2.9 Fine-Grained Turbidites

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1 Introduction

Fine-grained sediments (terrigenous and bioclastic) of turbidite origin are the most abundant type of deep-water sediment. They form thick sequences on prodelta slopes, deep sea fans, continental rises and abyssal plains. In the ancient geologic record, such sediments are a major component of accretionary wedges and the metamorphic belts of ancient orogens.

When the concept of turbidity currents was first developed, it was thought that mud beds could not be deposited from such currents, unless the mud was transported as aggregates or fecal pellets (Dzulynski et al. 1959). In the late 1960's, the importance of contour-following bottom currents in the modern oceans was recognised and many lithologies now interpreted as fine-grained turbidites were for a time regarded as "contourites" (Bouma and Hollister 1973). Criteria for the recognition of contourites, however, remain a disputed issue (Stow 1979). By the 1970's marine geologists recognised thick mud beds that clearly had a shallower-water source (Rupke and Stanley 1974) and graded fine carbonate beds deposited below the carbonate compensation depth were recognised as of turbidite origin, both in the sea and in ancient rocks (Hesse 1975). Beds with silt laminae, with an upward decrease in lamina thickness and grain size, were recognised as characteristic of mud turbidites (Piper 1972). By the late 1970's, there was widespread appreciation of the volumetric importance of fine-grained turbidites, and distinctive bed sequences were recognised as characteristic of fine-grained turbidites (Piper 1978; Stow and Shanmugam 1980; Stow and Piper 1984a). Fine-grained turbidites were recognised as having a distinctive microstructure (O'Brien et al. 1980). In the last decade, there has been new emphasis on the depositional processes and vertical cycles in fine-grained turbidites.

Because shales are generally extensively weathered in outcrop, most data on fine-grained turbidites is from piston cores of Holocene and late Pleistocene sediments and from DSDP/ODP holes (particularly on the Mississippi and Bengal fans); and to a lesser extent commercial hydrocarbon wells. The best data from ancient rocks is from well-lithified or low grade metamorphic rocks in which mudstones are not preferentially weathered.

This chapter is built on our 1984 paper (Stow and Piper 1984a), in which we provide a more complete bibliography of fine-grained turbidites. In this new review, we deal more fully with the depositional processes, significance of various facies

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types, and the development of larger-scale cyclicity. Fine-grained turbidites include a wide range of lithologies, just as coarse-grained turbidites are lithologically diverse. For this reason, simple models (such as we present in this review) may be misleading.

2 Deposits of Single Events

2.1 *Silt Turbidites*

In distal turbidite environments, silt beds (>70% silt-sized particles) are more abundant than sands and commonly occur as thin or medium-bedded turbidites. There is generally a progressive decrease in grain size of sand and silt beds distally in a turbidite system. Silt beds commonly exhibit the same suite of structures as classical sandy turbidites (Fig. 1a). Base-cut-out structural sequences are common (Fig. 2), so that in distal environments, medium and fine-grained silts with fine lamination and common internal load casting may predominate (Piper and Brisco 1975). Thick ungraded massive silts are found less commonly: they appear to be the fine-grained equivalents of AE sand turbidites.

2.2 *Mud Turbidites*

A mud turbidite may occur overlying a sand or silt bed deposited from the same turbidity current (Fig. 3a), or may occur independantly (Fig. 3d). Overlying any sand or silt bed are three divisions (Piper 1978): mud with silt laminae (which become thinner, finer and less frequent upwards), graded mud and ungraded mud. The latter is generally bioturbated with hemipelagic sediment. Grading is recognised both from grain size and petrography. Colour changes commonly mirror the grain size and textural changes. The interval of mud with silt laminae may show a distinctive hierarchy of structures in the silt (Fig. 1b), systematised by Stow and Shanmugam (1980). The complete set of structures illustrated in Fig. 1b is rarely present in a single bed: both base-cut-out and top-cut-out beds are common (Fig. 2) (e.g. van Weering and van Iperen 1984; Lash 1988). This may lead, for example, to the accumulation of sequences with thin parallel silt laminated mud (Fig. 4d), in which individual turbidite units cannot be readily distinguished: good examples are described by Stow et al. (1982, 1984a) and Walker (1985).

Medium and thick bedded mud turbidites up to many metres thick have been described (Rupke and Stanley 1974; Blanpied and Stanley 1981) in which most of the mud is structureless and not graded (Fig. 1c). Such beds are common in ponded basins, where they probably were deposited from flows with high concentrations of mud resulting from flow expansion and decrease in gradient (McCave and Jones 1988). Flow expansion and gradient reduction are probably more important than ponding, since thick bedded mud turbidites (0.3 to 2 m thick) also occur in situations where ponding is unlikely, such as the distal Bengal Fan (ODP site 717: Stow et al. 1989) (Fig. 3a). The Mississippi mid-fan channel is filled with up to 150 m of

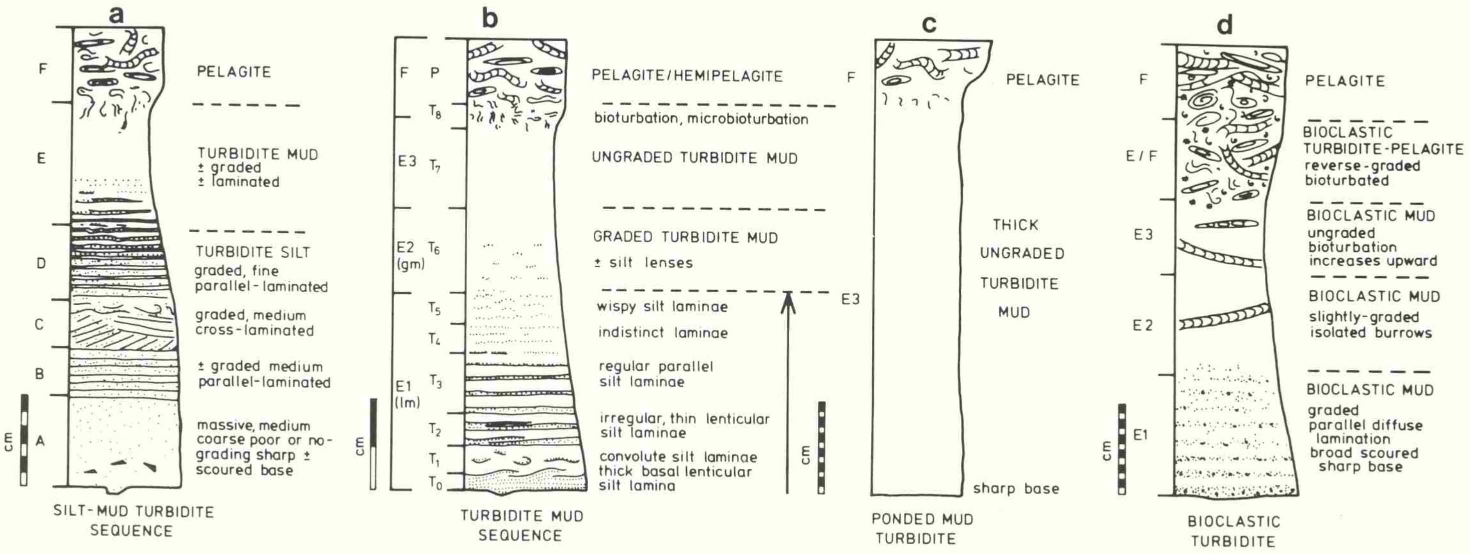


Fig. 1. Idealised vertical sequences for individual turbidite beds showing nomenclature of Stow and Piper (1984a) and Einsele (Chap. 2.7, this Vol.). **a** Silt turbidite (with Bouma *A-E* divisions). **b** Mud turbidite (with Piper *E1-E3*, Stow T_0-T_8 and Einsele *m-gm* divisions). **c** Massive and turbidite (with Piper *E3* division). **d** Bioclastic turbidite (with Stow and Piper *E1-F* divisions)

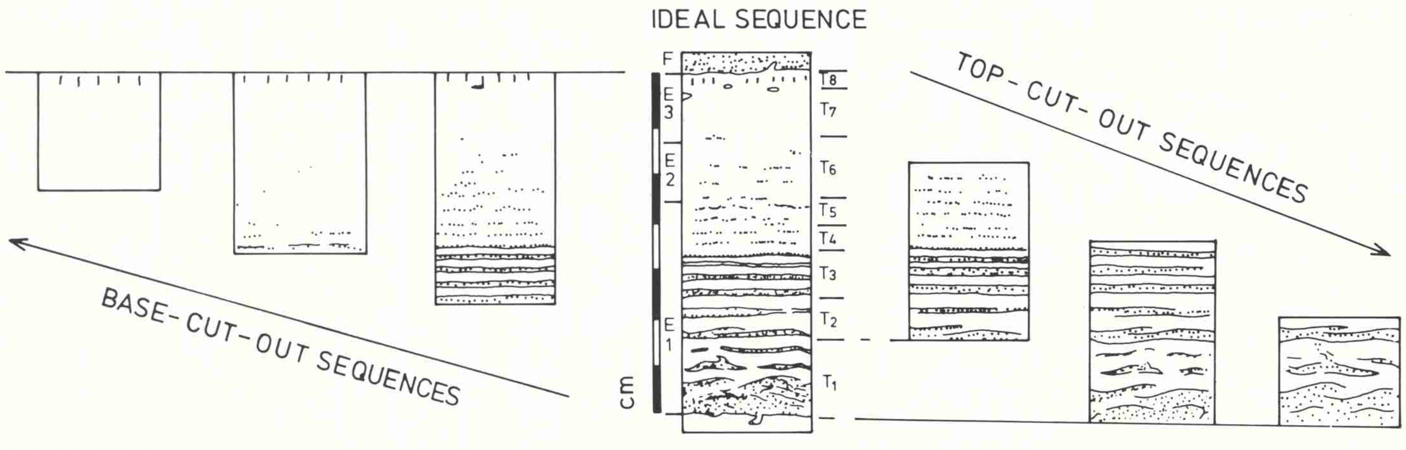


Fig. 2. Modifications to idealised mud turbidite sequence through base- and top-cut-out

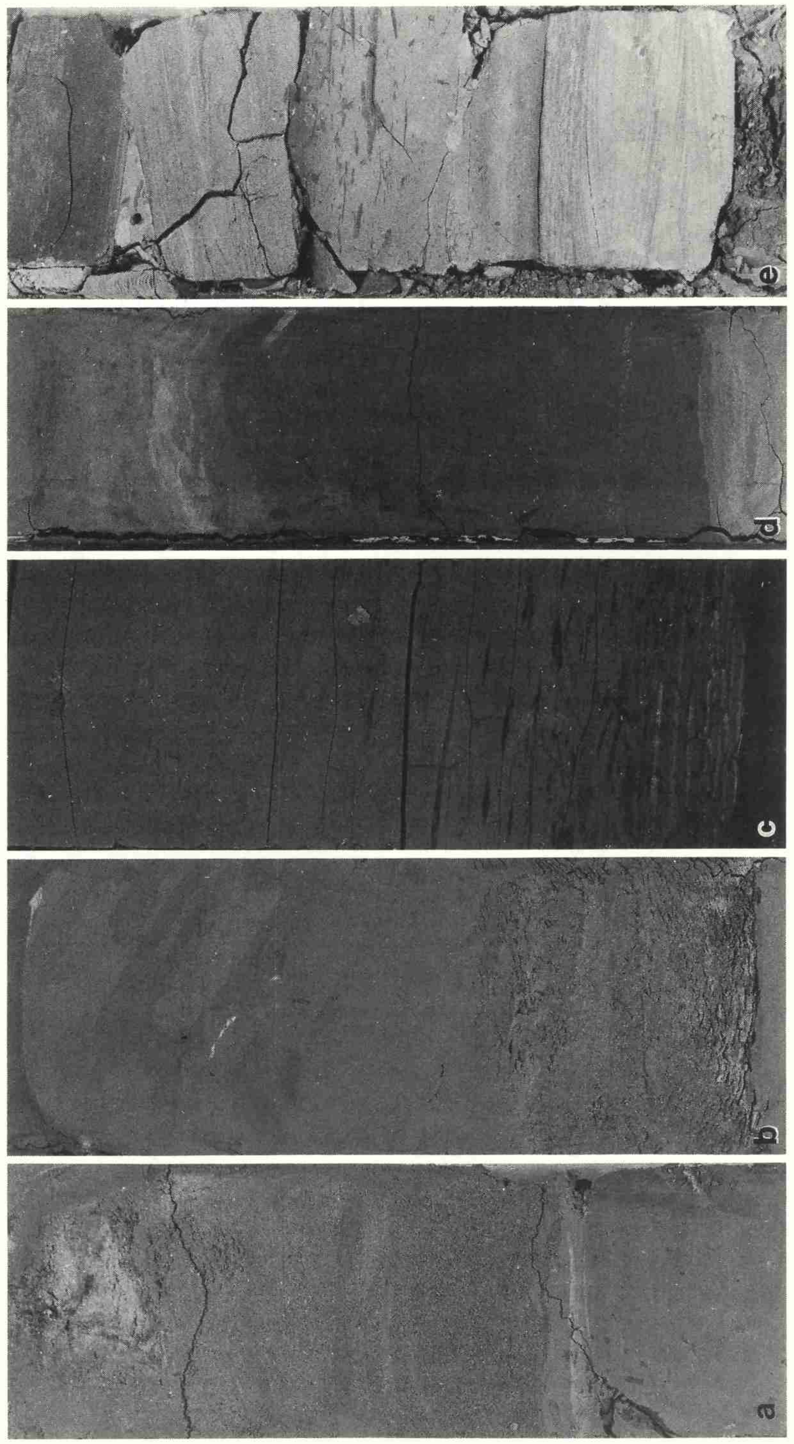
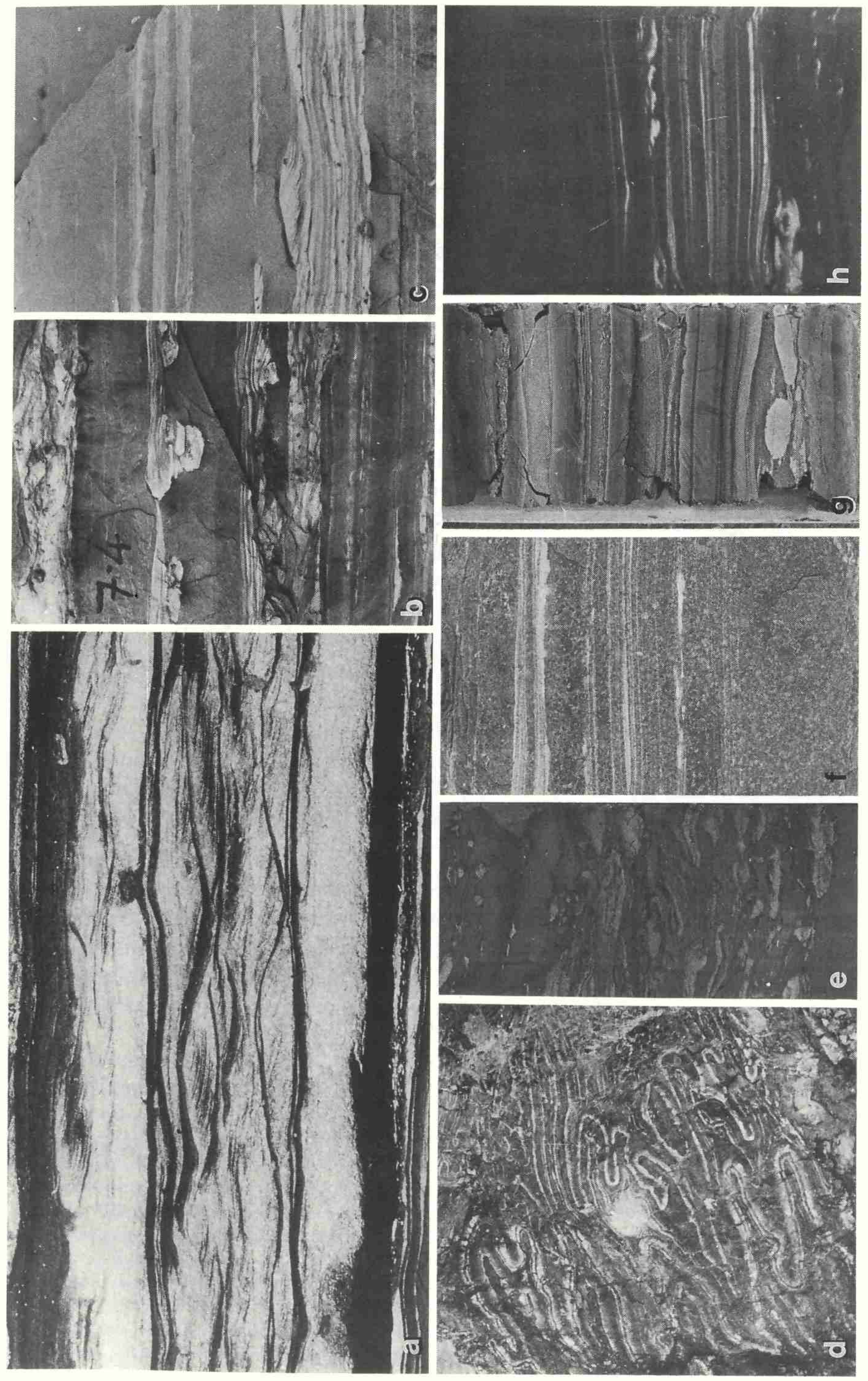


Fig. 3. Photographs of representative fine-grained turbidites. **a** Basal part of 2 m-thick graded silt to mud turbidite (Bengal Fan). **b** Graded, muddy-silt to mud turbidite (15 cm thick) (Bengal Fan). **c** Organic-carbon-rich silt-laminated mud turbidite (Angola Basin) -- upper part bioturbated. **d** Graded mud turbidite (10 cm thick) (Bengal Fan). **e** Two carbonate silt-mud bioclastic turbidites, each approximately 10 cm thick (Bengal Fan) *Scale:* core sections are all approximately 7 cm wide



completely structureless and ungraded muds, in which it is difficult to distinguish individual beds, that may have been deposited from high concentration currents developed from muddy debris flows (Stow et al. 1986).

Some thin and medium bedded mud turbidites contain abundant millimetre-sized mudstone clasts, are poorly graded, and lack a well-developed basal division of mud with silt laminae (see Aksu 1984). Such beds appear to have been deposited from muddy turbidity currents derived from debris flows. With further deposition or disaggregation of muddy clasts, such flows deposit the disorganised silty mud turbidites which we have interpreted as the deposits of "immature" turbidity currents (Stow and Piper 1984a).

2.3 Bioclastic Turbidites

Fine-grained bioclastic turbidites consist principally of either fine-grained carbonate (principally "micrite") or of siliceous organisms. They show a sequence of structures (Fig. 1d) similar to that in terrigenous turbidites, except that (1) the graded laminated division contains less distinct silt laminae than in terrigenous turbidites and (2) the transition to hemipelagic or pelagic ooze may be much more gradual and commonly involves an increase in mean grain size. Because individual bioclastic species may consist of individuals of similar size and shape, hydraulic sorting may concentrate particular species at a certain level in a bed (Einsele and Kelts 1982).

3 Criteria for Recognition of Mud Turbidites

The following criteria can be used to identify rocks as fine-grained turbidites. These are shown in photographs of various mud turbidites (Figs. 3 and 4) and schematically in Fig. 5.

1. Distinctive petrography may be diagnostic, particularly in Cenozoic sediments. Many fine-grained turbidites contrast with interbedded hemipelagic sediments in having few pelagic microfossils, different terrigenous components (e.g. clay minerals), different carbonate content (dependant on the position of the carbonate compensation depth), and different organic carbon content (generally higher). Such differences arise from both the source and the high rate of sedimentation, and are therefore difficult to mimic with contour current deposits.

Fig. 4. Photographs showing detailed characteristics of fine-grained turbidites. **a** Lenticular, ripple-laminated silty turbidites – note loads and flame-structures (Cretaceous, California). Width 15 cm. **b** Intense loading of silt laminae into mud turbidites (Cambro-Ordovician, Nova Scotia). Width 10 cm. **c** Parallel lamination, small-scale cross-lamination and fading ripples in fine-grained turbidites (Cambro-Ordovician, Nova Scotia) Width 12 cm. **d** Intense soft-sediment (slump) folding of "zebra-stripe" turbidites (Cretaceous, California), Width 150 cm. **e** Chaotic/lenticular silt-mud turbidite deposited on levee immediately adjacent to channel (Pleistocene, Mid-Mississippi Fan). Width 7 cm. **f** Very fine silt lamination in mud turbidites, with micro-loads and flames, and low-amplitude long-wave length cross lamination (Cambro- Ordovician, Nova Scotia). Width 5 cm. **g** Thin-bedded calciturbidites displaying range of typical features (Paleogene, Angola Basin). Width 7 cm. **h** Graded, silt-laminated mud turbidite showing basal and internal loading and low-amplitude rippling (Pleistocene, Mississippi Fan). Width 7 cm

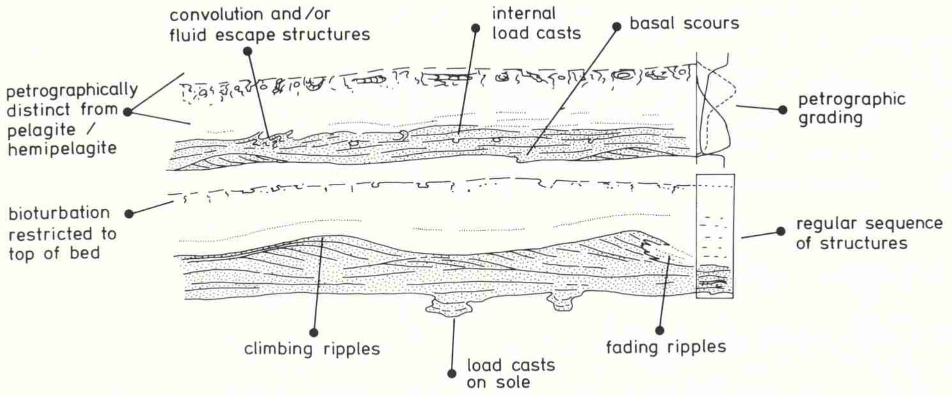


Fig. 5. Diagnostic criteria for the recognition of fine-grained turbidites

2. Sedimentary structures indicative of rapid deposition from suspension are characteristic of turbidites generally. In fine-grained turbidites, fading ripples (particularly if they are climbing) are particularly diagnostic (Fig. 4c). Sediment instability and fluid escape structures accompany rapid deposition from suspension (Fig. 4d,f). Escape burrows are rarely found, but are very characteristic if present. The restriction of bioturbation to the top of a bed generally indicates rapid deposition in normal marine sequences (Fig. 3c).
3. Regular grading, producing regular sequences of structures (Stow and Shanmugam 1980), becomes an increasingly diagnostic characteristic of fine-grained turbidites as the organisation and complexity of the grading increases.
4. Very thick massive mud beds of uniform petrography, lacking bioturbation and with a mud turbidite petrography are characteristic of fine-grained turbidites deposited as a result of rapid flow expansion. Similar beds may also be deposited from high concentration flows derived from debris flows, but the latter may also contain mud clasts.

We have found paleocurrent measurements to be useful only in particularly cases in distinguishing fine-grained turbidites from contour current deposits. The variability in flow directions both in individual turbidity current and in "abyssal storms" associated with bottom currents makes the interpretation of paleocurrent data difficult.

In the modern ocean, mud turbidites can be readily distinguished from hemipelagic sediments by petrographic criteria such as their paucity of pelagic microfossils: in pre-Mesozic rocks, such fossil criteria are more difficult to apply and only sedimentological criteria can be applied to recognise fine-grained turbidites.

There are several features which have at times been claimed to be evidence that beds are *not* of turbidite origin. However, since these features commonly occur in beds that are demonstrably of turbidite origin, they are not of diagnostic value. They include:

1. concentrations of microfossils or heavy minerals in silts;
2. starved ripples and silt lenses; and internal erosion above a rippled silt (such features may pass laterally into climbing fading ripples: Stow et al. 1984a);
3. a lack of grading in thick mud beds, or in thick well-laminated silt beds.

4 Turbidite Cycles

4.1 *Recognition and Controls*

Cyclicity in turbidite successions has been widely recognised and commonly used to infer depositional environments for ancient examples. Earlier work focussed on thinning-upward sequences (channel filling) and thickening-upward sequences (lobe progradation) (Walker and Mutti 1973). More recent work has recognised a greater variety of types and scales of cycles, although the relative importance of allocyclic and autocyclic controls is in many cases unclear (Mutti 1977; Ricci Lucchi 1977). Hiscott (1981) has questioned the validity of "observed" cycles that are not shown to be statistically significant.

Although cyclicity involves both coarser and finer grained turbidites, we use examples from more mud-rich systems. Entirely mud-dominated successions have rarely been subjected to careful sequence analysis. We arbitarily divide cycles on the basis of their thickness into mega- (>100 m thick), meso- (10–150 m) and micro-cycles (<15 m). Some general examples of turbidite cycles are shown in Fig. 6.

4.2 *Megacycles*

Turbidite cycles commonly change over a few hundreds of metres of vertical section from dominantly coarse-grained to fine-grained or non-turbidite and vice versa. Although this may be at the scale of a single basin-fill episode, repetition of such sequences is observable on seismic reflection profiles of larger turbidite systems (Manley and Flood 1988; Bouma et al. 1986).

Large-scale cyclicity of this type has been generally explained as allocyclic, resulting from sea-level fluctuations (Shanmugam and Moiola 1982) or variation in tectonic activity in the source area (Klein 1985). Possible autocyclic controls include distributary switching (Manley and Flood 1988) and progradation (Lash 1988).

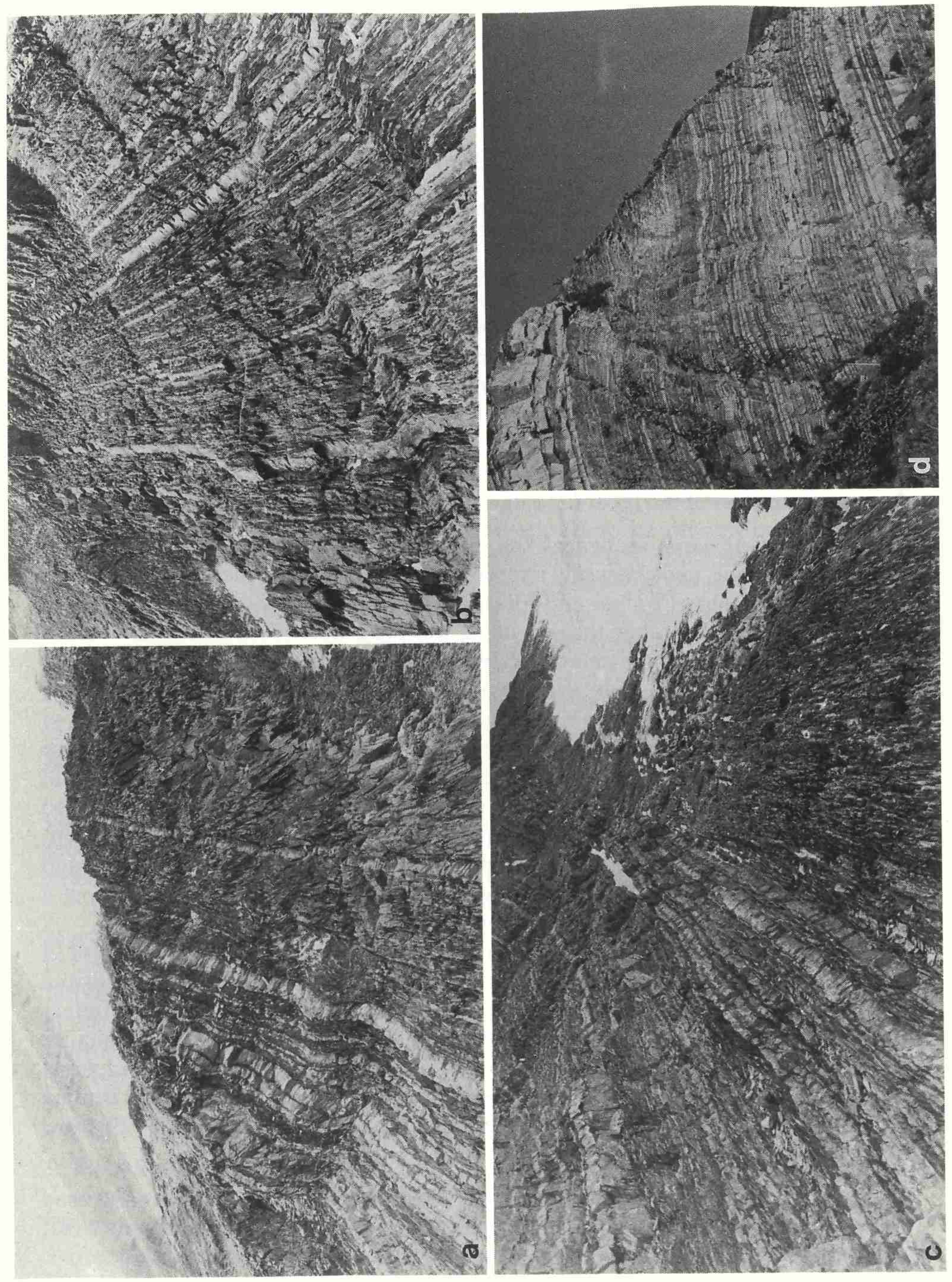


Fig. 6. Characteristic vertical sequences of fine and medium-grained turbidites. **a-c** Halifax Formation, Nova Scotia. **d** Mugu Point, California. **a** Coarsening-upwards mesocycle, with more irregular microcycles near top of section (*left*). **b** No distinct cycles evident within dominantly fine-grained section. **c** Probable symmetric cycle coarsening-up to mid photo then fines upward (to *mid upper left*). **d** Fining-upwards mesocycle (*bottom to top*), composed of coarsening-upwards and symmetric microcycles, and capped by block-like packet of thicker-bedded sandstones. *Scale*: all photos show sections of approximated 20 m stratigraphic thickness

4.3 Mesocycles

It is at the scale of good outcrops and within typical cored sections that most debate has centred on the recognition and interpretation of turbidite cycles.

1. Fining-upwards sequences (or thinning-upwards) are most common in ancient coarse turbidite sequences, where they have been interpreted as channel-fill deposits (Mutti and Ricci Lucchi 1975; Stow 1984b), perhaps involving channel migration (Walker 1985). Tectonic control has also been proposed (Stow et al. 1982). Similar sequences are less common in fine-grained sediments (Fig. 6d).

Few modern channel systems have been drilled. DSDP Sites 621 and 622 were cored to about 200 m within a prominent channel on the Mississippi mid fan and recovered predominantly mud. Both showed ill-defined fining-upward sequences, being more silty towards the base (bottoming in gravel at site 621). However, much of the sequence was structureless and unbedded (Pickering et al. 1986). DSDP Site 530 was drilled through a small, mud-dominated fan in the SE Atlantic Ocean. A weak fining-upward trend over the top 80–120 m has been interpreted as resulting from progradation of the inner fan rather than channel fill (Stow 1984b).

2. Coarsening-upwards sequences (or thickening-upwards) are also common in ancient successions and classically interpreted as representing basinward progradation of mid-fan lobes (Walker and Mutti 1973; Mutti and Ricci Lucchi 1975). The facies are typically finer than those in fining-upward sequences and many have been described from mud-dominated turbidite successions (Shanmugam 1980) (Fig. 6a). On the mud-dominated Late Precambrian Kongsfjord fan in northern Norway, Pickering (1981) interpreted coarsening-upwards meso-sequences as the result of catastrophic lobe switching, due to either fan channel avulsion or some source control. Two scales of coarsening-upward meso-sequences described by MacDonald (1986) from a Mesozoic back-arc basin on South Georgia are interpreted as due to autocyclic lobe switching (the thinner sequences) and allocyclic variation in sediment supply from the arc. MacDonald also argued that the lateral shifting of channels and lobes during aggradation is probably equally as common as progradation as a mechanism for producing coarsening-upward (and fining-upward) sequences.

There are few modern examples of mesocycles from fan lobes. DSDP Sites 614 and 615 were drilled up to 520 m through the channel terminal lobe of the Mississippi Fan. Fine sand, silt and mud turbidites were arranged in coarsening-upward, fining-upward, symmetrical and irregular units typically a few tens of metres thick. A similar range of sequence and non-sequence types was observed on mud-dominated channel levees and overbank sites on the Mississippi Fan (Sites 617, 620, 622 and 623: Bouma et al. 1986) and on the distal lobe of the Bengal Fan (ODP Sites 717, 718, 719; Stow et al. 1989).

3. Symmetric packets and bundles. Drilling of modern turbidite sequences (discussed in two preceding Sects.) and statistical analysis of ancient sequences (Hiscott 1981; Walker 1985) has shown that mesoscale cyclicity most commonly involves an approximately symmetrical arrangement of increasing or decreasing bed thickness and grain size. Symmetric packets that show gradational increase and then decrease in coarser-grained, thicker-bedded turbidites are particularly common in mud dominated successions (Fig. 6c): they occur in a variety of environments and have been interpreted as resulting from both allocyclic and autocyclic processes (Hiscott 1981; Martini et al. 1978).

Blocky packets of coarse-grained thick-bedded turbidites, showing relatively abrupt transitions with the encasing mudstones, are also widely recognised in ancient sequences both in outcrop (Fig. 6d) and from well logs. These have been generally interpreted as channel fill deposits (Surlyk 1987).

4. Random non-cyclic successions. Most turbidite workers would agree that a large proportion of both modern and ancient turbidite successions cannot be assigned to any form of regular cyclicity, symmetric or asymmetric (Nilsen 1980; Melvin 1986) (Fig. 6b). Hiscott (1981) has proposed that many reported cyclical sequences, identified solely on visual criteria, could be explained by chance occurrences within unordered sequences of turbidite beds. Such non-cyclic deposition may be most common in more distal turbidite environments.

4.4 Microcycles

The patterns recognised in mesocycles also appear to be present in microcycles, although grain size is not always closely linked with layer thickness. Mutti (1977) related microcycles (inferred to be autocyclic) from thin-bedded facies in the Eocene Hecho Group in Spain to depositional environments. Thickening-upward and symmetric cycles represent lobe-fringe and fan-fringe areas; bundles of thin-bedded sandy turbidites separated by mudstone units occur in interchannel areas; non-cyclic arrangements of irregularly bedded sandy turbidites were deposited at channel mouths and margins. More regularly bedded but equally non-cyclic sequences characterised the basin plain.

Lash (1988) ascribed fining-upwards microsequences (1–9 m thick) in the Ordovician Martinsburg Formation of the Appalachians to allocyclic controls. His sections also show the presence of symmetrical and a few coarsening-upward cycles, with much of the sequence appearing non-cyclic.

Mutti and Sonnino (1981) describe repeated thickening upward microcycles no more than a few beds thick. They term these compensation cycles and ascribe them to the influence of the slight positive relief of the previous turbidite on the next turbidity current. Other authors have shown more variability in turbidite deposition at this scale in both ancient rocks (Shanmugam 1980; Stow et al. 1984a; Melvin 1986; Kasper et al. 1987) and modern turbidites drilled by ODP (Stow et al. 1986; Stow et al. 1989).

5 Turbidity Current Processes

5.1 Principal Processes Acting in the Deep Sea

There may be a continuum of processes acting on fine-grained sediments in the deep sea (Walker 1978; Stow and Piper 1984a). These include settling of particles through the water column, normal bottom currents and mass gravity resedimentation processes (both debris flows and turbidity currents). The boundaries between these processes are not always clear-cut: for example, settling of silt particles from a deltaic plume may lead to an ignitive turbidity current; a debris flow may evolve into a turbidity current; and the low-density top or tail of a turbidity current may be deflected by contour-following bottom currents. Nevertheless, except adjacent to major sediment sources such as deltas or temperate ice margins, turbidity currents and debris flows are the principal means of depositing large amounts of fine-grained sediment in the deep sea. The deposits of bottom currents and distal pelagic settling tend to accumulate slowly and are thus well bioturbated.

5.2 Dynamics of Mud Transportation and Deposition

The physical processes involved in the erosion, transport and deposition of fine-grained, cohesive marine sediments have been recently reviewed by McCave (1984): we summarise here those aspects of transport and deposition that are most relevant to fine-grained turbidites. This discussion refers principally to terrigenous turbidites: there is insufficient work on bioclastic sediments to know to what extent the same principles apply.

The behaviour of mud suspensions during transport and deposition depends critically on the concentrations present. At concentrations of less than 0.3 kg/m^3, mud suspensions behave as Newtonian fluids; at concentrations of more than 5 kg/m^3 particle-to-particle interactions predominate and flows behave more like a consolidating soil than a turbulent suspension.

Under the conditions found in turbidity currents, mud particles will aggregate or flocculate. Krone (1978) showed that the shear strengths of aggregates from any particular sediment yield a few discrete values rather than a continuum, which he interpreted in terms of distinct orders of aggregation. Thus primary particles flocculate to form zero-order aggregates; several zero-order aggregates yield a less strong first-order aggregate, and these combine to form second-order aggregates of lesser strength. During transport, turbulence will lead to collisions between aggregates, leading to the formation of higher-order aggregates, but these higher-order aggregates will be most susceptible to break-up by turbulent shear.

At concentrations of less than 0.3 kg/m^3, with a bed shear stress of less than about 0.06 Pa, suspended sediment concentrations are observed to decrease logarithmically with time, as a result of entrapment of suspended sediment in the viscous sublayer (McCave and Swift 1976). Such deposition will take place at mean flow velocities of a few centimetres per second. At concentrations of more than 1 kg/m^3, a proportion of any given mud will deposit at shear stresses well above the critical depositional stress for low concentration flows: this appears to take place through the selective deposition of aggregates capable of forming the strongest bonds with the bed (Partheniades 1972): the importance of this effect increases with increasing concentration. For natural flows of concentrations of a few kg/m^3, this adhesive deposition is probably of minor significance and deposition by settling of aggregates trapped in the viscous sublayer results in depositional rates not exceeding a few mm/h.

Fine-grained cohesionless silts behave more like sand than mud flocs. Experiments in a circular flume using mixed grade silts with 30–40% very fine sand and clay at concentrations of 13–44 kg/m^3 (Banerjee 1977) have shown the development of partial Bouma (1962) sequences as a result of flow deceleration. Initial instantaneous deceleration to 0.46 m/s produced normal grading and then further deceleration to about 0.1 m/s over a period of several hours led to progressive development of parallel lamination, ripple lamination, sinusoidal ripple lamination and finally a suspension blanket as the flow ceased. Mantz's (1978) experiments on cohesionless quartz silts with increasing flow velocities again demonstrated that the bedform sequence produced was analogous to that for coarser sand-sized particles. However, for micaceous silts the only observed structure was parting lineation.

5.3 Dynamics of Turbidity Currents and the Deposition of Fine-Grained Turbidites

Because of the practical difficulty of monitoring marine turbidity currents, the physical behaviour of such currents must be inferred from turbidite deposits or from indirect phenomena such as cable breaks (velocity) and erosional structures (thickness). Standard physical properties of flows can be applied to turbidity currents, and in cases where some parameters can be constrained, inferences can be made on the behaviour of specific turbidity currents. Almost all well-known turbidity currents in the deep sea transported principally terrigenous sediment.

In most analyses of turbidity currents, the parameter most difficult to constrain is sediment concentration. Analyses of several currents that have deposited fine-grained turbidites have estimated concentrations in the order of a few kg/m^3 (Stow and Bowen 1980; Bowen et al. 1984). McCave and Jones (1988) have suggested that decelerating flows may reach concentrations of 50–100 kg/m^3, with this high-concentration slurry damping both turbulence and the entrainment of water at the upper interface of the turbidity current. Times available for deposition of fine-grained turbidites have been generally found to be many tens of hours.

Thus deposition through entrapment of aggregates in the viscous sublayer provides an adequate explanation for fine-grained turbidite beds up to a few decimetres in thickness. The structureless mud turbidites in beds metres thick require deposition from high concentration flows either through the processes of adhesion or in ponded settings through dewatering of high concentration slurries, as proposed by McCave and Jones (1988).

The dynamics of lamina deposition in fine-grained turbidites remain uncertain. Several authors have presented hypotheses for the origin of alternating silt and mud laminae, invoking mechanisms within the boundary layer such as turbulent bursts disrupting the boundary layer (Hesse and Chough 1980 – but see Allen 1985), disruption of flocs by shear within the boundary layer (Stow and Bowen 1980) and adhesion of clay onto clay beds (Piper 1978). Although Carey and Roy (1985) have produced such laminae in flume experiments, and invoke aspects of all the three above processes, we know of no specific experimental work directed at further understanding the origin of such lamination. This may be a fruitful area of future research, since variation in flow concentration may have an important influence on the style of mud deposition. Neither do we know of work in which variations in the structure of lamination is specifically linked to variations in mineralogy of fine-grained sediment.

6 Facies Significance of Different Types of Mud Turbidite in the Geologic Record

The variability of mud turbidites with depositional environment was synthesised by Piper (1978, Fig. 12–8), who provided an extensive bibliography. We present a new synthesis (Fig. 7) which draws on the greater understanding of the dynamics of turbidity currents and mud deposition, together with many new descriptions of fine-grained turbidites. There is insufficient data on fine bioclastic turbidites to propose any general synthesis.

Variability in mud turbidite facies results both from variations in initiation processes, which influence the type of sediment and the nature of initial flow in the turbidity current; and variations in transport and depositional processes.

6.1 Turbidite Initiation and Facies Variation

The initiating mechanisms for most turbidity currents are unknown, so that relating facies to initiating mechanism is at present speculative. The influence of initiating mechanism is greatest on the continental slope and in proximal parts of turbidite systems. Processes such as direct flow of river bedload into prodelta valleys (Prior et al. 1987) and rip current removal of sand from submarine canyon heads (Inman et al. 1976) result in coarse-grained turbidites, except where mud is incorporated by subsequent erosion. The role of large accelerating turbidity currents in eroding older proximal deposits of smaller flows is important in transporting muds to the distal parts of turbidite basins (Piper and Normark 1983).

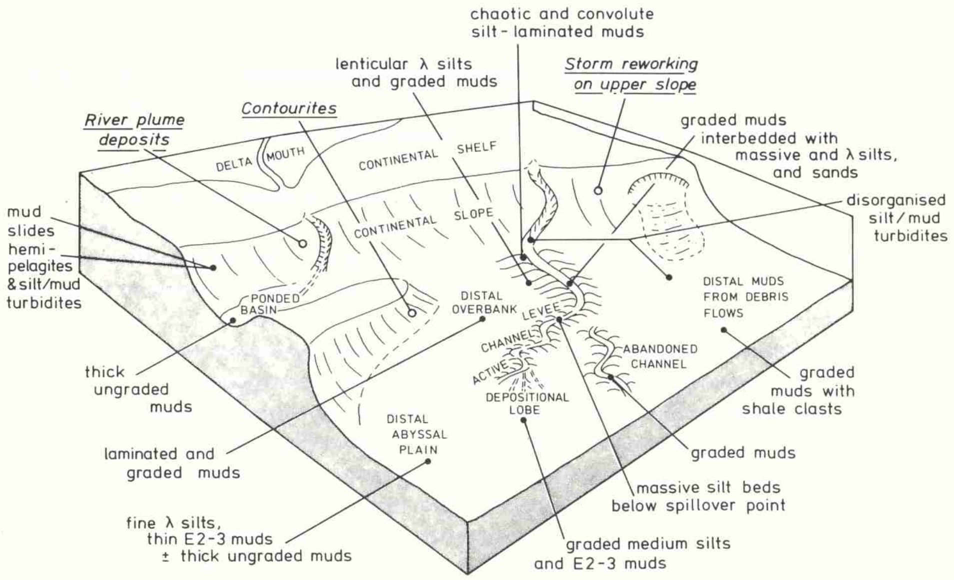


Fig. 7. Schematic facies distributions of different mud turbidites and associated sediments. [Based principally on data in Piper (1978); Stow and Piper (1984a) and references cited in this chapter]

Processes that put fine-grained sediment into suspension, such as outer shelf storms and river plume discharge, provide sediment that may be initially relatively well sorted. If these processes are effective, they are likely to result in frequent small turbidity currents, and the resulting proximal deposits may consist of thinly laminated well-sorted silts and muds (Hill 1984). The extent to which such small flows may become ignitive (Parker et al. 1986) and erode older proximal deposits is unclear.

The character of muddy turbidity currents derived from slumps is variable. Thick slump masses may break up to produce thick, poorly sorted mud turbidites, which may contain mudstone clasts (Aksu 1984). Mud turbidites derived from slumping of surficial sediment (<2 m burial) may resemble those derived from upper slope suspension.

6.2 Turbidite Flow Processes

The character of more distal fine-grained turbidites depends principally on flow conditions at the time of deposition. Many flows are initially channelized. Flow expansion, which generally results in deposition, may occur from overbank spillover, channel widening or termination, and change in gradient (Bowen et al. 1984). Unchannelised flows (whether distal overbank or lower fan) will experience flow expansion due to change in gradient. In ponded basins both gradient reduction and basin-margin reflection may be important (Hiscott and Pickering 1984). Flow expansion can have a variety of influences on deposition. It will normally result in a rapid decrease in flow velocity and an increase in entrainment of ambient water. Thus while overall sediment concentration will decrease, concentration near the base of the flow may increase temporarily, particularly in coarser silt and mud aggregates. Velocity decrease will result in a decrease in break up of aggregates.

Most source-area muds on outer continental shelves or upper continental slopes have silt contents in excess of 50%. Over flow distances of hundreds of kilometres, the silt content of turbidite muds decreases to less than 40% and there is a concomitant increase in the number of discrete beds of (principally medium or fine) silt in very distal fine-grained turbidite sequences (Piper 1978, Fig. 12–7). The decrease in silt content of muds probably reflects the gradual exclusion of silt from strong floc aggregates through turbulent shear disruption and reforming of aggregates during turbulent flows of long duration. Although this process may increase the abundance of fine silt not bound up in aggregates, source-related processes may also influence the abundance of silt beds. Gradually, as silt is lost almost entirely from the flow, then the number of discrete silt laminae decreases.

6.3 *Facies Variation*

Deposits on known *levees* and *channel termination areas* consist of muds with well-developed silt laminae, frequently with evidence of sediment starvation such as fading ripples. Silt laminae become thinner, rarer and less rippled away from channels. The features of apparent flow instability on levees and the decrease in granular sediments away from levee crests are features well known from studies of sandy turbidites: in fine-grained turbidites they are represented by irregularly interlaminated silts and muds.

Graded muds, lacking prominent silt laminae, are the most common type of fine-grained turbidite within *channels*. These may result from either deposition from the "tail" of a turbidity current, or from rapid velocity decrease in flows that have been stripped off at low points on levees (Piper and Normark 1983). In addition, thick massive silts appear to be restricted to channels.

Steady *unchannelised flows* appear to deposit poorly graded muds with thin basal silt laminae. In distal environments, these may interbed with thin medium and fine silt beds. *Ponded basins* are characterised by thick ungraded turbidites resulting from rapid decrease in velocity leading to the development of very high concentration flows. Similar turbidites may be deposited in channel termination areas where again there is a rapid velocity decrease.

7 Conclusions

1. Fine-grained turbidites, both terrigenous and bioclastic, are major components of most turbidite systems.
2. Individual beds of silt, mud and bioclastic turbidites show systematic sequences, summarised in Fig. 1.
3. Fine-grained turbidites may be distinguished from other fine-grained facies by distinctive petrography, sedimentary structures indicating rapid deposition from suspension, regular grading and structure sequences, or by the occurrence of thick unbioturbated uniform beds (Fig. 5).
4. Both asymmetric and symmetric depositional cycles are present in fine-grained turbidite sequences. Asymmetric cycles are less common than suggested in the classical models and are not restricted to lobes and channels. It is important that the presence of cycles be demonstrated by objective statistical techniques; there is a particular need for study of microcycles (<10 m thick). There are few studies that convincingly demonstrate the origin of observed cyclicity.
5. Although there is a continuum between turbidity currents and some other depositional processes in the deep sea, in most places debris flows and turbidity currents are the principal means of depositing large amounts of fine-grained sediment in the deep sea. The complex behaviour of flocs has an important influence on the grain size distribution and lamination present in fine-grained turbidites.
6. Facies distribution of fine-grained turbidites is influenced by turbidity current initiation and flow processes. Variation in facies is summarised in Fig. 7.