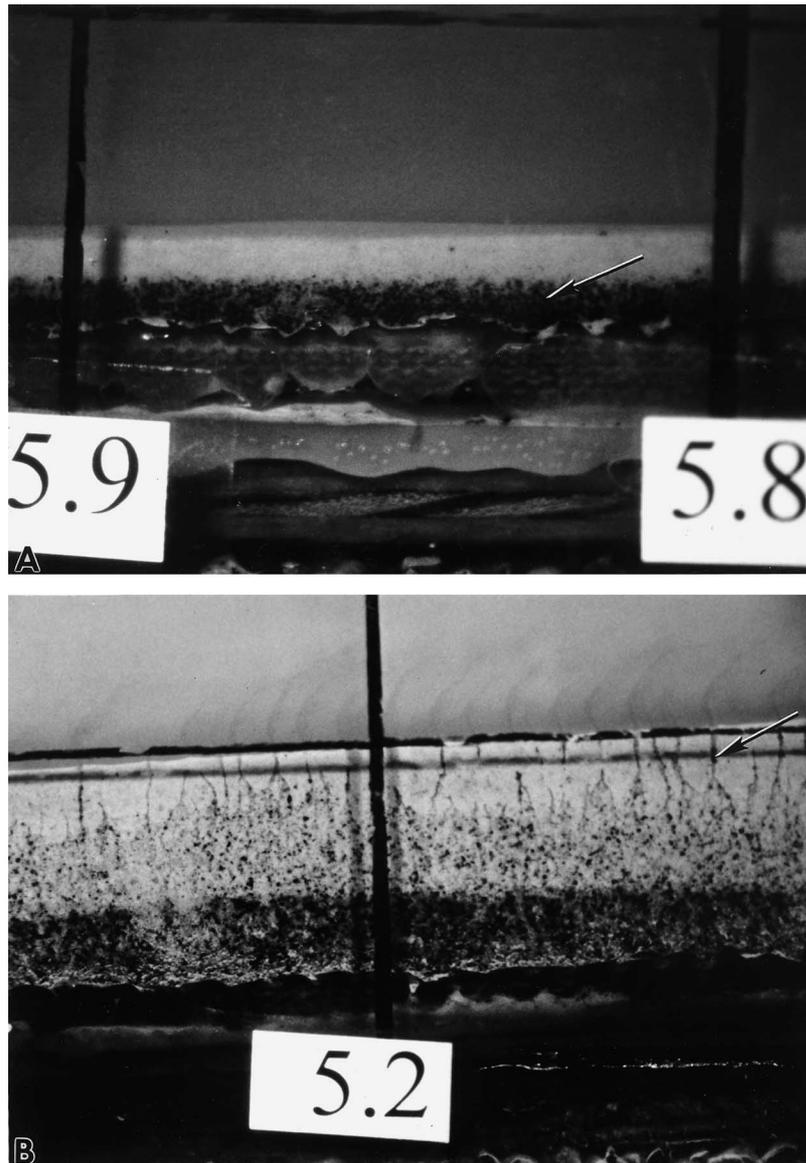


Fig. 17. (A) Side view of flume tank showing sandy debris flows with a high concentration of coal slag forming a distinct basal black layer (arrow). This basal layer formed through hindered settling after the flow had stopped. This could be mistaken for 'normal grading' deposition from turbidity currents in the rock record. Normal grading has been reported from muddy debris flows in the rock record (Vallance and Scott, 1997). Horizontal distance between 5.8 and 5.9 markers is 10 cm. Flow direction from right to left. Note smooth upper surface. (B) Side view of flume tank showing sandy debris flows with a moderate concentration of coal slags forming a faint basal black layer. Note that the amount of coal slag gradually decreases upward, resembling 'normal grading'. In comparison to the above example (A), this example suggests a stronger flow that resulted in a severely hindered settling. Vertical pipes (arrow) were created by the escape of water. Width of photo is approximately 10 cm. Flow direction from right to left.

depositional processes (e.g., turbidity currents, liquefied and fluidized flows), and for tectonic activity (duplex structures). There are no vertical facies models for deposits of sandy debris flows.

4.8. Bottom currents

In large modern ocean basins, such as the Atlantic, thermohaline-induced geostrophic bottom currents within the deep and bottom water masses commonly

flow approximately parallel to bathymetric contours (i.e., along slope, Fig. 21) and are generally referred to as 'contour currents' (Heezen et al., 1966; Ewing, Ettoreim, Ewing, & Pichon, 1971; Flood & Hollister, 1974). However, because not all types of bottom currents follow regional bathymetric contours, I prefer that the term 'contour current' be applied only to currents flowing parallel to bathymetric contours, and other currents be termed 'bottom currents' (Shanmugam et al., 1993a, 1993b, 1995c). For example, wind-driven surface currents

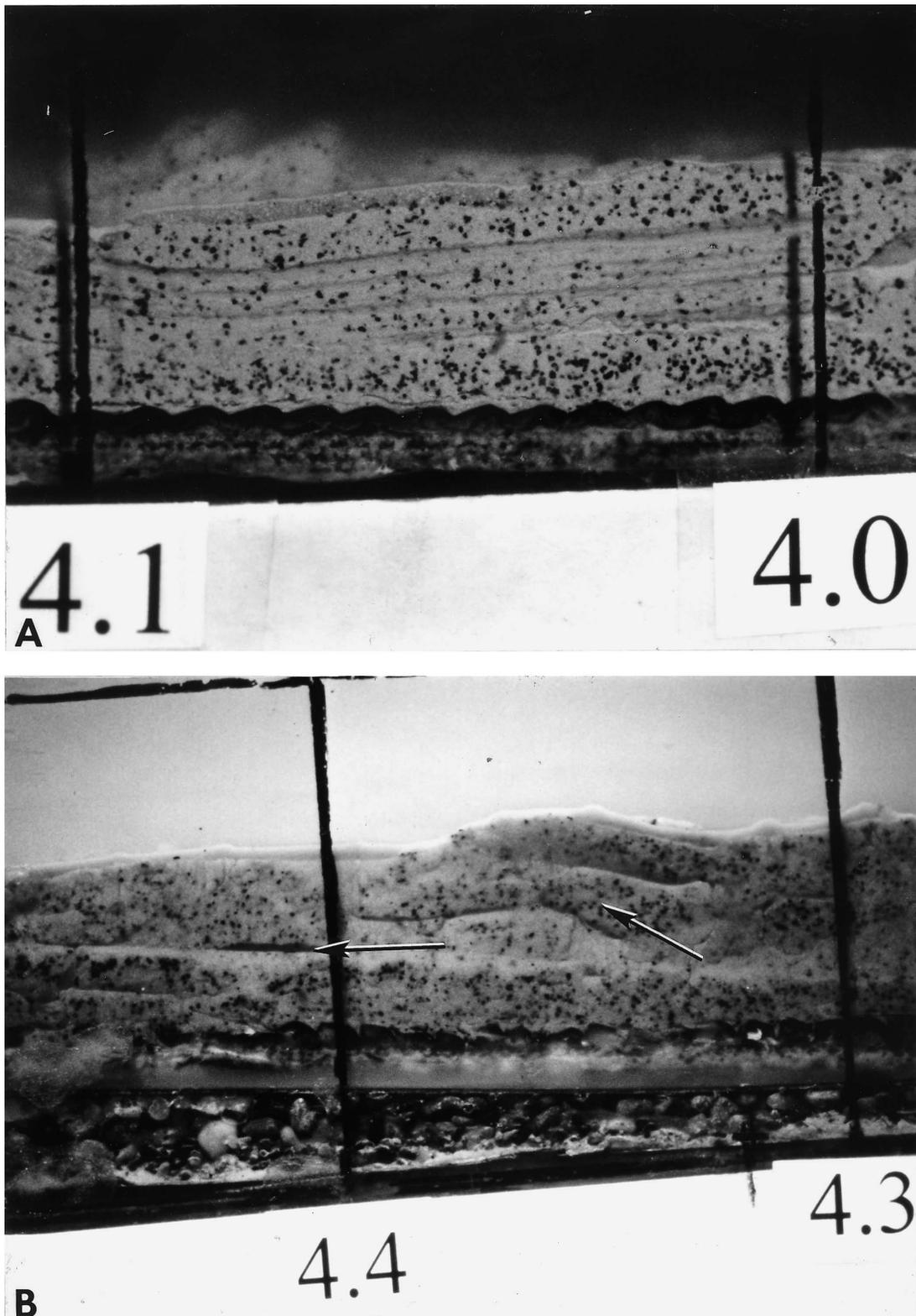


Fig. 18. (A) Side view of flume tank showing sandy debris flows with random distribution of coal slag (black grains) in massive sand. Horizontal distance between 4.0 and 4.1 markers is 10 cm. Flow direction from right to left. (B) Side view of flume tank showing sandy debris flows with imbricate slices (inclined arrow). Imbricate slices develop in sandy debris flows when the front of a flow freezes, the body of the flow breaks and thrusts over the slice in the front due to compression. Similar features (duplex-like structures) have been reported from the rock record and have been ascribed to synsedimentary slumping processes (Shanmugam et al., 1988). However, duplex structures are commonly associated with tectonic activity. Note nearly horizontal or gently dipping internal layers (horizontal arrow). These layers are caused by post-depositional movement along failure planes (or secondary glide planes) during remobilization of flows. These layers could be misidentified as parallel lamination in the rock record, which may result in erroneous interpretations of depositional processes. Horizontal distance between 4.4 and 4.3 markers is 10 cm. Flow direction from right to left.

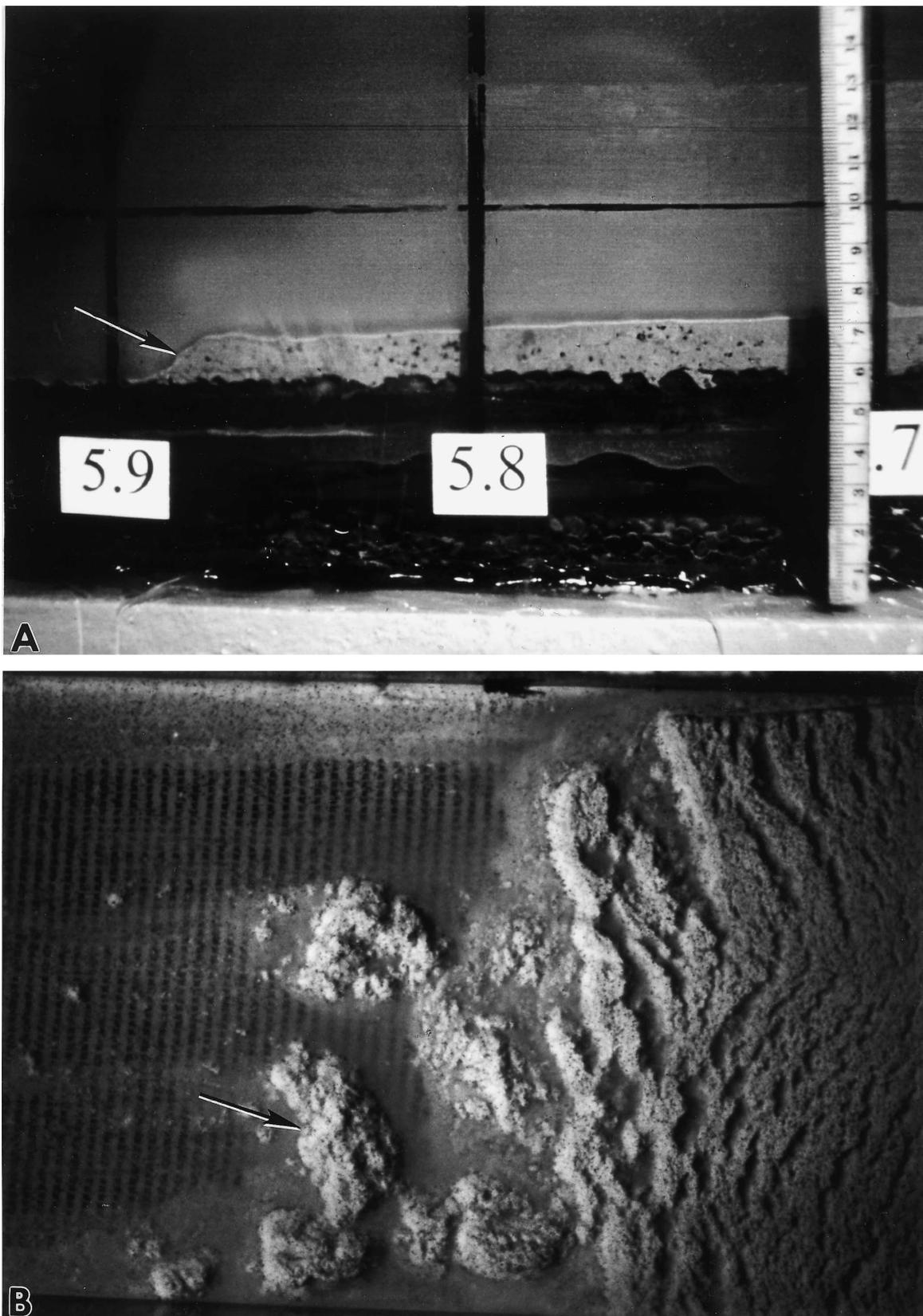


Fig. 19. (A) Side view of flume tank showing sandy debris flows with a sharp and irregular snout (arrow). Sharp and irregular snout is due to freezing of the flow. Random distribution of coal slags is due to freezing of the flow with strength. Horizontal distance between 5.8 and 5.9 markers is 10 cm. Flow direction from right to left. (B) Map view of experimental sandy debris flows showing isolated blocks of sand bodies (arrow). These bodies slowly get detached from the main body by tension. Some detachments may be explained by hydroplaning and related faster moving head with respect to the body. Width of photo is approximately 10 cm. Flow direction from right to left.

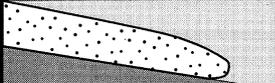
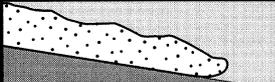
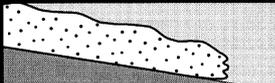
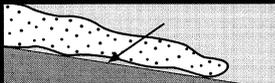
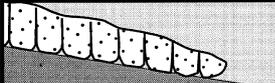
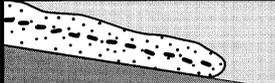
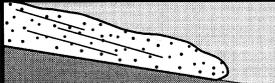
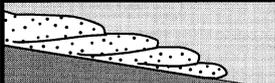
Features	Observation	Interpretation
	Sharp Upper Contact	Freezing of Flow and Plastic Rheology
	Irregular Upper Contact and Lateral Pinch-out Geometry	Freezing of Primary Relief and Plastic Rheology
	Irregular Front (Snout)	Freezing of Primary Relief and Plastic Rheology
	Non-Erosive Base and Water Entrapment (↙)	Laminar Flow and Hydroplaning
	Dish Structures and Water Entrapment (↙)	Hydroplaning and Water Escape
	Vertical Pipes	Hydroplaning and Water Escape
	Grain Segregation and Normal Grading	Grain Settling from Weak Flow
	Planar Fabric and Inverse Grading	Laminar Flow and Flow Strength
	Random Fabric	Flow Strength and Freezing of Flow
	Internal Layers	Mass Movement and Secondary Glide Planes
	Imbricate Slices	Mass Movement and Compression
	Isolated Blocks	Mass Movement and Tension
Flow Direction →	 120 μm Silica Sand  500 μm Coal Slag (bulk density: 2.6 g/cm ³)	

Fig. 20. A summary of features observed in experimental sandy debris flows.

may flow in a circular motion and form eddies that may reach the deep-sea floor, such as the Loop Current in the Gulf of Mexico (Pequegnat, 1972; Bouma, 1972), and the Gulf Stream in the North Atlantic. Local bottom currents that move up and down slope can be generated by tides and internal waves; especially in submarine canyons (Bouma & Hollister, 1973; Shepard, Dill & Von Rad, 1969). These currents are quite capable of erosion, transportation, and redeposition of fine to coarse sand in the deep sea.

Bottom currents: (1) are generally persistent for long time intervals and can develop equilibrium conditions; (2) transport sand primarily by traction (bedload movement—sliding, rolling, and saltation of Allen (1982)); (3) are sometimes free of sediment, and for this reason, are

termed ‘clear water currents’ (Bouma & Hollister, 1973); (4) entrain and transport passive sediment particles (Lowe, 1979); (5) are driven by thermohaline, wind, wave, or tidal forces; and (6) commonly flow parallel to the regional slope, but can also flow in circular motions (gyres) unrelated to the slope (Pequegnat, 1972). These characteristics clearly discriminate deep-sea bottom currents from turbidity currents. Bottom currents operate parallel to slope in most deep-water settings independently of down-slope turbidity currents, debris flows, slumps, etc. As a result, sands introduced into the basin episodically by down-slope gravity processes would be constantly reworked by bottom currents. This interplay of processes would result in a vertical sequence not unlike the ‘Bouma Sequence’ (Shanmugam, 1997a).

TYPES OF DEEP-SEA CURRENTS

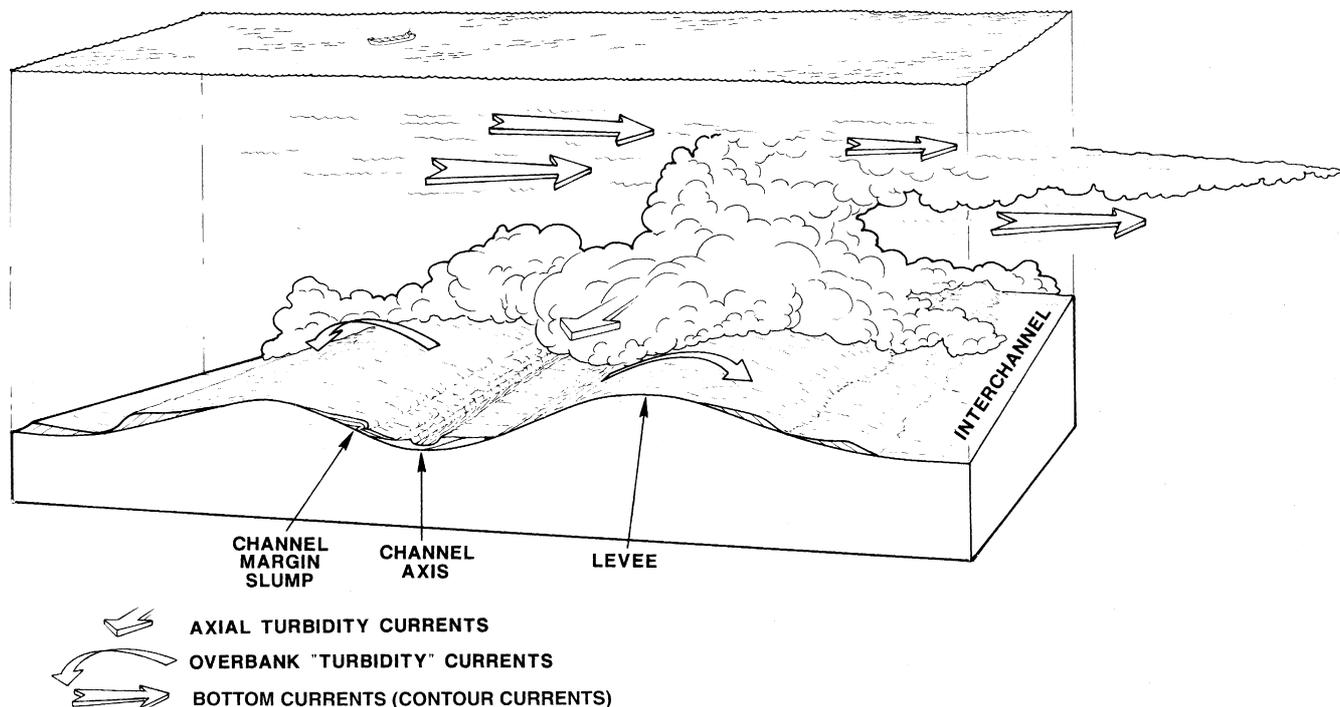


Fig. 21. A schematic diagram showing gravity-driven downslope turbidity currents, and parallel-to-slope bottom currents (also known as contour currents). From Shanmugam et al. (1993a).

Deposits of 'contour currents' (i.e., bottom currents) have been termed 'contourites' (Hollister, 1967). Two distinct types of contourites, namely 'muddy contourites' and 'sandy contourites', have been recognized (Stow & Lovell, 1979; Stow & Holbrook, 1984). Although criteria have been proposed to distinguish muddy from sandy contourites (Stow & Lovell, 1979; Stow, Faugeres, Viana, & Gonthier, 1998), the real distinction between the two types in terms of sand content has not been established. There exists a continuum of facies between muddy and sandy types, and the sand percentage that demarcates the muddy type from the sandy type has not been defined. In fact, the Faro Drift area in the Gulf of Cadiz, which has been used as the type area for the general model of both muddy and sandy contourites (Stow et al., 1998), contains only 5% sand (Gonthier, Faugeres & Stow, 1984). I would set a lower limit of 25% sand for sandy contourites. I prefer the general term 'bottom-current-reworked sands' to 'sandy contourite' irrespective of the sand content, so long as evidence for reworking of sands can be established.

Contour currents have been shown to be complex and can form strong circular eddies causing current reversals and generate 'abyssal storms' (Hollister & McCave, 1984). For these reasons, the use of paleocurrent directions to recognize bottom-current deposits (Lovell & Stow, 1981) under the assumption that all bottom cur-

rents follow regional bathymetric contours may be tenuous.

Bottom-current-reworked sands can be recognized using primary physical sedimentary structures (Hubert, 1964; Hollister, 1967; Hollister & Heezen, 1972; Bouma & Hollister, 1973; Unrug, 1977; Stow & Lovell, 1979; Lovell & Stow, 1981; Shanmugam et al., 1993a; & Stow et al., 1998). Traction structures are considered to be the only reliable criteria for recognizing bottom-current reworked sands (Shanmugam et al., 1993a, 1993b).

I do not advocate any standard vertical facies model for bottom-current reworked sands, however, I do suggest that the following criteria may be useful in recognizing bottom-current reworked sand in core and outcrop of deep-water strata (Fig. 22):

1. Predominantly fine-grained sand and silt.
2. Thin-bedded to laminated sand (usually less than 5 cm) in deep-water mud.
3. Rhythmic occurrence of sand and mud layers.
4. Numerous sand layers (50 or more per 1 meter of core).
5. Sharp (non-erosional) upper contacts and sharp to gradational bottom contacts.¹
6. Internal erosional surfaces.¹

¹ Diagnostic criteria.

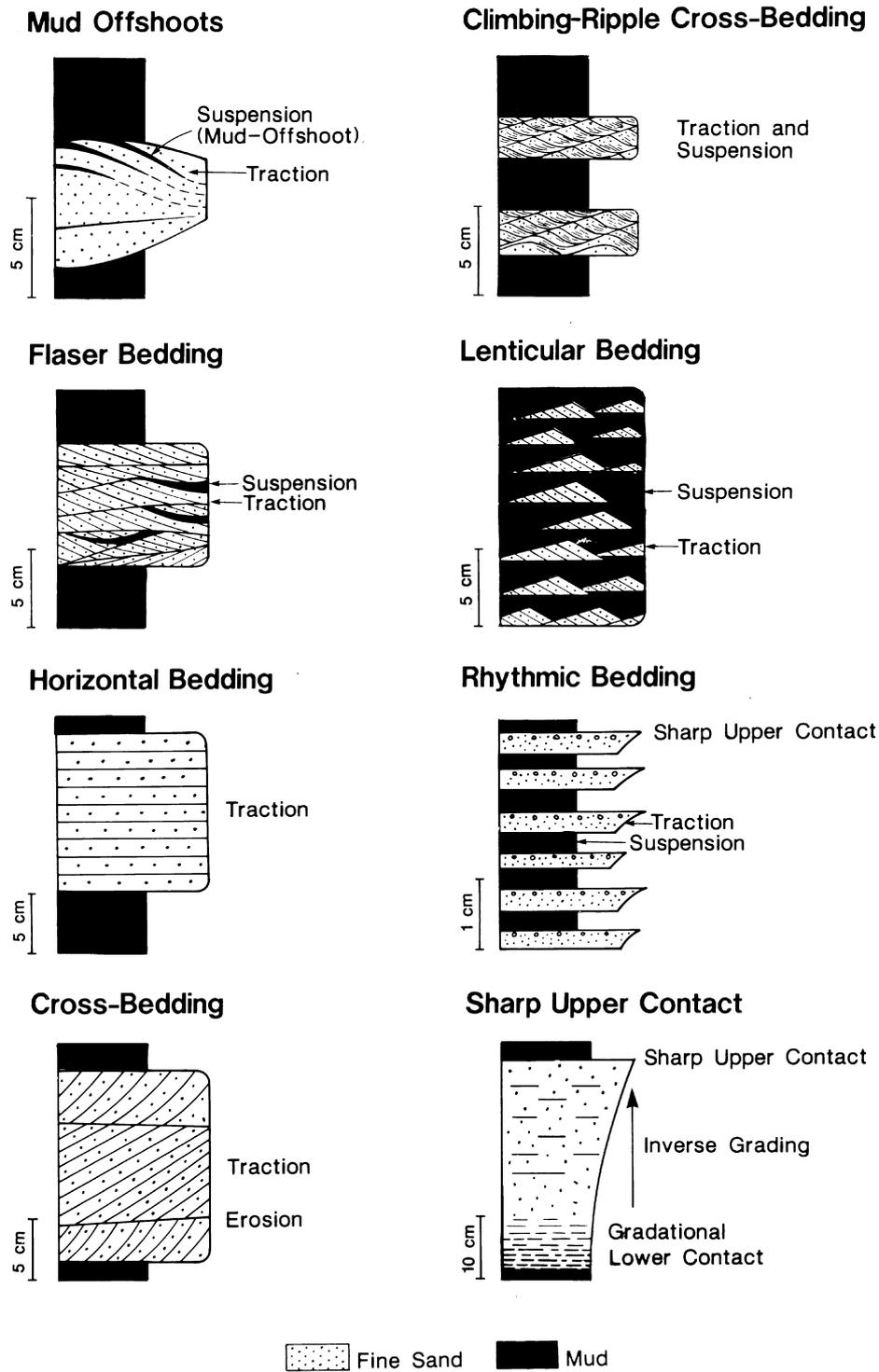


Fig. 22. Suggested traction structures for recognizing deep-marine bottom-current reworked sands. From Shanmugam et al. (1993a).

7. Well-sorted sand and low depositional matrix (clean sand).
8. Inverse size grading (coarsening upward) at various scales.¹
9. Horizontal lamination and low-angle cross lamination.¹
10. Cross-bedding. Although Mutti (1977) advocated the origin of cross-bedding in deep-sea channel

mouth deposits due to by-passing of turbidity currents, steady and equilibrium flow conditions required for the formation of cross-bedding are difficult to envision in episodic turbidity current events at channel mouths.¹

11. Lenticular bedding/starved ripples at the core scale.¹
12. Current ripples with preserved crest or eroded crest. Some ripple forms with curved bases may represent wave ripples.¹
13. Mud-offshoots.¹
14. Double mud layers (tidal).¹
15. Sigmoidal cross bedding (tidal).¹
16. Flaser bedding.
17. Occurrence of sand layers with traction structures in discrete units, but not as part of a vertical sequence of structures, such as the Bouma (1962) sequence with basal graded division. Base-missing 'Bouma Sequences' are products of bottom currents.¹

Although deep-marine bottom-current reworked sands can resemble tidal and shallow marine (outer shelf) deposits, they can be recognized by their close association with other deep-marine facies, such as turbidites, debris-flow deposits, and hemipelagic mud. Influence of tidal forces can generate tidal deposits in deep-water settings. For example tidal rhythmites have been reported from deep-water estuaries (Cowan, Cai, Powell, Seramur & Spurgeon, 1998). Tidal features (e.g., double mud layers, sigmoidal cross bedding etc.) in ancient deep-water sands in southeastern France, offshore Brazil, and Equatorial Guinea have been observed.

I emphasize that no single criterion by itself is unique to bottom-current reworked facies. Although many of the features listed above can be attributed to processes other than bottom-current reworking, the association of several of the above features in the Gulf of Mexico cores (Shanmugam et al., 1993a), along with the knowledge of the regional depositional setting, greatly enhances the chance for recognizing bottom-current reworked facies. Distinguishing deposits of bottom currents from those of overbanking turbidity currents is especially critical in developing realistic depositional models and in evaluating reservoir potential. In the Gulf of Mexico, hydrocarbon-bearing sands of bottom-current origin show high porosity values (25–40%), and high permeability values (100–1800 mD). From petroleum exploration point of view, bottom current is a viable mechanism that is capable of forming 'clean' sands in the deep sea.

5. Deep-water facies models

5.1. Philosophy

A facies model, by definition, must act as a norm, a framework, a predictor, and a basis for interpretation (Walker, 1992b). My view is that facies models may be

more useful in interpreting subaerial and shallow-marine deposits than deep-water deposits. Unlike fluvial and deltaic environments, it is not practical to observe and analyze features and processes directly in deep-water environments. We are also hampered by our inability to emulate deep-water conditions realistically in laboratory experiments. This is further complicated by the problems of comparing modern and ancient deep-water systems (Shanmugam et al., 1985a, 1985b; Mutti & Normark, 1987; Pickering et al., 1989). As a result, deep-water facies models are mostly based on incomplete observations made on modern and ancient systems. This is one of the reasons why past attempts to develop general facies models of deep-water systems (e.g., Mutti & Ricci Lucchi, 1972; Normark, 1978; Walker, 1978) have failed.

The attraction to a facies model is that it serves as a short cut to complex geologic interpretations. Anderton (1985) believes that facies models are ephemeral, and that each facies model is unique. Because each facies model is unique to a certain environment, we are programmed to align our thinking and observation along a pre-destined path. In maintaining the integrity of the model, we are often forced to de-emphasize features that are 'foreign' to the model. The reality is that those 'foreign' features are as important as the features advocated by the model. This is where facies models have the potential to restrict our ability to observe objectively all the features that are present, irrespective of whether those features are part of a model or not. After all, a facies model is developed from a local example, and we cannot expect it to encompass all possible variabilities. In criticizing the application of rigid fluvial facies schemes to the rock record, Leeder (1997) cautioned, "the main philosophical reason is that it, and other schemes like it, are lazy intellectually and deny the great potential richness of the sedimentary record, full of possible variation not adequately taped by rigid classification." Once a model is established, it is not easy to erase it from our mind or practice. Science is a journey, whereas facies models terminate that journey and become the final destination.

5.2. Order vs chaos in nature

Any attempt to construct a general facies model is an attempt to distill order in nature.

Order is an arrangement in which everything is organized in its right place, whereas chaos is disorganization. Order is believed to facilitate prediction because of its simplicity, whereas chaos is believed to deter prediction because of its complexity. This is why turbidite facies models flourished in the 1960s (e.g., Bouma, 1962), the 1970s (e.g., Piper, 1978), and the 1980s (e.g., Lowe, 1982). But I stress that aspects of nature are chaotic and therefore the study of chaos is equally important in understanding the geologic record.

The common tendency is to over-emphasize order and

de-emphasize chaos in facies models. This practice has led to a skewed representation of order in the rock record. For example, Muiola and Shanmugam (1984) interpreted the Pennsylvanian Jackfork Group in the Ouachitas as being composed of classic turbidites organized into channels (thinning up sequences) and crevasse splays (thickening up sequences). This was based on observations of the trends on large-scale packages (several meters thick) without paying much attention to details at the centimeter scale. Later, Shanmugam and Muiola (1995) reinterpreted the same Jackfork Group as being composed of deposits of sandy debris flows, slumps, and bottom current reworking stacked in a disorganized (i.e., chaotic) a manner. This later study was based on detailed observations made at the centimeter to decimeter scale. We have observed the chaotic occurrence of slump and debris flow facies at core scale, but these same chaotic facies are stacked in an orderly and predictable manner at a larger scale in Equatorial Guinea (Famakinwa & Shanmugam, 1998).

The distinction between order and chaos is not always clear cut, and may change with time. What was once considered order may later be considered chaos. For example, the Bouma Sequence is considered to represent depositional order of a single turbidity current (Fig. 23). This is true only if we assume that no process other than a turbidity current can generate the Bouma Sequence. As I have pointed out (Shanmugam, 1997a), the Bouma Sequence can also be explained by the combination of a sandy debris flow and bottom-current reworking. If so, the Bouma Sequence is no longer a representation of natural order by a single process.

Although Mutti and Normark (1987) routinely classify all deep-water systems as 1st, 2nd, 3rd, 4th and 5th order features, core studies have shown that chaotic pattern is the norm in many deep-water systems at the core scale (Shanmugam et al., 1995a). Pickering et al. (1995) applied a bounding surface hierarchy, composed of six orders, to deep-water deposits. This bounding surface concept was originally developed for fluvial deposits (e.g., Miall, 1985). However, fluvial processes and submarine processes are not one and the same (Table 1). The perceived order in deep-water systems, at least in part, is due to model-driven description of deep-water strata.

5.3. Generalization vs precision of facies models

The applicability of a facies model depends on its generalization. The more general a facies model gets, the more applicable the model becomes beyond its origination point. On the other hand, the more precise a facies model gets, the less applicable the model becomes beyond its birth place. For these reasons, generalists tend to lump and diffuse the details, whereas purists prefer to split the details. For example, a single division in the Bouma Sequence has been correlated with five divisions

of fine-grained turbidite sequence (Fig. 23). The challenge in constructing useful facies models has always been where to draw the line between lumping and splitting. This is particularly true for deep-water systems because of their highly complex and variable facies distribution. A classic example is the basal division in the Bouma Sequence (T_a) in which both massive and graded beds are lumped together (Fig. 7). This has led to eight different interpretations (e.g., grain flows, sandy debris flows, high-density turbidity currents etc.) for the basal massive division of the Bouma Sequence (see Shanmugam, 1997a). Clearly, the Bouma Sequence cannot be the norm for turbidites.

5.4. Problems with turbidite facies models

Bouma (1962) proposed the first vertical facies model for turbidites (Fig. 23), which eventually has been referred to as the Bouma Sequence and comprises five divisions (T_a , T_b , T_c , T_d , T_e). Later workers realized that the muddy division of the Bouma Sequence (T_e) was not adequate to satisfactorily represent all divisions that are present in muddy turbidites (e.g., Piper, 1978). This realization led Stow and Shanmugam (1980) to propose a new vertical facies model just for the fine-grained turbidites with nine divisions (T_0 , T_1 , T_2 , T_3 , T_4 , T_5 , T_6 , T_7 , T_8). Similarly, Lowe (1982) introduced a new vertical facies model for coarse-grained turbidites (i.e., deposits of high-density turbidity currents) with six divisions (R_1 , R_2 , R_3 , S_1 , S_2 , S_3).

In natural environments, there is only one type of turbidity current, a Newtonian flow in which sediment is suspended by fluid turbulence. Natural turbidity currents, no matter what grain size sediment they transport, will always behave the same in terms of fluid dynamics. Therefore, an ideal turbidity current that carries gravel to mud size material should deposit a continuum of divisions representing coarse-grained turbidites at the bottom (R_1 , R_2 , R_3 , S_1 , S_2 , S_3), classic turbidites in the middle (T_a , T_b , T_c , T_d , T_e), and fine-grained turbidites at the top (T_0 , T_1 , T_2 , T_3 , T_4 , T_5 , T_6 , T_7 , T_8). There are no physical laws that dictate that turbidity currents, which carry coarse sediment must cease deposition at Lowe's (1982) S_3 division or turbidity currents that carry fine sediment must commence deposition with Stow and Shanmugam's (1980) T_0 division. The established divisional boundaries between these three ideal facies models is an artificial one. In other words, there is no fluid dynamics reason why a turbidity current carrying a gravel to mud sediment load cannot deposit all its divisions from gravel (R_1) to mud (T_8). In fact, Lowe (1982) suggested a continuum of deposits from coarse-grained turbidites to classic turbidites (R_1 to T_e) totaling 11 divisions. I have added the nine divisions of fine-grained turbidites to this continuum (Fig. 24). In this composite model, an ideal turbidite bed should comprise a total of 16 divisions,

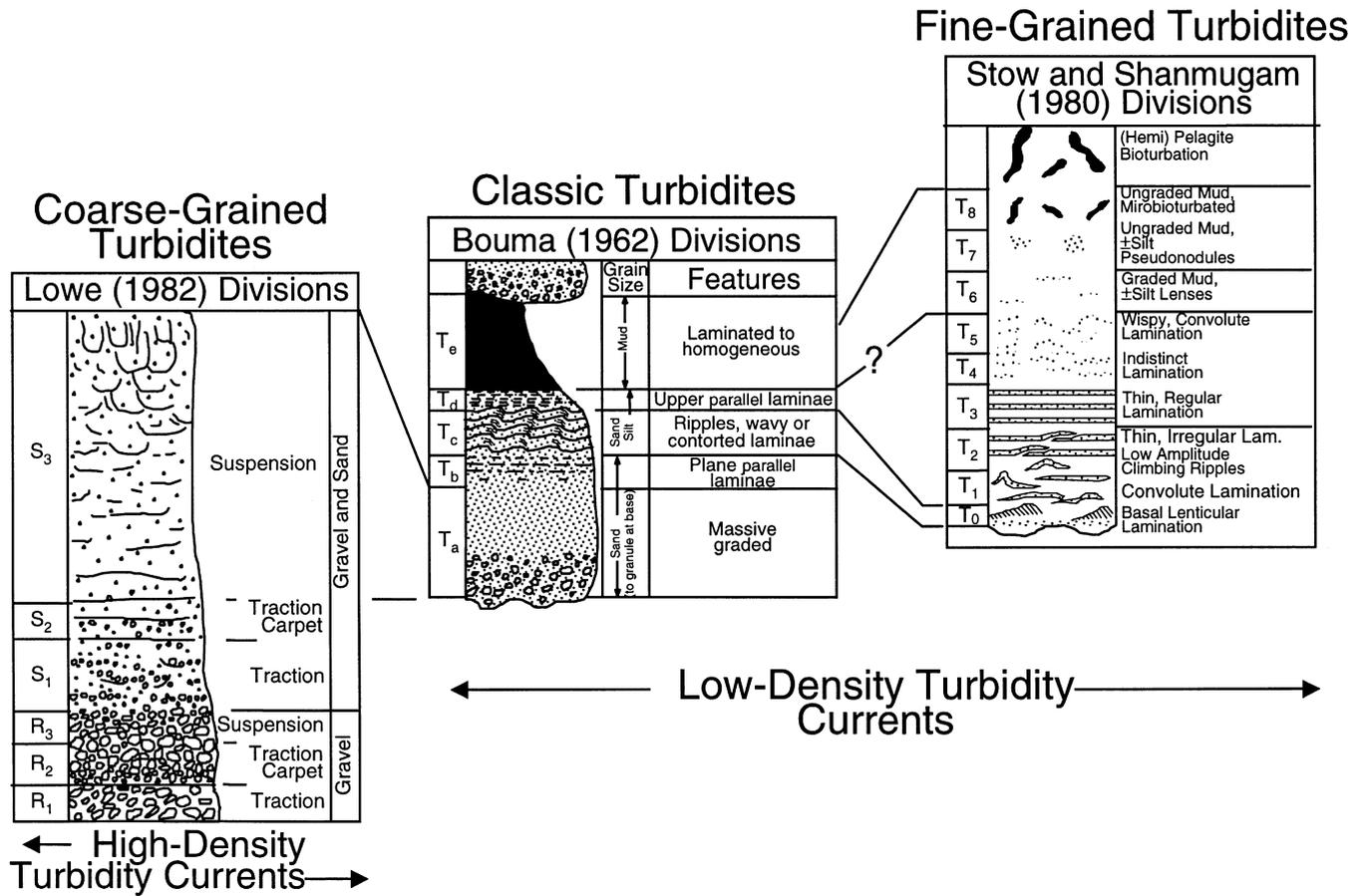


Fig. 23. Existing vertical facies models of (1) coarse-grained turbidites (Lowe, 1982), (2) classic turbidites (also known as the Bouma Sequence), and (3) fine-grained turbidites (Stow and Shanmugam, 1980). Correlation of the S₃ division of coarse-grained turbidites with the T_a division of the Bouma Sequence is after Lowe (1982). Correlation of various divisions between classic turbidites and fine-grained turbidites is after Pickering et al. (1989).

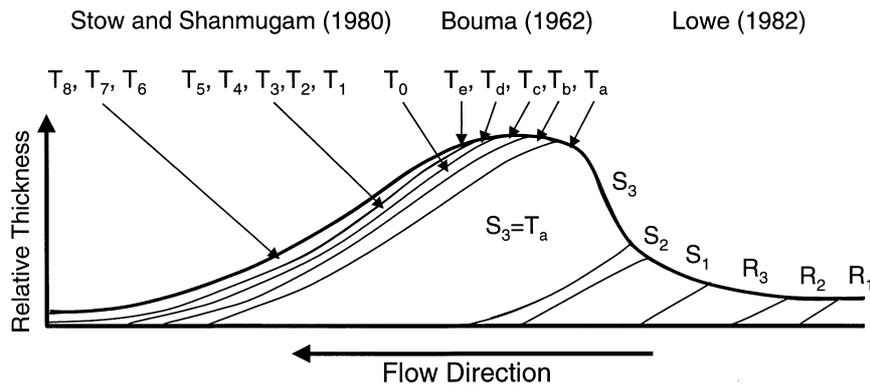


Fig. 24. A schematic diagram showing downslope changes in turbidite divisions from coarse-grained turbidites (Lowe, 1982), through classic turbidites (Bouma, 1962), to fine-grained turbidites (Stow and Shanmugam, 1980). A total of 16 divisions is expected from an ideal turbidite bed, however, no one has ever documented such a turbidite bed. Diagram is from Lowe (1982), and modified using concepts from Pickering et al. (1989).

eliminating four overlapping divisions. Such an expectation is not unrealistic because many deep-water sequences contain gravel to mud range lithologies. To my knowledge, no one has ever documented a complete

turbidite bed with 16 divisions in modern or ancient deposits. The absence of a complete turbidite bed with 16 divisions in the geologic record suggests that the ideal turbidite facies models are wrong.

5.5. Problems with traction-carpet models

The notion that traction carpets in high-density turbidity currents are analogous to bed-load transport in river currents is flawed. This is because deposition from ‘traction carpets’ occurs in the absence of sand movement by true traction, and in the presence of pervasive laminar shearing (Middleton, 1970). For this reason, Carter (1975) abandoned the use of the term ‘traction carpet’.

The precise mechanism of a traction carpet has been the subject of speculation for nearly four decades since its inception by Dzulynski and Sanders (1962). This speculation has resulted in the following multiplicity of models and processes: (1) fluxoturbidity currents, (2) grain flows, (3) slurry flows, (4) flowing-grain layers, (5) inertia-flow layers, (6) fluidized flowing grain layers, (7) avalanching flows, (8) liquified cohesionless coarse-particle flows, (9) high-density turbidity currents, and (10) sandy debris flows (see Sanders, 1965; Carter, 1975; Lowe, 1982; Postma et al., 1988; Shanmugam, 1997a; Sanders & Friedman, 1997). This many terminologies for a single flow type can only mean that we do not have a clear understanding of the mechanics of the flow involved in the ‘traction carpet’.

The most recent addition to the long line of traction-carpet models is the one called ‘laminar sheared layers’ (Vrolijk & Southard, 1997). According to Vrolijk and Southard (1997), ‘laminar sheared layers’ are products of turbidity currents. As the name ‘laminar sheared layers’ implies, these laminar layers are products of laminar (plastic) flows; therefore, they cannot be products of turbulent turbidity currents (see Middleton, 1993).

Another recent addition to the plethora family of traction carpets is the one proposed by Sohn (1997), who states, “the model is generally qualitative and partly speculative, not fully supported by experimental or observational evidence.” Such speculative models would have been appropriate when the concept of traction carpet was first introduced. What we need today is hard data, not more speculations.

Sohn (1997) states, “It seems that traction carpets and overlying turbulent flows cannot be separate entities, the former being subordinate to the latter”. Using Sohn’s logic, one could argue that turbidity currents, which develop on top of debris flows through dilution of debris flows (see Fig. 11), are not separate entities from debris flows. In other words, one could classify these overriding turbidity currents as ‘low density debris flows’ because they are derived from the debris flows below (Fig. 11). The problem with this approach is that it fails to take into account the rheology and sediment-support mechanism, which are the foundation for classifying sediment-gravity flows (e.g., Lowe, 1979).

Sohn (1997) states, “Traction carpets can be separate entity only when they move independently of the overlying flows, for example, on steep fan-delta slopes”. First

of all, it is misleading to call a layer a ‘traction carpet’ without the overlying turbulent flow. Secondly, what are the criteria for distinguishing deposits of a density-stratified flow (i.e., traction carpet *with* overlying turbulent flow) from that of a density-unified flow (i.e., sandy debris flow *without* overlying turbulent flow)? Norem, Locat and Schieldrop (1990) suggested that a turbidity current evolved from a debris flow (density stratified) may outrun the mother debris flow and become a density-unified turbidity current (Shanmugam, 1997a). In cases like this, what criteria should be used in recognizing traction carpets?

Sohn (1997) in his fig. 4 claims that traction carpets can generate five types of deposits, namely, (1) thick-bedded and inversely graded, (2) thick-bedded and massive with only the basal part inversely graded, (3) diffusely stratified, (4) thinning-upward stratified, and (5) thickening-upward stratified. If this is true, virtually all deep-water sands could be interpreted as deposits of traction carpets! The issue here is how to distinguish these five deposits of traction-carpet origin from those of other processes (e.g., sandy debris flows) that also generate inversely graded or massive sands.

Finally, the problems surrounding the concept of ‘traction carpet’ can be traced, at least in part, to another confusing concept known as ‘fluxoturbidity current’ (Kuenen, 1958). The link is that both concepts advocate the presence of non-turbulent (i.e., laminar) layers at the base of a depositing turbidity current (Carter, 1975). Although Carter (1975) favored the use of the term ‘fluxoturbidites’ for the deposits of fluxoturbidity currents, Hsu (1989) pointed out that no one seems to know what the term ‘fluxo’ stands for in fluxoturbidites. Furthermore, the term ‘fluxoturbidites’ was first applied to ‘sand-avalanche deposits’ in the Polish Carpathians by Dzulynski et al. (1959) because Ph. H. Kuenen felt that the term ‘sand-avalanche deposits’ was too long, and that the term ‘fluxoturbidites’ was short, descriptive, and therefore more appropriate (see Hsu (1989), for a fascinating history behind the application of the term). Until we decide to discard these meaningless terminologies, problems will persist.

5.6. Problems with contourite facies modes

Stow et al. (1998) proposed a composite facies model for muddy and sandy contourites (Fig. 25). This model is the same as the one proposed for the modern Faro Drift that parallels the northern margin of the Gulf of Cadiz, south of Portugal (Gonthier et al., 1984). It consists of a basal negatively (inversely) graded unit overlain by a positively (normally) graded unit (Fig. 25). The boundary between the positively graded and negatively graded units occurs in the middle of a massive (structureless) sandy silt unit (Fig. 25). Sand and silt comprise only 5% of the sediment. The grain size vertically varies from mud at the bottom, sandy silt in the middle, and

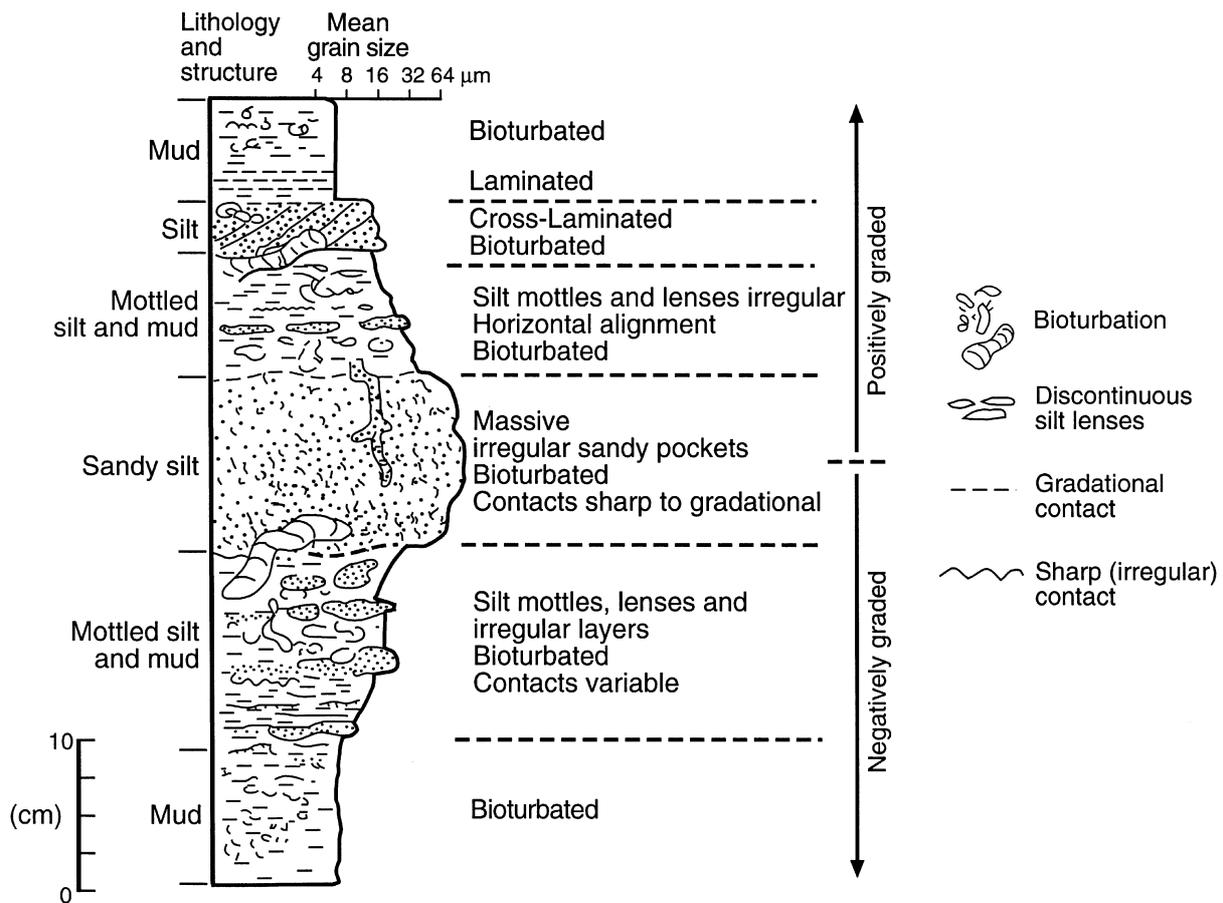


Fig. 25. Composite facies model for muddy and sandy contourites (Stow et al., 1998). Vertical grain size variation and bioturbation, advocated by the model, are not unique to contour currents. This general model for sandy contourites is based on an example (Faro Drift) that is 95% mud, and only 5% sand and silt (see Gonthier et al., 1984).

mud at the top. Bioturbation is ubiquitous throughout. Gonthier et al. (1984) attributed the vertical change in grain size (vertical increase followed by vertical decrease) to corresponding variations in current velocity (vertical increase followed by vertical decrease) associated with the deep Mediterranean Outflow.

Stow et al. (1998) have provided a precise definition of 'contourites', which is good. By their definition, contourites are sediments that have been deposited or reworked by geostrophic bottom currents that follow bathymetric contours in water depths greater than 300 m. Stow et al. (1998) do not consider 'contourites' to include the deposits of bottom currents induced by surface wind currents, tidal currents, or clear-water canyon currents that operate in water depths greater than 300 m. When we deal with ancient strata, it is not always possible to differentiate whether a bottom current that followed bathymetric contours reworked a bed or a bottom current that did not follow bathymetric contours reworked a bed. This is because not all bottom currents follow bathymetric contours (e.g., The Loop Currents in the Gulf of Mexico).

Therefore, Stow et al.'s general contourite model is applicable only to those ancient examples where it can be demonstrated that the geostrophic currents followed bathymetric contours in paleo water depths in excess of 300 m. In other words, the general model of Stow et al. (1998) is of limited value; it fails to represent a variety of bottom currents that are common in the deep sea.

The term 'sandy' is used loosely for both quartz sands (i.e., clastic contourites of Stow et al., 1998) and biogenic sands (i.e., biogenic contourites of Stow et al., 1998). Quartz sands have a bulk density of 2.65 g/cm³, whereas biogenic sands (mostly foraminiferal calcitic grains) have a bulk density of 2.71 g/cm³. More importantly, foraminiferal sands are globular in shape with hollow interiors, whereas, quartz grains are variable in shape with dense interiors. As a consequence, foraminiferal sands, in comparison to quartz sands, generally float in water, although calcite has a higher bulk density than quartz! These differences are important in controlling the settling velocity of quartz and foraminiferal sands. Differences in settling velocity would generate different

disposition between quartz and foraminiferal sands. Therefore, lumping both siliciclastic and biogenic sands in the ‘sandy contourites’ category is confusing from a settling velocity point of view.

In the original model of the Faro Drift, sands and silts form about 5% of the sediment (Gonthier et al., 1984). The composite contourite model is claimed to be a general model for both muddy and sandy contourites (Stow et al., 1998). It is misleading to propose a sandy contourite model based on an example (Faro Drift) that is composed of more than 95% mud.

In discussing the composite contourite facies model (Fig. 25), Stow et al. (1998) state that in deep-water drifts, “. . . direct evidence of current influence is often meagre”. I find it ironic that a general model for ‘contour currents’ has neither strong direct evidence for currents nor evidence for currents that follow bathymetric contours. A facies model is expected to reveal something unique about a particular environment or process; the contourite model does not reveal anything unique about contour currents.

The model (Fig. 25) strongly suggests that bioturbation is characteristic of contourites (see also Lovell & Stow (1981)). This was based on the belief that active bottom currents would increase the oxygen concentration of the water mass (Chough & Hesse, 1985), and thereby would increase the activity of organisms. However, Tucholke, Hollister, Biscaye and Gardner (1985) suggested that the degree of preservation of bioturbation is a function of bottom current intensity; strong bottom currents do not favor preservation of biogenic structures.

There is nothing unique about bioturbated mud in deep-water sequences that suggests deposition from contour-following, deep geostrophic currents. Bioturbated mud is quite common in areas that are not affected by contour currents in the deep sea. Even if bioturbation is prevalent in areas of contour currents, bioturbation does not reveal anything unique about contour currents directly. In the rock record, convincing cases of contourites have been documented without the presence of bioturbation. For example, in the Neoproterozoic Sheepbed Formation (Windermere Supergroup) of Canada, certain deep-water intervals have been interpreted to be deposits of contour currents, even though there is no bioturbation (Dalrymple & Narbonne, 1996).

Many workers have interpreted ancient strata as ‘contourites’ or bottom-current reworked deposits (Stanley, 1988; Mutti, 1992; & Shanmugam et al., 1993a). In their disagreement over the above interpretations, Stow et al. (1998) stated, “the attempt to address the problem solely from work of ancient turbidite sequences (e.g., Stanley, 1988; Mutti, 1992; Shanmugam et al., 1993a) has led to several serious errors in interpretations . . .”. Admittedly, the features of these ancient examples have very little in common with the features of the general facies model developed from a modern drift (Stow et al., 1998). My view is that we don’t fully understand the similarities and

differences between modern and ancient bottom currents. Until we do, any general facies model of contourites is of only limited practical value.

6. Submarine-fan models

Submarine fans are considered to be products of primarily turbidity currents. However, a few modern fans have been ascribed to debris flows (Elverhoi et al., 1997). Submarine-fan models, based on turbidite concepts, have been the most influential sedimentologic tool in petroleum industry for interpreting deep-water environments. These models have a long history, and it is worth analyzing how they have influenced both sedimentologists and sequence stratigraphers.

6.1. Modern-fan model

Normark (1970) presented the first widely used model for modern submarine fans based on studies of small, sand-rich, fans such as the San Lucas and Navy fans, offshore of California. He introduced the term ‘suprafan’ to describe the lobe-shaped bulge found immediately downfan of the termination of the major feeder channel on modern fans. This morphologic feature was presumably formed by rapid deposition of coarse sediment by turbidity currents at the termination of the upper-fan valley (Normark, 1970, 1978). The suprafan lobe was thought to exhibit an overall mounded, hummocky morphology in high-resolution seismic data because the irregular surface of the suprafan produced multiple and overlapping hyperbolic reflections (Normark, 1991).

6.2. Ancient-fan model

Mutti and co-workers proposed submarine-fan models based on outcrop studies in Italy and Spain, which popularized the concept of submarine fans with channels in the middle-fan setting and depositional lobes in the lower-fan setting (Mutti & Ricci Lucchi, 1972; Mutti, 1977). Mutti and Ghibaudo (1972) were the first to apply the term ‘depositional lobe’ to ancient deep-sea fan sequences. The general characteristics of the depositional lobes of ancient submarine fans (Mutti & Ghibaudo, 1972; Mutti & Ricci Lucchi, 1972; Mutti, 1977) include the following: (1) they are considered to develop at or near the mouths of submarine-fan channels analogous to distributary mouth bars in deltaic systems; (2) they show an absence of basal channeling; (3) they usually display thickening-upward depositional cycles composed of classic turbidites; (4) their common thickness range is 3–15 m, and (5) they exhibit sheet-like geometry.

6.3. General-fan model

Walker (1978) combined the major elements of Normark’s (1970) model for modern fans with facies concepts

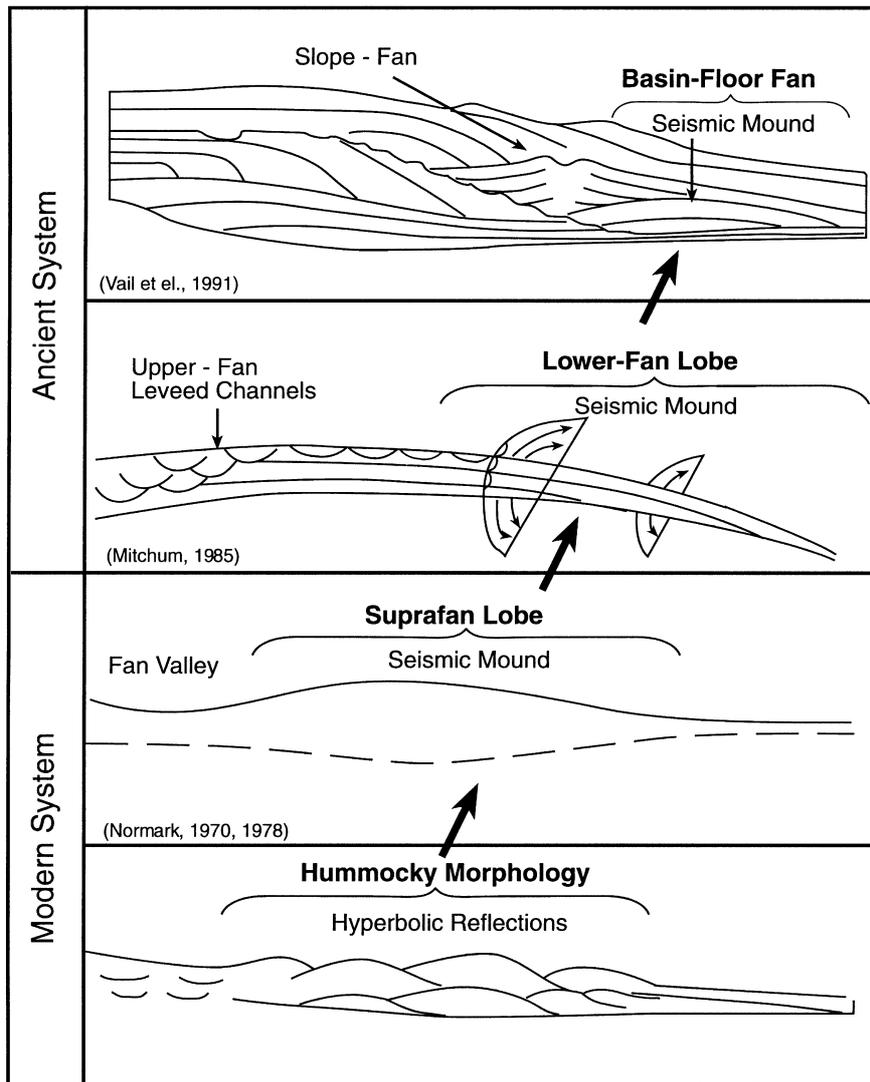


Fig. 26. Evolution of concepts on seismic mounds. Normark (1970) first proposed the seismic mound concept based on his study of suprafan lobes of modern systems. Mitchum (1985) proposed a general seismic model for submarine fans, based on the seismic mound concept of Normark (1970), in which lobes exhibit an external mounded geometry with internal bidirectional downlaps. Vail et al. (1991) proposed a basin-floor fan model, which is based on Mitchum's (1985) lobe concept. Thick upward arrows show the link between seismic mound concepts. See text for details.

of ancient submarine fans (Mutti & Ricci Lucchi, 1972), and advocated a general fan model with a single feeder channel in the upper-fan area and suprafan lobes in the middle/lower fan areas. Subsequently, this general fan model, became influential in hydrocarbon exploration and production because of its predictive capabilities.

6.4. Sequence-stratigraphic models

The concept of suprafan lobes with mounded seismic forms had its influence in seismic sequence stratigraphy (Fig. 26). Sarg and Skjold (1982) applied the suprafan concept to the Paleocene sands in the Balder area, North Sea and mapped eight distinct suprafan lobes with mounded seismic geometries. Each individual mound was interpreted as a 'suprafan lobe' containing an inner fan with

fining-upward channelized deposits and an outer fan fringe with coarsening-upward sheet sands (Sarg & Skjold, 1982). Mitchum (1985), following Normark's (1970) model, proposed a general seismic model for ancient fans that consist of an upper and a lower fan (Fig. 26). The upper fan consists of leveed channels (i.e., channel-levee complex of Normark (1970)), and the lower fan is composed of lobate and mounded deposits (i.e., suprafan of Normark, 1970). It is important to note that Mitchum (1985) equated mounded seismic facies with sheet-like turbidite sandstones of ancient depositional lobes. In Mitchum's (1985) model, a lobe is considered to exhibit mounded external form and bidirectional downlap, suggesting that the lobe is fully developed and has well-defined outer limits.

In a sequence-stratigraphic framework, the lowstand

systems tract is composed of the basin-floor fan, the slope fan and the prograding wedge (Vail, 1987; Vail, Audemard, Bowman, Eisner & Perez-Cruz, 1991). Slope fans and basin-floor fans of Vail (1987) represent Mitchum's (1985) upper fan with leveed channels and lower fan with seismic mounds, respectively (Fig. 26). In short, the basin-floor fan concept is nothing but a combination of Normark's (1970) suprafan lobe concept (i.e., mounded seismic geometry) and Mutti and Ricci Lucchi's (1972) depositional lobe concept (i.e., sheet-like sandstone bodies). However, there is an important distinction between fan models of sedimentology and sequence stratigraphy. In sedimentologic fan models, channels and lobes are contemporaneous elements; whereas in sequence-stratigraphic models, leveed fan channels are part of the slope fan, and are therefore younger, and not contemporaneous with the lobes, which are part of the older underlying basin-floor fan.

The application of shallow-water sequence-stratigraphic terms, such as 'maximum flooding surface' and 'parasequence' to deep-water sequences creates a conceptual problem. For example, Normark, et al. (1997) have applied the term 'maximum flooding surface' to the modern Amazon Fan. The term 'flood' literally means that a river or sea is flowing over its usual limits. At 3000–4000 m of water depths, irrespective of sea level changes, nothing is flowing over its usual limits. The closest thing to a 'flooding' event in bathyal environments is the 'overbanking' of turbidity currents from channels. Although this flooding surface on the Amazon Fan may have occurred at a time of flooding of the time-equivalent Amazon shelf, the term 'maximum flooding surface' at 3000–4000 m of water depths is a conceptually confusing one. This example exemplifies the potential for confusion when we use sequence-stratigraphic terminologies in a sedimentologic context.

Another example is the application of the parasequence concept to deep-water (i.e., bathyal) turbidite sands of the Kakegawa Group in Japan (Sakai & Masuda, 1996). By definition, a parasequence is a deposit of a paracycle (Van Wagoner et al., 1988; Kamola & Van Wagoner, 1995). A parasequence is a relatively conformable succession of genetically related beds or bedsets bounded by flooding surfaces or their correlative surfaces (Van Wagoner et al., 1988).

Because a parasequence is bounded by flooding surfaces, recognition of flooding surfaces is the key to establishing a parasequence. Van Wagoner et al. (1988) defined a flooding surface as a surface that separates younger from older strata across which there is evidence of an abrupt increase in water depth. Sakai and Masuda (1996) have recognized parasequence boundaries in outcrops. Accordingly, these parasequence boundaries must correspond to flooding surfaces. In shallow-water environments, it is possible to recognize flooding surfaces because small changes in water depths (i.e., a few m)

are reflected in the deposits. However, in bathyal water depths minor changes in water depths cannot be recognized. The common tendency to interpret a mudstone interval in deep-water sequences as evidence for increasing water depths is not meaningful. Condensed sections commonly are used as evidence for a rise in sea level. However, condensed sections simply reflect low rates of deposition (Loutit, Hardenbol & Vail, 1988), and cannot be routinely equated with a marine flooding surface or a rise in sea level. Therefore, it is not clear what the parasequence boundaries recognized by Sakai and Masuda (1996) represent in terms of changing water depths.

A parasequence tends to show a gradual upward shallowing trend within the interval bounded by flooding surfaces. Sakai and Masuda (1996) do not present any evidence for upward shallowing trends within the parasequences in the Kakegawa Group. Considering that the sands deposited by turbidity currents and mass flows in deep-water environments occur episodically, in a matter of hours or days (e.g., earthquake induced mass flows), it is not practical to apply the parasequence concept to deep-water deposits in terms of changing water depths (i.e., upward shallowing followed by sudden deepening). In short, there are no tools to recognize parasequences in deep-water deposits (Shanmugam, 1997b).

6.5. *Abandonment of submarine-fan models*

Reflecting on the current unpopularity of submarine-fan models, Miall (1999) opined, "the simple, all-purpose submarine-fan model of Mutti and Ricci Lucchi (1972) and Walker (1978) served the geological community well for about a decade, but is now all but obsolete". There are good reasons for the demise of submarine-fan models.

Data gathered from the modern Navy Fan since the publication of the suprafan lobe concept revealed that the 'suprafan' area of modern fans is composed of a complex array of channel, lobe and large-scale scour elements. This led Normark (1991) to reassess the validity of his suprafan concept: "... the suprafan concept is no longer viable as a mappable, defining structure of turbidite systems". Because the morphologic characteristics of modern suprafan lobes are either not preserved in the rock record or they cannot be planimetrically mapped in outcrops, Normark (1991) abandoned his 'suprafan lobe' concept altogether. Walker (1992a) also abandoned his general fan model by stating, "A submarine fan model of the channel-depositional lobe type, influential in its time, but now obsolete because it ignored external controls, especially sea level fluctuations".

The general premise behind popular fan models (Walker, 1978; Mitchum, 1985; Vail, 1987), which equated the suprafan lobe concept of modern fans (Normark, 1970) with depositional lobe concept of ancient fans (Mutti & Ricci Lucchi, 1972), was ill-founded because:

(1) modern suprafan lobes are defined on the basis of convex-upward surface morphology observable in high-resolution seismic data, but their internal architecture and sedimentary facies are not known due to lack of long cores from closely spaced wells; (2) concepts of ancient depositional lobes are based on internal architecture observable in outcrop/core, but their true surface morphology and seismic expression are not known because of discontinuous outcrops, tectonic complications, diagenesis, and thin lobe packages (3–15 m); (3) concepts of modern suprafan lobes were developed from convergent continental margins, whereas sequence-stratigraphic concepts were developed from divergent continental margins; (4) depositional lobes using Mutti's (1977) criteria have been documented in the ancient rock record, but have not been recognized in modern submarine fans (Flood et al., 1995); and (5) modern suprafan lobes do not form discrete mappable units (Normark, 1991), whereas ancient depositional lobes do. In short, the data from modern and ancient fans simply are not compatible to make any meaningful synthesis (Shanmugam et al., 1985; 1988).

By abandoning the suprafan lobe concept, Normark (1991) effectively eliminated a major source of confusion in the literature. However, Normark (1991) also created major problems by applying the term 'depositional lobe' to the modern Navy fan. This is because the lobes on modern Navy fan have not been cored to sufficient depths to establish the thickening-up trends and sheet-like geometries of true depositional lobes are present, as required by Mutti's (1977) definition of depositional lobes. Cored lower-fan intervals in the modern Amazon Fan also do not show thickening-up trends characteristic of 'lobes' (Normark, et al., 1997). Although the outer fan area of the Mississippi fan is termed 'depositional lobe' (Nelson, Twichell, Schwab, Lee & Kenyon, 1992), core from this area is composed primarily of slumps and debris flows rather than turbidites (Nelson et al., 1992). In fact, I am not aware of a single published example of a depositional lobe from modern fans that has had its turbidite facies and thickening-up trends documented using conventional core data, or its laterally continuous, sheet-like, sand-body geometry documented by correlation of sand units between closely spaced wells.

Problems also exist in recognizing depositional lobes in the ancient rock record. The *thickening-up* trend has always been an important criterion for recognizing depositional lobes (Mutti, 1977). Recently, however, Mutti (1992) interpreted certain intervals with *thinning-up* trends as depositional lobes in the Pennsylvanian Jackfork Group in the Ouachitas. By definition, depositional lobes are characterized by classic turbidites (Mutti, 1977). However, I think that the intervals that Mutti (1992) interpreted as depositional lobes in the Pennsylvanian Jackfork Group are dominated by slumps and debris flows, not turbidites (Shanmugam & Muiola, 1994).

The irregular upper surface of the suprafan lobe produces multiple and overlapping hyperbolic reflectors causing mounded, hummocky morphology (Normark, 1991). Modern slides and debris flows also generate mounded, hummocky morphology because of their irregular upper surfaces (Jacobi, 1976; Embley, 1980; Prior et al., 1984). Therefore, a mounded, hummocky morphology is not unique to suprafan lobes. In fact, irregular upper surfaces are more characteristics of slides, slumps and debris flows in modern oceans than turbidites. Unlike turbidity currents, the plastic rheology and flow behavior (like wet concrete) of slumps, slides and debris flows allow them to form deposits with topographic relief above the existing sea floor (e.g. Jacobi 1976; Embley & Jacobi, 1977; Embley 1980; Prior et al., 1984; Hiscott & Aksu, 1994).

The conceptual basin-floor fan model, characterized by mounded seismic facies, predicts sheet-like turbidite sands (Vail et al., 1991). However, I, along with several co-workers, have conducted detailed description and interpretation of about 12,000 feet of core through a number of mounded seismic forms of 'basin-floor fans' in the North Sea and Norwegian Sea. These studies show that turbidites are extremely rare in these mounded features (<1%). Mass-transport deposits, especially slumps, slides and debris flows, are predominant in the core (50–100%) taken from mounded seismic facies (Shanmugam et al., 1995a). Our data also suggest that some of these sands are laterally discontinuous (Shanmugam et al., 1994). While features identified as basin-floor fans may occur at specific and predictable stratigraphic positions within a depositional sequence and produce characteristic seismic facies and reflection patterns on seismic data, our core study indicates that basin-floor fans do not represent specific depositional facies (e.g., turbidites) and geometries (i.e., sheet-like) as the model predicts. I suggest that seismic mound models (e.g., basin-floor fan) should be abandoned because they are not reliable and they are based on the now defunct suprafan-lobe model.

7. Seismic facies and geometries

7.1. Depositional processes

Seismic facies and geometries are used to classify deep-water systems into basin-floor fans and slope fans in a sequence-stratigraphic framework (Vail et al., 1991), and in turn, these models are used to predict specific depositional processes (e.g., turbidity currents). However, as discussed above, the term 'turbidity current' has precise meanings in terms of rheology (i.e., Newtonian), and sediment-support mechanism (i.e., turbulence). Evidence for Newtonian rheology and flow turbulence cannot be established directly from seismic-reflection profiles or

wireline-log motifs; rather, these properties can only be ascertained from actual sediment facies in cores or outcrops. Furthermore, the interpretation of specific seismic facies and geometries (e.g., sheet, mounded, continuous, hummocky etc.) as to sediment processes may vary from one worker to the next depending on one's experience.

7.2. *Mounded seismic facies of sheet sands*

Deep-water sheet sands are a major attraction to the petroleum industry because of their potential to hold large volumes of hydrocarbons and because their simple geometry allows easy reserve calculations and hydrocarbon recovery. Thus, the appeal of a conventional submarine-fan model is that sheet sands can be predicted to develop in outer fan areas and in front of distributary channels by turbidity currents, and that they appear mounded in seismic profiles. However, care must be exercised in interpreting mounded seismic facies as sheet sands.

For example, modern lower-fan deposits of the Amazon and Mississippi fans, which contain sheet-like sands, show no evidence of mounded external geometry or sea-floor relief on seismic data of any scale (e.g. Damuth et al., 1988; O'Connell, Normark, Ryan & Kenyon, 1991; Shanmugam & Moiola, 1991). Simply, there are no data from either modern or ancient fans to support the view that sheet-like sandstones of submarine fans generate the mounded seismic geometries that are characteristic of basin-floor fans in the sequence-stratigraphic framework. Furthermore, it is not clear to me why sheet-like sand bodies of depositional lobes on the lower portion of a submarine fan would be expected to produce mounded features with relatively steep convex-upward upper surfaces in seismic sections (Shanmugam & Moiola 1991; Swarbrick, 1991). Individual depositional lobes, observed in outcrops with thicknesses ranging from 3 to 15 m, are not thick enough to generate mounds that can be discriminated on seismic reflection profiles.

7.3. *Channels and lobes*

The outer fan areas of the modern Mississippi Fan were used as the modern analog for turbidite fans with sheet-like geometries (Shanmugam, Moiola, McPherson & O'Connell, 1988b). Such a notion was based strictly on parallel and continuous reflection patterns observed on seismic profiles. However, a SeaMARC 1A sidescan-sonar survey coupled with piston coring of a portion of the outer Mississippi Fan reveal that this portion of the terminus of the Mississippi Fan is not entirely sheet-like as previously thought, but channelized and dendritic in nature (Twichell et al., 1992; Twichell, Schwab & Kenyon, 1995). Also, piston and gravity cores (Nelson et al., 1992; Schwab et al., 1996) taken from channels in the

outer Mississippi Fan reveal that channels are filled with debris flows for the most part; turbidites, although also present, are not the dominant facies (Shanmugam, 1997a).

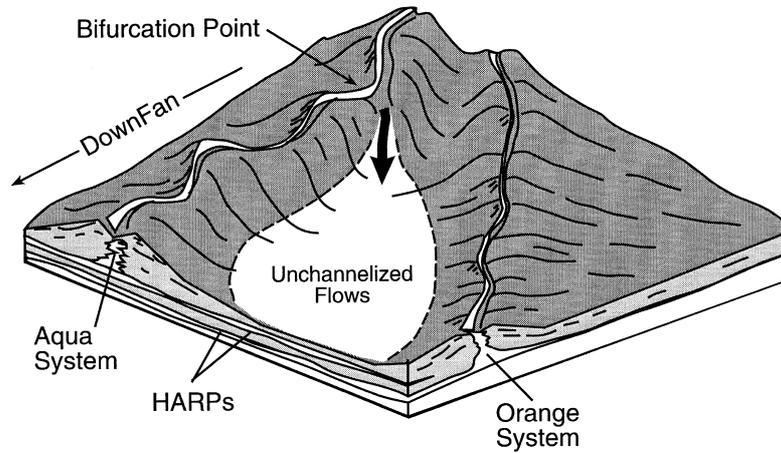
Although Twichell et al. (1992) and Schwab et al. (1996) still label the outer fan areas as 'depositional lobes', true depositional lobes, as defined by Mutti (1977), are absent in the outer Mississippi Fan. In other words, what were once considered to be non-channelized turbidite lobes of the Mississippi Fan have now been reinterpreted to be channel-fill debris flows. This change of interpretation is the result of recent acquisition of high-resolution data. In cases where high-resolution geophysical data and core information are absent, I prefer to use the more general term 'lobe form' for features that appear lobate in map view, but whose origin has not been established using core information.

Amplitude extraction maps showing channel-like forms (e.g., linear and sinuous patterns) are used to interpret channel-fill turbidites, but channels can also be filled by debris flow, slump and pelagic deposits. Because processes that cut channels are not always the same processes that fill channels (Mutti & Normark, 1987), process-based interpretation of channel-looking features in seismic data will always be a challenge. Also, debris flow chutes and retrogressive slumping can create channel-like features. More importantly, spill over deposits from debris flow chutes may mimic gull-wing geometry of channel levee complexes in seismic data. For these reasons, I prefer the general term 'channel form' when interpreting seismic data, without the benefit of core information needed to confirm the presence of turbidites.

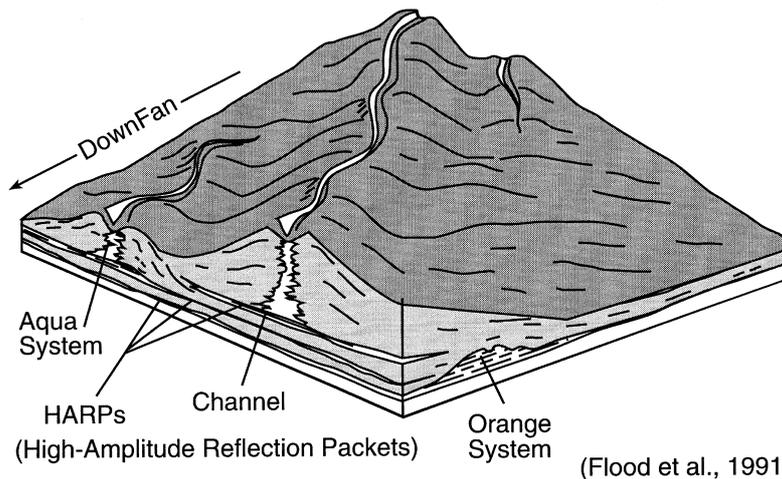
7.4. *High-amplitude reflection packets (HARPs)*

In the Amazon Fan, channel bifurcation through avulsion is thought to initially lead to deposition of unchanneled sandy flows in the interchannel area (Fig. 27, top diagram). Subsequent channel and levee development and progradation over these sandy deposits (Fig. 27, bottom diagram) produces a sheet-like geometry at the base of the new channel-levee system that returns high-amplitude reflections (HARPs) on seismic data (Flood, Manley, Kowsmann, Appi & Pirmez, 1991; Flood, et al., 1995). These sheet-like HARPs overlain by a channel-levee system (gull-wing geometry) are in many ways identical in appearance to a basin-floor fan overlain by a slope fan in a sequence-stratigraphic framework. However, there is a major difference between a basin-floor fan and HARP. For example, a basin-floor fan is formed by progradation primarily during lowstands of sea level (allocyclic process), whereas HARPs are the results of channel bifurcation (autocyclic process). More importantly, the basin-floor fan and the slope fan are not contemporaneous and form at different times (Vail et al., 1991); whereas a HARP unit and its overlying channel-

Channel Bifurcation



Channel Reestablishment



(Flood et al., 1991)

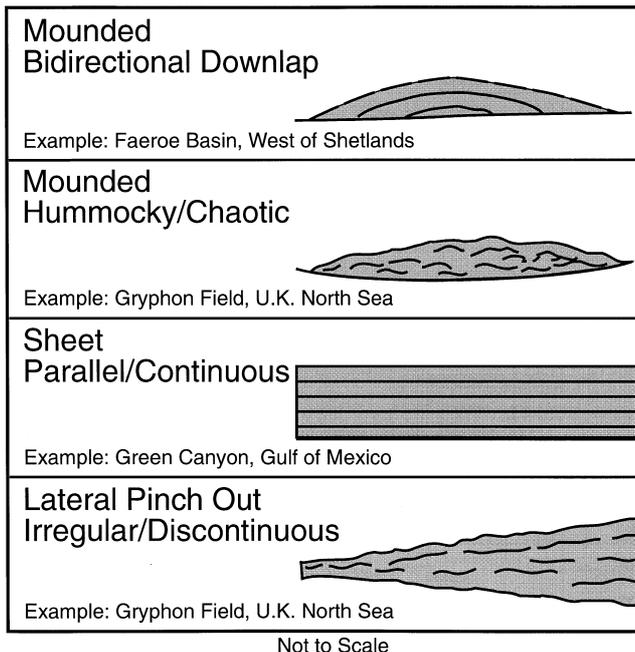
Fig. 27. Channel bifurcation through avulsion on a deep-sea fan results in unchannelized sandy flows (top diagram) breaching the confining levee of the active channel through a crevasse and then spreading out initially as unchannelized flows into lower relief interchannel areas to form a sandy deposit termed a HARP unit, because it forms a 'high-amplitude reflection packet' on seismic data (Flood et al., 1991). With subsequent, establishment of a new leveed channel over these sandy HARP deposits (bottom diagram) can result in sheet-like geometry (Flood et al., 1995). Sheet-like HARPs overlain by channel-levee complex (gull-wing geometry) can mimic a basin-floor fan overlain by a slope fan in a sequence-stratigraphic framework (see Shanmugam et al., 1995a). However, a basin-floor fan is formed by progradation during lowstands of sea level (allocyclic process) and is older than the overlying slope fan, whereas HARPs are formed by channel bifurcation (autocyclic process) that are contemporaneous with channel-levee formation. Therefore, caution must be exercised in interpreting seismic geometries in terms of processes.

levee system are essentially contemporaneous features (Flood et al., 1991; Flood et al., 1995). This again illustrates that caution must be exercised in interpreting seismic geometries in terms of processes.

7.5. Seismic facies and geometries vs depositional facies

Calibration of cored intervals with seismic reflection profiles suggests that seismic facies and geometries alone may not be reliable indicators of depositional facies because a single depositional facies (e.g., sandy debris

flow) can return a variety of seismic facies or geometries (Fig. 28). For example, in the Faeroe Basin, west of Shetlands, conventional cores recovered from mounded seismic facies and geometries with bidirectional downlap are composed of sandy debris flows and slumps (Shanmugam et al., 1995a). In the Agat area in the Norwegian North Sea, mounded seismic facies with chaotic internal reflections are documented in cores to be composed of sandy debris flows and slumps (Shanmugam et al., 1994). In the Gulf of Mexico, sheet seismic facies and geometries with parallel and continuous reflections are also com-



Not to Scale

Fig. 28. Schematic diagram showing that a single depositional facies of sandy debris flow can generate several seismic facies and geometries (e.g., mounded, sheet, and pinch out). See text for details.

posed of sandy debris flows (Shanmugam & Zimbrick, 1996). In the Gryphon Field, North Sea, lateral pinch out geometries with irregular and discontinuous reflections are composed of sandy debris flows (Shanmugam et al., 1995a).

A single seismic facies or geometry can represent more than one depositional facies. In the Ewing Bank 826 Field of Gulf of Mexico, for example, Plio-Pleistocene sands were cored and interpreted to be deposited primarily by bottom currents (Shanmugam et al., 1993a). Calibration of these cores with seismic profiles suggests that there are no differences in seismic reflection patterns between these reworked sands and associated channel turbidites. In other words, a single seismic facies can be returned from two very different depositional facies.

At present, our understanding of the sedimentary facies that form different seismic facies and geometries is poor because of insufficient 'ground truthing' by core data. Seismic facies of deep-water sequences can be deceptive, and therefore, mapping of seismic facies in deep-water sequences should be done with the realization that these patterns may not represent distinct depositional facies. Core is needed to ground truth and calibrate depositional facies with seismic facies.

8. Depositional mud matrix in deep-water sands

Depositional (primary) mud matrix, which occludes porosity and reduces permeability, is of economic importance in evaluating the reservoir potential of deep-water

sands. In the 1950s and 1960s, turbidites were considered to be poor reservoirs because of their high mud content. The 'turbidite-greywacke-flysch-dirty sand' linkage and its negative influence on petroleum industry is eloquently summarized by Sanders and Friedman (1997). Pettijohn (1957) championed the link between high detrital matrix of deep-water sandstones (greywackes) and their turbidity current origin. In referring to turbidite sandstones, Pettijohn (1957) stated, "The second group, therefore, probably owes its detrital matrix or 'paste' to deposition from fluids with higher sediment/fluid ratios. Such media are the subaqueous turbidity flows found in some lakes and in many marine environments . . .".

Sullwold (1960) reported high silt and clay content (13.5–34.5%) from sieve analysis of upper Miocene sandstone beds that were interpreted to be turbidites. The following comments of Sullwold (1961) reflect the then prevailing views in the early 1960s concerning the muddy nature of turbidity currents and their deposits:

1. "A turbidity current is opaque and muddy (by definition) . . ."
2. "Poor sorting is an expected feature in turbidites."
3. "The large percentage of silt and clay in these sands has caused them to be termed wackes and graywackes by most workers."
4. "Sorting is directly related to porosity, and turbidites must therefore have less original porosity than shallow-water sands . . ."

Although the term 'greywacke' is no longer used synonymously with turbidites, the above comments are still valid because turbidity currents are considered to be a type of sediment-gravity flow with Newtonian rheology in which sediment is held in suspension by flow turbulence. Sanders and Friedman (1997) emphasize, "From the point of view of petroleum geology, sands deposited from turbulent suspension are poorly sorted and includes large amounts of silt and clay". It makes sense that turbidity currents would deposit mud-rich sediment because it is easier to transport mud, rather than sand or gravel, in turbulent suspension.

In the 1990s, however, there has been a tendency to perpetuate the opposite notion: i.e., turbidites are clean (i.e., mud poor) sands. Mitchum, Sangree, Vail and Wornardt (1990, 1993), for example, considered the turbidites of basin-floor fans to be ". . . clean, well sorted sandstone with good reservoir quality". In my opinion, this popular notion is based on the misinterpretation of clean, deep-water, massive sands as 'turbidites' using the traction carpet analogy (see Shanmugam et al., 1995a; Shanmugam, 1996a). Some might even use the low mud content of certain deep-water sands as a criterion for interpreting them as turbidites. As discussed earlier, experiments have shown that sandy debris flows can emplace sands with only minute amounts of clay (i.e., 0.5% by weight) (Marr et al., 1997). Therefore, low mud

content does not appear to be a valid criterion for establishing the turbidity current origin of deep-water sands.

Sanders and Friedman (1997) maintain that simply ‘dirty’ (i.e., mud rich) sands are turbidites, and ‘clean’ (i.e., mud free) sands are non-turbidites. When compared to turbidity currents, sandy debris flows have better chances of depositing mud-poor, clean, sands for the following reasons:

1. Experiments have shown that sandy debris flows can emplace clean sands as basal layers (see section on Experimental Sandy Debris Flows).
2. Subaqueous debris flows commonly undergo dilution during transport (Hampton, 1972). The dilution generates turbidity currents due to the removal of mud from the underlying debris flow (Fig. 11). This process not only depletes the underlying debris flow of mud but also enriches the overriding turbidity current with mud, a kind of mass balance of mud. The longer the depletion of mud, the cleaner the sand would become in a debris flow. As discussed earlier, experiments have shown that sandy debris flows are capable of operating with only minute amounts of clay (Marr et al., 1997).
3. Mud is an integral component of turbidity currents that are generated from debris flows. Turbulence keeps the mud in suspension during transport. During deposition, mud is emplaced along with the fine-grained sand. Thus, turbidite sands should always contain mud (Sanders & Friedman, 1997). Pure sand flows, without mud, cannot support sand and gravel in turbulent suspension for long periods of time during transport, and will collapse. Therefore, mud-free sandy turbidity currents are short lived, and are not important sand transport mechanisms in the deep sea.
4. Subaqueous debris flows are prone to develop hydroplaning (Mohrig et al., 1998). Furthermore, debris flows are laminar in state. As a result, subaqueous debris flows with hydroplaning are not likely to erode the sea-floor and incorporate the eroded mud into the flow. In contrast to debris flows, turbidity currents are always turbulent in state (Middleton, 1993). Turbulence tends to cause erosion of the sea-floor, and the eroded sea-floor mud invariably gets incorporated into the flow.

In summary, the emplacement of ‘clean’ sands in deep-water environments may be better explained by: (1) sandy debris flows, and (2) bottom currents (Hubert, 1964; Hollister, 1967; Shanmugam et al., 1993a), rather than by turbidity currents.

9. Perpetuation of the turbidite paradigm

In this section, I have selected the following studies in demonstrating how the turbidite paradigm has been perpetuated during the past 50 years.

Early experiments of ‘the turbidity currents of high density’ by Kuenen (1950) have been very influential. Unfortunately, these experiments did not deal with true turbidity currents. Carter (1975) considered Kuenen’s experimental turbidity currents as slurry flows, a type of debris flows. In commenting on Kuenen’s (1950) experiments of high-density turbidity currents, Oakeshott (1989) stated, “. . . it is obvious from the high content of clay in these experimentally formed flows that they were actually debris flows.”

Middleton (1967) conducted experiments on ‘high-concentration turbidity flows’. However, Middleton’s (1967) experimental ‘high-concentration turbidity flows’ meet all the criteria for mass flows (i.e., debris flows), as defined by Dott (1963): (a) they were flows of non-Newtonian fluids that exhibit plastic behavior, (b) they were high-concentration flows in which the sediment is supported by dispersive pressure, and (c) deposition from these flows occurred by ‘freezing’. Therefore, these experimental flows were not true turbidity currents (see Shanmugam, 1996a).

Experiments on ‘high-density turbidity currents’ by Postma et al. (1988) have also been very influential. As I pointed out earlier, these experimental flows are composed of both sandy debris flows and turbidity currents. According to Oakeshott (1989), Postma et al. (1988) experimental flows, ‘would probably be described as debris or density modified grain flows’. In these experiments, the term ‘high-density turbidity current’ is a euphemism for ‘debris flows’ ever since it started with Kuenen’s (1950) experiments.

Arnott and Hand (1989) claimed that their experiments were of particular relevance to deposition from turbidity currents. However, Sanders and Friedman (1997) questioned the relevance of these experiments to turbidity currents because the current was not carrying the sediment in suspension.

Deformation of a 2.5 cm-diameter steel rod was ascribed to damage done by ‘turbidity currents’ in the Scripps submarine canyon, offshore California (Inman, Nordsrom & Flick, 1976). However, no evidence was presented for bending of the steel rod by turbidity currents. The deformed rod itself is evidence only for some powerful force or event that caused the damage. In other words, turbidity current is only one of several options; other possibilities are submarine slides, submarine slumps, submarine avalanches, submarine debris flows, and even bottom currents. In fact, mass movements are quite common in submarine canyons (Shepard, 1951). Slumping activity was reported from the Scripps submarine canyon (Dill, 1964), and from the La Jolla submarine canyon (Shepard, 1979). However, attempts to generate turbidity currents at the head of the Scripps submarine canyon were unsuccessful (Dill, 1964).

The classic case of submarine telegraph cable breaks

by ‘turbidity currents’ is the one associated with the 1929 Grand Banks Earthquake (Heezen & Ewing, 1952). Similar to the case of the bent rod in the Scripps Canyon, there is no direct link between cable breaks and turbidity currents. The presence of thin turbidite layers in this area is not the proof for cable breaks. In fact, Heezen and Ewing (1952) recognized the possibility of cable breaks by slumps as well. In discussing the breakage of the Cable H in the Grand Banks area, Hsu (1989) states, “This scenario suggests that the trans-Atlantic cable near the base of the slope was not broken by a turbidity current, but by a high-speed, sediment-gravity flow”. Hsu (1989) suggests that the Cable H was broken by a debris avalanche. Sanders and Friedman (1997) ascribed cable breaks in the Grand Banks area to liquefied cohesionless coarse-particle flow, a type of submarine avalanche. In support of their hypothesis, Sanders and Friedman (1997) pointed to the presence of small pebbles wedged into the frayed strands of the cable’s armor. In my view, submarine slumps and avalanches are better candidates for breaking cables than turbidity currents because of the fast-moving solid masses of material involved in slumps and avalanches.

Piper, Shor and Hughes Clarke (1988) suggested that deep-sea gravel waves in the Grand Banks area are products of bed load transport by turbidity currents, analogous to dune bed forms in subaerial rivers, involving traction processes. The implication is that these gravel waves are composed of cross bedding; however, no core information is available to prove the presence of cross bedding in these gravel waves. Hsu (1989) proposed an alternative, debris avalanche, origin for the gravel waves in the Grand Banks area. To my knowledge, no one has ever generated cross beds in flume experiments from turbidity currents.

Hay et al. (1982) reported the first remote acoustic detection of a modern ‘turbidity current’ in the Rupert Inlet, British Columbia. The ‘turbidity current’ event in this case was detected using acoustic sounders operating at 42.5, 107, and 200 kHz. It is conceivable that this event was a turbidity current. It is also possible that this event was a debris flow, or a basal plastic flow with an overriding Newtonian flow. The problem with any acoustic data is that they cannot detect fluid rheology or sediment-support mechanism in establishing the precise nature of the flow (i.e., turbidity current vs debris flow).

Turbidity currents simply cannot exist without turbulence (Middleton, 1993). However, the term ‘turbidity currents’ was used for non-turbulent (i.e., laminar state) flows (McCave & Jones, 1988). Similarly, the term ‘laminar sheared layers’, implying deposition from laminar (i.e., non-turbulent) flow, was used for deposits of ‘turbidity currents’ (Vrolijk & Southard, 1997).

Chikita (1989) used the term ‘turbidity currents’ synonymously for subaerial river currents. Turbidity current is a subaqueous process and it is not analogous to suba-

erial river current (Table 1). Otherwise, fluvial deposits would be misinterpreted as “turbidities”.

Peira Cava and vicinity in SE France, where the Annot sandstone is exposed, served as the type locality for the formulation of the ‘Bouma Sequence’. An important attribute of these deep-water sandstone beds is the claim that virtually every bed is described to show normal grading (Bouma, 1962; Pickering & Hilton, 1998, their fig. 62, Log A). However, these ‘normally graded’ beds also show inverse grading at their base (e.g., Pickering & Hilton, 1998, their fig. 62, Log A), floating armoured mud balls (e.g., Stanley et al., 1978, their fig. 8.8D), and large floating mudstone clasts in the middle (e.g., Pickering & Hilton, 1998, their fig. 62, Log A). Normal grading of a deep-water sandstone can be used as evidence for deposition from suspension settling of a turbidity current only if the sandstone is devoid of inverse grading at the base, armoured mud balls and floating mudstone clasts in the middle. This is because inverse grading and floating armoured mud balls suggest freezing of plastic debris flows.

Bouma (1962) did not include the presence of inverse grading, floating armoured mud balls, and floating mudstone clasts as part of the vertical facies model of a turbidite (i.e., the Bouma Sequence) in the Annot Sandstone. As a result, many of us emphasize only the presence of ‘normal grading’, but ignore the importance of inverse grading and armoured mud balls while interpreting the origin of the Annot Sandstone. For example, in spite of their observation of inverse grading, armoured mud balls, and floating mudstone clasts in the Annot sandstone, Pickering and Hilton (1998) concluded that “The Gres d’ Annot Formation in the Peira Cava sub-basin is interpreted to represent a base-of-slope sub-basin fill with proximal-to-distal changes showing deposition of predominantly *sand-rich turbidites* (italics mine) in the proximal parts of the sub-basin, and relatively *sand-deficient turbidites* (italics mine) in the distal parts of the sub-basin”. Pickering and Hilton (1998) also concluded that many basal beds of the Annot Sandstone are deposits of high-concentration turbidity currents, but they conceded, “Of course, the precise hydrodynamic conditions and sediment concentrations of high-concentration turbidity currents remains unresolved”.

Perhaps, the single most important source of perpetuation of the turbidite paradigm is the biased way we describe ‘normal grading’, which serves as the gateway to turbidite interpretation. There are three types of normal grading: (1) distribution grading in which all grain sizes decline upwards over the entire bed (Middleton, 1967), (2) coarse-tail grading in which only the coarsest components decline upwards (Middleton, 1967), and (3) delayed grading in which grain size declines gradually for the most part of the bed, but rapidly near the top of the bed (Walton, 1956). All of them can be used as evidence for turbidite deposition. However, none of them can be used if any one of them contain inverse grading at the

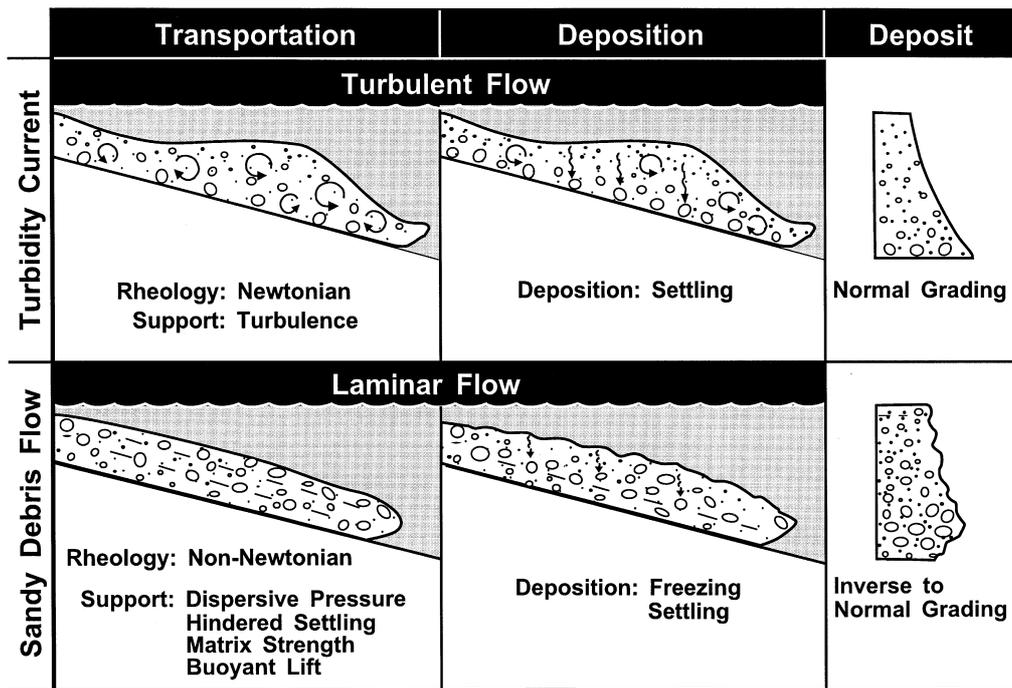


Fig. 29. Top: Schematic diagram showing development of simple normal grading by suspension settling from a turbulent turbidity current. Bottom: Schematic diagram showing development of inverse to normal grading by freezing and late-stage settling from a laminar debris flow.

base indicating plastic flows, or contain floating mudstone clasts in the middle indicating plastic flows, or associated with parallel lamination suggesting traction deposition. Although inverse to normal grading is common in deposits of debris flows (Fig. 29), many ignore the presence of inverse grading and emphasize only the normal grading in arriving at the preferred turbidite interpretation.

Because the description and meaning of normal grading varies from one worker to another, it is not clear how many of the published examples of 'normal grading' truly represent turbidite deposition (Fig. 29). For example, describing a cross-bedded sandstone that is coarser at the base than it is at the top as 'graded' is not meaningful. In cases like this, "... the term *graded* has lost its original descriptive meaning so clearly set forth by Pettijohn and Kuenen" (Murphy & Schlanger, 1962). I suggest that the concept of 'normal grading' should be reserved only to describe deep-water intervals that do not contain cross-stratification, horizontal stratification, contorted bedding, inverse grading, floating mudstone clasts, floating quartz granules, pockets of gravels, etc. Otherwise, deposits of slumps, debris flows, and bottom currents would be misinterpreted as 'turbidites'.

In sandstones showing divisions of the 'Bouma Sequence', it is more important to establish that the basal division (Ta) is normally graded than the entire 'Bouma Sequence' is normally graded. Otherwise, virtually every sandstone-shale sequence in the entire geologic record

could be described as 'normally graded' on the assumption that the overlying shale represents the pelagic upper division (Te) of the 'Bouma Sequence' and that the shale is finer grained than the underlying sandstone.

Finally, even though Normark (1991) and Walker (1992a) have now abandoned their popular fan models, many petroleum geologists still use these models (e.g., Coleman, Swearingen & Breckon, 1994; McGee, Bilinski, Gary, Pfeiffer & Sheimanan, 1994; Galloway, 1998). So, the perpetuation of the turbidite paradigm goes on. It is by design, not by accident.

10. A paradigm shift

In the 1970s and early 1980s, I and my co-workers proposed ideal vertical facies models for fine-grained debris flows (Shanmugam & Benedict, 1978), for fine-grained turbidites (Stow & Shanmugam, 1980), for the rhythmic order of turbidites (Shanmugam, 1980), and for turbidite fans (Shanmugam, 1980). But my skepticism about the dominance of turbidites in deep-water systems and my perception of the inadequacy of facies models began to take root when I started describing cores and outcrops worldwide in great detail (Fig. 30). Prior to my involvement in describing deep-water sequences for Mobil, which began in 1978, I thought that most deep-water sands are turbidites and that they are commonly organized into channels and lobes in a submarine-fan

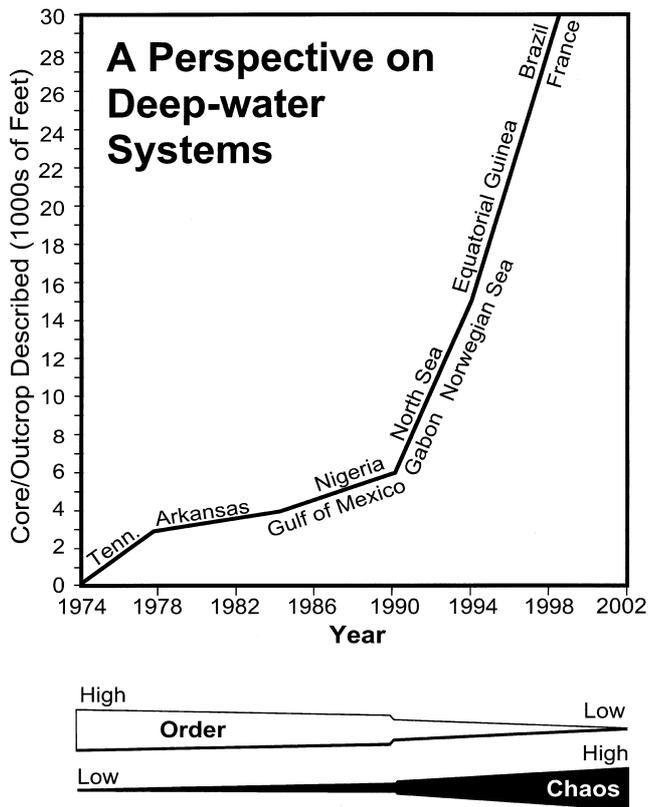


Fig. 30. Top: Graph showing the total thickness of intervals of deep-water core and outcrop that I have described since 1974, when I began my Ph.D. research at the University of Tennessee (Shanmugam, 1978). Bottom: Bars showing my changing perspectives of deep-water systems at a scale of depositional units with my increasing exposure to deep-water sequences, from one of order and simplicity in 1974 to one of chaos and complexity in 1998. Note that a major shift in my perspective occurred in 1990 when I began describing cores from the North Sea reservoirs, composed primarily of deep-water massive sands.

setting, reflecting natural order. Now, I realize that deep-water systems are extremely complex and variable, reflecting mostly chaos at the scale of depositional units (Fig. 30). A major shift in my perspective of deep-water systems occurred in 1990 when I began describing cores from the North Sea (Fig. 30). This shift was due to my exposure to some of the most complicated deep-water facies that occur in the form of ‘massive’ sands. Aspects of deep-water massive sands are addressed by Stow and Johansson (1999).

Our understanding of depositional processes and sand distribution in deep-water environments is still in its infancy. No single facies model can adequately represent all deep-water systems (Shanmugam, 1990; Mutti, 1992). Submarine fan studies are presently in a state of flux (Walker, 1992a). The days of interpreting complex deep-water sequences as channels and lobes using fan models are over. Sedimentologic and sequence-stratigraphic lineages of fan concepts dominated by lobes show that their popularity escalated in the 1970s and 1980s but declined

in the 1990s to a point of their abandonment (Fig. 31). The turbidite paradigm has come a full circle in the 1990s, completing a remarkable scientific journey set in motion in the 1950s. Consequently, we are not in any better state today in terms of deep-water facies models than we were 50 years ago.

However, we are in a better state today in terms of available marine geological data, core and outcrop studies, theoretical considerations, and flume experiments. We have learned that deep-water systems are quite complex in terms of sea-floor topography, depositional processes, geometries, and stacking patterns. We have also learned that no single facies model can possibly explain all variations in the complex deep-sea environments.

10.1. Slope models for the 21st century

Mass transport processes (slides, slumps, sand flows, and debris flows) have been observed in modern oceans (e.g., Shepard, 1951, 1979; Dill, 1964, 1966); however, convincing direct observations of turbidity currents in modern oceans are lacking. I find it ironic that there are numerous deep-water facies models for deposits of turbidity currents that we don’t observe, but there are no facies models for deposits of mass flows that we do observe. This is perhaps because of the simplicity of turbidity current concepts and submarine-fan models, and the historical association between turbidites and sheet geometries. It is true that basinal turbidites are sheet-like in geometry, however, these turbidite sands are commonly thin bedded, fine grained, and contain high amounts of mud. In contrast, slope sands of debris flow origin are thicker bedded, coarser grained, and contain lower amounts of mud in comparison to turbidites. The current trend in petroleum industry is to routinely apply submarine-fan models, developed for base-of slope settings with smooth sea floors, to intraslope settings with highly irregular sea floors, such as in the Gulf of Mexico (Holman & Robertson, 1994). However, we need to develop separate models for slopes emphasizing slope processes and products. The conventional wisdom that slopes are areas of ‘bypassing’ of sand is not valid in all cases. Slopes are important future target areas where major petroleum reservoirs are waiting to be found. Stow and Faugeres (1998) aptly noted, “. . . back to the slope is the way forward into the next century”.

Although Galloway’s (1998) recent paper emphasized the importance of ‘slope’ systems in petroleum exploration, the paper is misleading because it uses confusing terminology, abandoned concepts, and selective facies. Galloway (1998) uses the term ‘slope’ for base-of-slope systems, for the sake of brevity. This is misleading because slope systems and base-of-slope systems are quite different from one another in terms of: (1) sea-floor topographies (irregular vs smooth), (2) slope gradients (high vs low), (3) gravity tectonics (common vs rare), (4) ero-

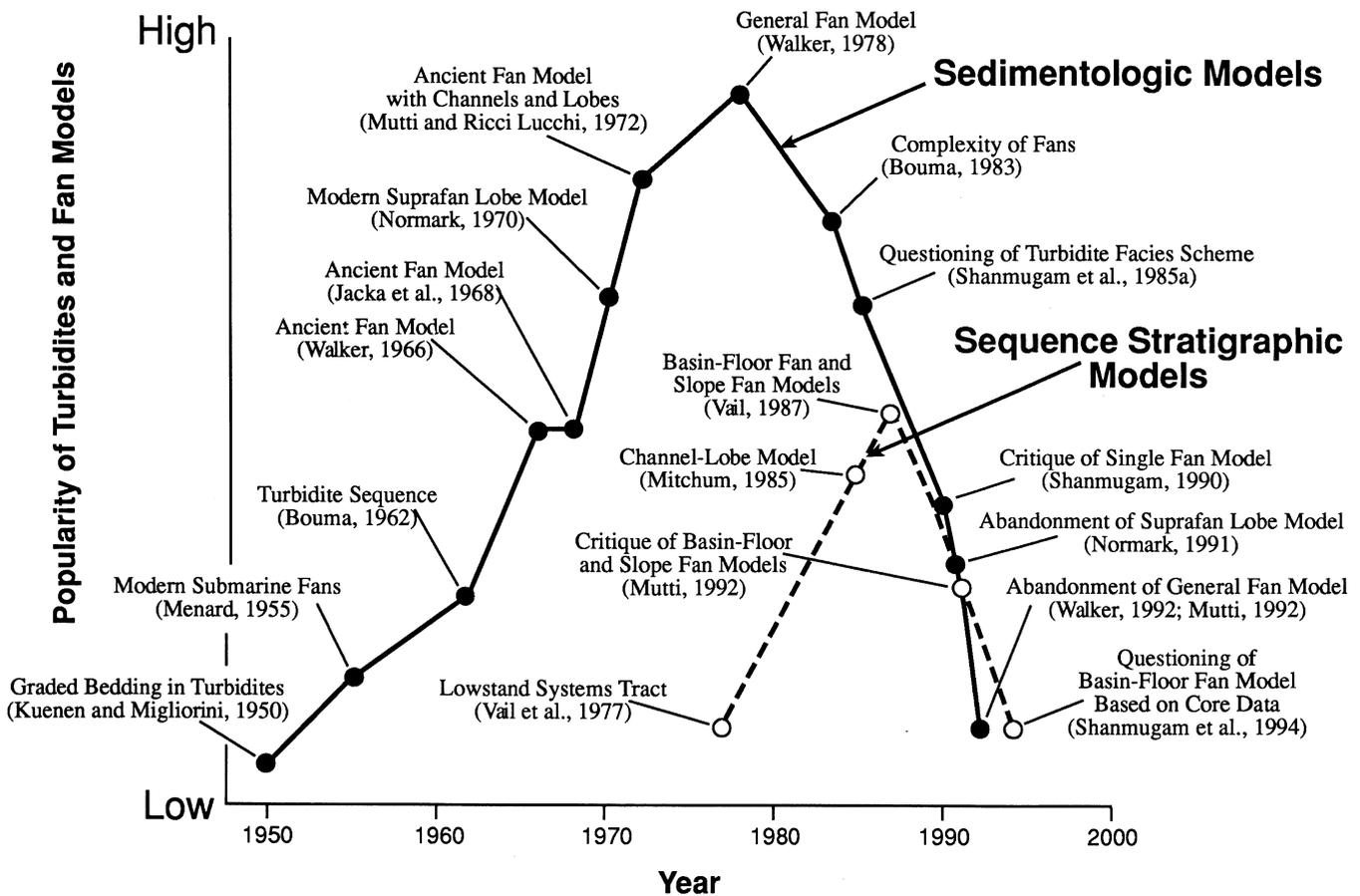


Fig. 31. Rise and fall of popularity of submarine-fan models in sedimentology and sequence stratigraphy during the past 50 years.

sional elements, such as canyons and gullies (common vs rare), (5) depositional processes (mass movements vs turbidity currents), and (6) openness of depositional sites (constrictive vs. open). Galloway (1998) states, “submarine fans are the best known slope depositional elements ...” and uses the Mississippi, Amazon, and Indus fans as examples of ‘slope’ fans. This is confusing because the bulk of major modern fans, such as the Mississippi, are clearly developed on the basin floor, not on the slope. Also, the classic submarine-fan models with channels and lobes (e.g., Mutti & Ricci Lucchi, 1972) are meant for base-of-slope systems (where channels can spread out to form lobes on the vast open sea floors), not for slope systems. Because of the casual usage of the terms ‘slope’ and ‘fans’, the geologic literature is saturated with ‘fans’ in the intraslope areas of the Gulf of Mexico (e.g., Weimer et al., 1994). The correct and precise usage of the terms ‘slope’ and ‘fans’ has major implications for establishing paleogeography and predicting reservoirs.

Galloway (1998) promotes the mounded, sand-rich, suprafan lobe concept. This is outdated information because the suprafan lobe concept, originally introduced by Normark (1970, 1978), has now been abandoned by Normark

(1991) himself. Galloway (1998, his fig. 3) claims that wire-line log motifs can be useful in interpreting depositional facies. This is misleading because different depositional facies can generate similar log motifs, and a single depositional facies can generate a multitude of log motifs (Shanmugam et al., 1994, 1995a, 1995b, 1996). Galloway (1998) equates turbidite channels with fluvial channels. This is misleading because turbidity currents and river currents are not one and the same (Table 1).

Galloway (1998, his fig. 7) discusses only the muddy types of slides, slumps, and debris flows in his seven types of slope facies. This is selective because there are sandy slides (Fig. 32), sandy slumps (Fig. 32), and sandy debris flows (Shanmugam et al., 1995a). Galloway (1998) discusses only the muddy types of contourites (i.e., sediment drifts) in his seven types of slope facies. This is selective because there are also sandy contourites (Stow & Lovell, 1979). Hydrocarbon-bearing sands of bottom current origin (i.e., sandy contourites) have been reported from the Plio-Pleistocene intraslope basins of Gulf of Mexico (Shanmugam et al., 1993a). From petroleum industry point of view, there is a need to understand the distribution of sand in intraslope basins.



Fig. 32. Sheet-like geometry of ancient sandy submarine slides. Ablation Point Formation, Kimmeridgian Alexander Island, Antarctica. Note the large sandstone sheet with rotated/slumped edge (left). Person (arrow) 1.8 m tall. From Macdonald et al. (1993).

By definition, continental slopes represent the steep sea-floor areas between shelf-slope break (about 200 m water depth) and slope-basin break (Fig. 1). Although most continental slopes have gradients of 3–6° slope, with an average slope of 4° (Heezen, Tharp & Ewing, 1959), actual slopes are much smaller (0.5–2°). In general (see Pratson & Haxby, 1996), slopes of active margins are relatively steeper than those of passive margins. Some slopes undergo extensive gravity tectonic deformation, which leads to development of diapirs and intraslope basins with erosional features, such as canyons and gullies (e.g., northern Gulf of Mexico, Niger Delta). Deposition of thick sand bodies can occur in intraslope basins.

Future models should take into account the great wealth of information available on modern and ancient slope processes and products, such as, ancient sandy slides (Fig. 32), muddy slides, slumps and debris flows. Debris flows can travel hundreds of kilometers on gentle gradients (Masson, van Niel & Weaver, 1998). On glaciated continental margins, debris flows tend to develop finger-like patterns (Elverhoi et al., 1997). These details are seldom included in popular deep-water models.

Ancient sandy slides in Antarctica exhibit sheet-like geometries and can have abrupt terminations (Fig. 32).

Thick sandy slides that are encased in deep-water mud are likely to produce blocky wireline log motifs. Slide sand bodies in Antarctica that are 1000 m long and 50 m thick may be recognized in seismic data. Such sands are likely candidates for developing stratigraphic traps because of their isolated occurrence in deep-water mud. Ancient sandy slumps have been correlated throughout a distance of 18 km in Spain (Mutti, 1992). Thus, slides, slumps, and debris flows are capable of traveling long distances, comprising sandy lithofacies, and forming sheet-like geometries, and should be included in standard models for petroleum exploration.

As a counterpart to turbidite dominated fan models suited for base-of-slope settings, I offer an alternative model that is representative of debris-flow dominated systems suited for some slope, and possibly for some base-of-slope settings (Fig. 33). Unlike submarine fans with organized turbidite packages in channels and lobes (Mutti & Ricci Lucchi, 1972), the proposed slope model advocates a complexity of deposits of debris flows and other processes (Fig. 33). Debris-flow dominated systems can be broadly classified into (1) non-channelized and (2) channelized types (Fig. 33). Most deep-water reservoirs in the North Sea (Shanmugam et al., 1995a), Norwegian

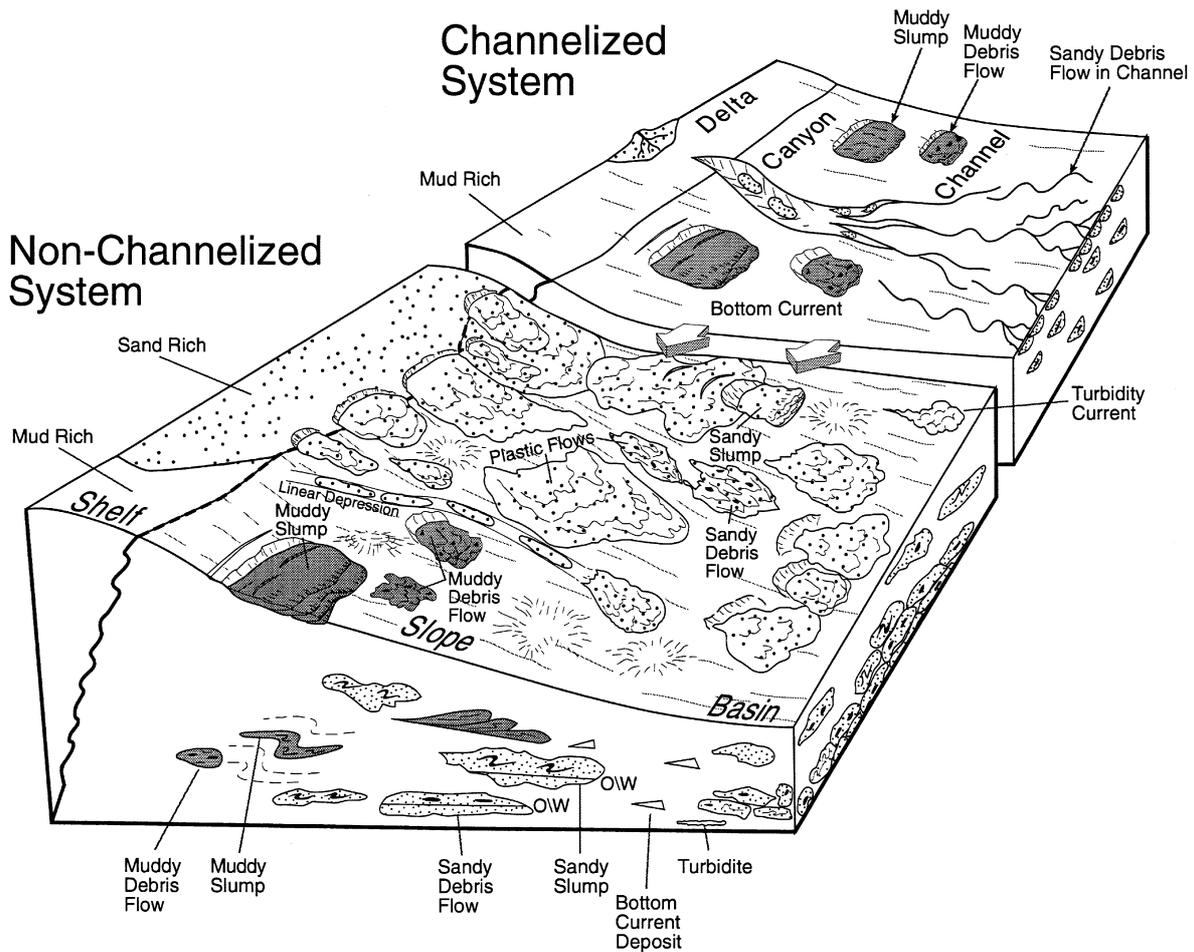


Fig. 33. Proposed depositional model for non-channelized and channelized debris-flow dominated systems, which are common in slope and base-of-slope settings. In non-channelized systems, sandy debris flows are expected to occur downdip from sand-rich shelf (modified after Shanmugam, 1997a). In channelized systems, sandy debris flows are expected to occur mainly within channels and at their terminus. Although debris flows may generate lobate sand bodies, they are not analogous to typical depositional lobes formed by classical turbidity currents in submarine fans (e.g., Mutti & Ricci Lucchi, 1972). Different oil-water contacts (O/W) may be encountered in debris-flow reservoirs because of their lateral discontinuity. However, there are cases where debris-flow reservoirs are sheet-like with good vertical and lateral connectivity caused by amalgamation of sand units.

Sea (Shanmugam et al., 1994), Gulf of Mexico (Shanmugam & Zimbrick, 1996), and offshore Equatorial Guinea (Shanmugam et al., 1997b) are considered to be non-channelized type. Channelized type includes certain intervals in the Edop Field in offshore Nigeria (Shanmugam et al., 1995b), and the modern Mississippi Fan. In this slump and debris-flow dominated slope model, nature of shelf (sand rich vs mud rich), sea-floor topography (smooth vs irregular) and depositional process (settling vs freezing) tend to control sand distribution and geometry. Contrary to popular belief, sandy debris flows can be thick, areally extensive, and excellent reservoirs (Shanmugam & Zimbrick, 1996). High frequency flows tend to develop amalgamated debris-flow deposits with lateral connectivity and sheet-like geometry.

According to the model (Fig. 33), amalgamated sandy debris flows may be predicted to occur downdip from a sand-rich shelf. Experimental studies of subaqueous

debris flows have shown that hydroplaning can dramatically reduce the bed drag, and thus increase head velocity (Mohrig et al., 1998). This would explain why subaqueous debris flows can travel faster and farther on gentle slopes than subaerial debris flows.

Although deposits of sandy debris flows are complex, they are capable of developing sheet-like geometries in the rock record (Fig. 34). The notion that all deposits of debris flows are discontinuous is ill founded because amalgamated deposits of debris flows can develop laterally connected sand bodies (Fig. 34). In some ways, deposits of both turbidity currents and sandy debris flows are alike; and in many ways, they are different from one another.

The conventional notion that debris-flow reservoirs do not have good reservoir properties is not true because the lower Eocene sands of the Frigg Formation (Frigg Field, Norwegian North Sea), which are interpreted to be of

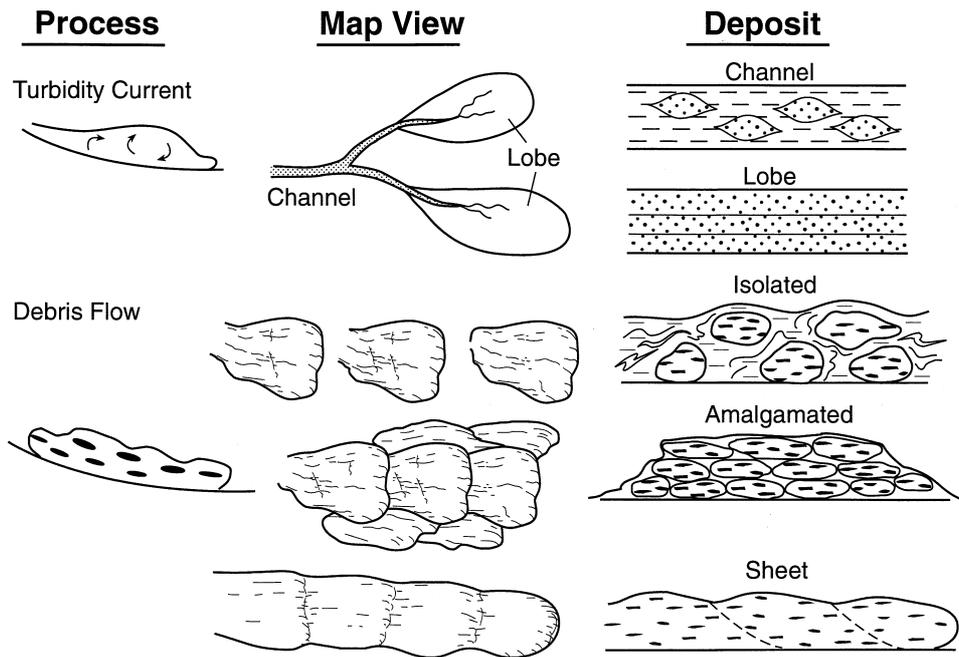


Fig. 34. Comparison of deposits of sandy turbidity currents and sandy debris flows. Turbidity currents are shown to develop a submarine fan with channels and lobes. Debris flows are shown to develop isolated flows, amalgamated flows, and tongue or sheet flows in a non-channelized system; debris flow in a channelized system is not shown. Processes and deposits are shown as cross sectional views. Note that debris flows are capable of forming sheet sands.

slump and debris flow origin, exhibit extremely high porosities (27–32%) and permeabilities (900–4000 mD) (see Shanmugam et al., 1995a). Also, experiments have shown that sandy debris flows can deposit sands with only a minute amount of clay (less than 1% by weight). Although deposits of debris flows are chaotic at core scale, they can organize themselves into an orderly, therefore predictable, stacking pattern (Famakinwa & Shanmugam, 1998). In short, the proposed debris-flow dominated slope model is in some respects better than the turbidite fan model.

11. A critical perspective

During the past 50 years, our misplaced affinity to the turbidity current concept has grown phenomenally because of its simplicity and predictability. Consequently, we have deviated from using the single precise definition of turbidity currents into using a multitude of definitions that allow us to classify any deep-water sand as some kind of turbidite. As a result of the prevailing turbidite mind set, we have manufactured a plethora of ‘turbidites’: (1) fluxoturbidites, (2) megaturbidites, (3) seismoturbidites, (4) atypical turbidites, (5) problematica turbidites, (6) high-density turbidites, (7) unusual turbidites, (8) ungraded turbidites, (9) inversely graded turbidites, and (10) base-missing turbidites. None of these ‘turbidites’ are the deposits of true turbidity currents; they are deposits of avalanches, slumps, debris flows, and

bottom currents. By this critique, I do not suggest that there are no turbidites. However, I do advocate that our interpretation of rocks must always be based on observational evidence, not on mind set and models.

What is troubling, is that the definition of the term ‘turbidity current’ has been changed almost 180° over the years. In the 1950s and 1960s, turbidity currents were considered to be flows with turbulent state, waning velocity, and Newtonian rheology, but in the 1980s and 1990s, turbidity currents are considered to be flows with laminar state, waxing velocity, and plastic rheology. A consequence of this reversal of definitions is that it allows us to interpret deposits of debris flows as ‘turbidites’. In light of the emerging new data from my studies that revealed the dominance of debris-flow facies and the obsolescence of turbidite facies in many parts of the world, it is understandable as to why it is necessary to redefine turbidity currents that includes debris flows. Only through such a redefinition of ‘turbidity currents’, we could keep the turbidite paradigm alive in the 21st century.

Equally troubling, is the use of the term ‘turbidite fan’ loosely for any deep-water sand (Weimer et al., 1994). This addictive practice, which is prevalent in both petroleum industry and academia, must stop. My critique of the loose usage of the terms ‘turbidites’ and ‘fans’ is not just a quibble over semantics; the precise meaning of these terms has serious implications for fluid dynamics, sandbody geometry, reservoir predictability, and economics in petroleum industry.

In the 21st century, when all is said and done, data will dictate that a majority of 'sandy turbidite fans' exists only in facies models and in our minds, not in the rock record. Perhaps, it is time to refocus our attention to describing and interpreting rocks without the distraction of facies models. In concluding this rather long and reflective article, I am optimistic that in the 21st century, a new paradigm for deep-water systems will emerge that will be more inclusive in terms of slope processes and products than just basinal turbidity currents and fan models.

Acknowledgements

I dedicate this paper to all those deep-water rocks that quietly challenged and influenced my thinking during the past 25 years. I thank Dorrik Stow for inviting me to present this paper as a keynote talk at *Geoscience 1998* Symposium entitled 'Deep-Water Sedimentary Systems: Reservoirs and Source Rocks' held at Keele University, England, in April 1998. I also thank journal reviewers J. E. Damuth and an anonymous reviewer for their critical review and exhaustive comments, and journal editor Prof. D. G. Roberts for his helpful suggestions. I thank R. J. Moiola, D. W. Kirkland, S. H. Gabay, and N. Houghton for reviewing the manuscript, Mark Lindsey for drafting, J. E. Krueger for managerial support, and Mobil Technology Company for granting permission to publish this paper. I wish to thank Mobil and Office of Naval Research for funding experimental studies of sandy debris flows that were carried out at St. Anthony Falls Laboratory of the University of Minnesota in Minneapolis during 1996–1998, and Jeff Marr, Peter Harff, and Gary Parker for providing me with data from sandy debris flow experiments and for their valuable discussion. I thank Jean Shanmugam for editorial comments, and Pam Luttrell (VP-NEPV) for absorbing the cost of reprints.

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