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Thin-Bedded Turbidites: Overview and Petroleum Perspective

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ABSTRACT

Among the broad range of transport and depositional processes that operate in deep-water, turbidity currents are widely recognized as one of the most common. Turbidite deposits, therefore, are a common facies in many deep-water systems, and within these the thin-bedded (TBTs) and very-thin-bedded turbidites (VTBTs) are most abundant. In many hydrocarbon-bearing turbidite systems, they represent a huge and relatively neglected potential for exploration and production; hence we have used data gathered from modern, ancient, and subsurface systems to synthesize their principal characteristics. They are generally deposited from low-concentration flows ($0.25\text{--}50\text{ kg/m}^3$ [$0.02\text{--}3\text{ lb/ft}^3$]) that have reached relatively low velocities ($0.15\text{--}0.5\text{ m/s}$ [$0.5\text{--}1.6\text{ ft/s}$]) with individual beds deposited between 1 hour (thin sandy turbidites) and several days (silt-mud turbidites). The standard Bouma facies model best represents TBTs, and the Stow model typifies VTBTs. Turbidites typically show many partial-sequence variations from the ideal complete sequence. Distinctive facies associations are characteristic of turbidites in channel, lobe, open slope, and basinal settings, whereas vertical sequences of bed thickness are less easily attributed to specific environments. Small-scale (micro-sequences), typically of three to seven beds arranged in symmetric to asymmetric patterns, are the most commonly observed. For quantitative characterization of TBTs and VTBTs, we have developed a series of attribute indices—including facies net-to-gross, sand connectivity, facies ratio, and sediment textural indices. These serve as input data for reservoir modeling and simulation and for characterizing associated architectural elements.

INTRODUCTION

Thin-bedded turbidites (TBTs) are widespread throughout the deep sea—across submarine fans, slope aprons, and covering huge areas on basin plains. Arguably they are volumetrically the dominant facies

in deep-water systems, both modern and ancient, but have been relatively less studied than their coarser grained counterparts (Piper and Stow, 1991; Stow et al., 1996; Mutti and Tinterri, 2000; Stow and Mayall, 2000; Hansen et al., 2015; Pickering and Hiscott, 2016). In some cases the mud-silt fraction is dominant, especially

as very thin-bedded turbidites (VTBTs), whereas other settings comprise over 80% sand fraction.

Thin sand and silt turbidites are known to form important reservoirs and parts of reservoirs in many hydrocarbon basins, and may contain much hidden or residual oil in producing turbidite reservoirs (Weimer et al., 2000; Shanmugam, 2006). Specific fields with a high proportion of TBTs include the Ram and Powell fields in the Gulf of Mexico (Clemenceau et al., 2000), the Ngatoro and Kaimiro fields offshore New Zealand (Browne and Slatt, 2002), the deep-water Block SB-G off northwest Sabah (Karimi et al., 1997), and the Sequoia field on the Nile Delta offshore Egypt (Cross et al., 2009). Mud-rich turbidites (thin- and thick-bedded) are also important as source rocks (Huc et al., 2001), unconventional oil and gas reservoirs, and, because of their lateral extent and tabular geometries, partial or complete seals.

Based on a large number of studies of modern, ancient, and subsurface turbidite systems made by the authors over more than four decades in the field, and also drawing from an extensive published literature on the subject (Mutti, 1977, 1985; Stow and Piper, 1984; Walker, 1992; Pickering et al., 1995; Hüneke and Mulder, 2011; Talling et al., 2012; Hansen et al., 2015; Pickering and Hiscott, 2016), we synthesize here the principal characteristics of TBTs and VTBTs. This work demonstrates that specific attributes of the TBT and VTBT family are very diagnostic of particular architectural elements. Discrimination between and characterization of these elements has great significance both in the exploration for and production from deep-water systems, as well as in full reservoir characterization and the understanding of deep-water shale properties.

Because they are both very common in deep-water and of significant economic interest, this chapter focuses principally on TBT and VTBT sediment facies, which have been deposited by low-concentration turbidity currents. However, we first provide a brief definition of the terminology used herein and then review the most recent understanding of the processes involved in their deposition.

DEFINITION

The sedimentological definition of thin beds is 3–10 cm (1.2–3.9 in.) thick, whereas very thin beds are less than 3 cm (<1.2 in.) thick. Where less than 1 cm (0.4 in.) thick, a very thin bed is commonly referred to as a lamina (or lamination; e.g., Stow, 2005). Industry terminology for TBT, however, is less restrictive of bed thickness and can be used to refer to turbidites below wireline-log resolution (<0.3 m [1 ft] approximately)

or to the generally thinner bedded turbidites associated with the thick sandstones of the main reservoir. Many turbidite events are represented by beds with a sand-silt lower unit grading upward into a muddy upper unit, with a sharp to gradational boundary between the two. The turbidite thickness is, therefore, that of the complete sand-mud event. However, for the petroleum industry, there is a greater focus on the sand thickness rather than the actual turbidite event thickness.

For these reasons, we have modified the sedimentological definition of bed thickness for the purposes of this chapter as follows (Figure 1). Furthermore, it should be recognized that any such definitions are simply placing artificial boundaries on a natural continuum of process and deposit for the purpose of better scientific description and understanding.

TBTs are here defined as having a sand-silt unit 0.03–0.1 m (1.2–3.9 in.) thick. They are the thinner bedded variety of sand-mud turbidites, generally deposited from fully evolved, medium- to low-density waning turbidity currents in the uniform-depletive modes of the Kneller time-space matrix. They are best represented by the classic Bouma facies model and its full range of variations (see Facies and Facies Models).

VTBTs are here defined as having a silt-sand unit less than 0.03 m (1.2 in.) thick. They are typical of tiger-stripe and shale-rich successions, generally deposited from fully evolved, low-density turbidity currents under a variety of conditions. They are best represented by the Stow facies model and its variations (see Facies and Facies Models).

PROCESSES OF TRANSPORT AND DEPOSITION

Range of Processes

There are a wide range of processes that operate in deep-water to erode, transport, and deposit sediment. These include a variety of gravity-driven (or downslope), current-driven (or bottom-current), pelagic (or vertical settling), and chemogenic processes (Table 1). Comprehensive reviews of these processes and their deposits have been compiled recently in texts by Pickering and Hiscott (2016), Hüneke and Mulder (2011), and Rebesco and Camerlenghi (2008). These authors also illustrate the growing number of synonyms and partial synonyms in current use, which tend to confuse rather than aid understanding.

The classification used here for sediment gravity flows (Table 1) is based on the latest and most widely accepted process classification schemes of Mulder and

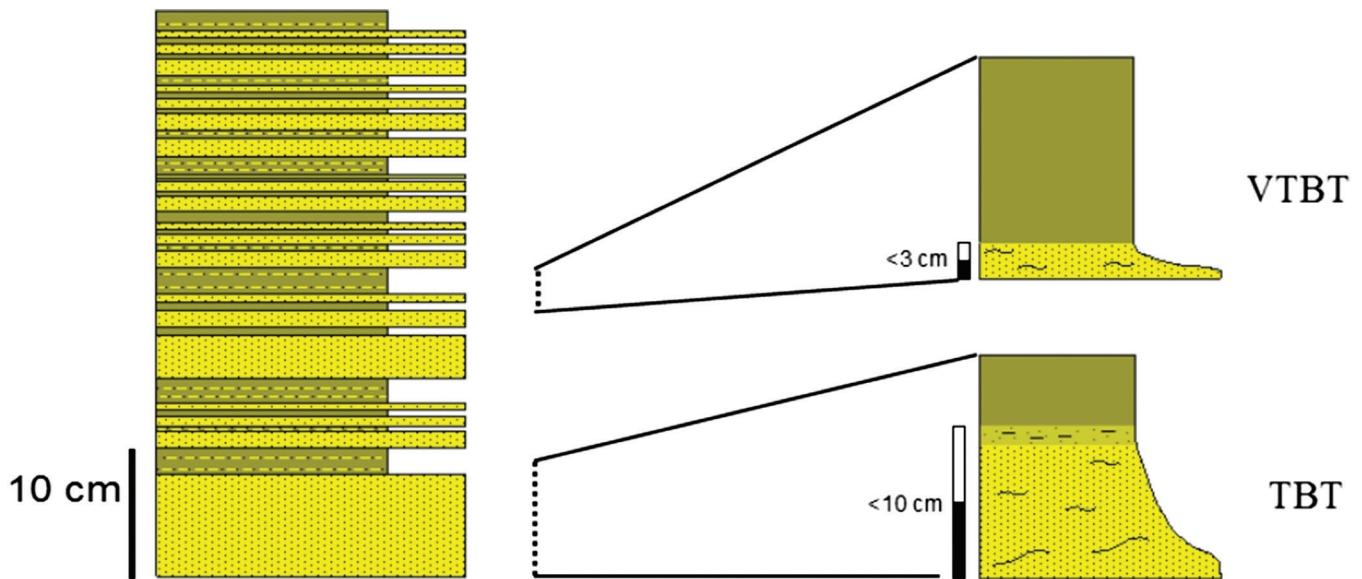


Figure 1. Definitions of thin-bedded turbidites and very thin-bedded turbidites. Note that we take the thickness of the sand and silt basal part of the turbidite as the measure of “bed” thickness.

Table 1. Principal deep-water processes and deposits: Classification and terminology.

Process: This Chapter	Deposit: This Chapter	Alternative Process Terms in Use
<i>Mass transport</i> - Rock fall - Creep - Sliding - Slumping - Debris flow /Mudflow	<i>Mass transport deposit (MTD)</i> - Avalanche deposit - Creep deposit - Slide - Slump - Debrite	<i>Mass movement, Submarine landslide</i>
<i>Sediment gravity flow</i> - Muddy debris flow - Sandy debris flow - High-concentration turbidity current - Low-concentration turbidity current	<i>Sediment gravity flow deposit (SGF)</i> - Debrite - Sandy debrite - Coarse-grained turbidite - Medium- and fine-grained turbidites	<i>Gravitational processes</i> - Cohesive debris flow, mudflow ^{1,2} - Inflated sandflow, ¹ Hyperconcentrated density flow ² - Concentrated density flow, ¹ High-density turbidity current ³ - Turbidity flow, ² Low-density turbidity current ³
<i>Hyperpycnal flow</i> <i>Bottom current processes</i> - Downwelling bottom currents - Thermohaline bottom currents - Wind-driven bottom currents - Deep-water tidal currents - Internal tides and waves	<i>Hyperpycnite</i> <i>Bottom-current deposits</i> - Contourites - Contourites - Contourites - Bottom-current (tidal) deposit - Bottom-current deposits	<i>Alongslope processes</i> - Contour currents - Contour currents
<i>Pelagic/hemipelagic processes</i> - Pelagic processes - Hemipelagic processes	<i>Open ocean processes</i> - Pelagite - Hemipelagite	
<i>Chemogenic processes</i>	<i>Chemogenic deposits</i>	<i>Authigenic processes</i>

¹Pickering and Hiscott (2016), ²Mulder and Alexander (2001), ³Stow and Mayall (2000), and Stow et al. (1996).

Alexander (2001) and Pickering and Hiscott (2016) but with a simplified terminology. This aims both to simplify the growing proliferation of terms and to acknowledge academic precedence—in particular for turbidity *current* rather than turbidity *flow*. However, turbidity currents are a type of Newtonian flow so that the following text also refers to their flow characteristics. The terms muddy and sandy debris flows are preferred to the newer terms such as inflated sand flow or hyperconcentrated density flow. The older terms, liquefied flow and grain flow (Middleton and Hampton, 1976), are no longer in general use as they have a much more limited application. Shanmugam (2000, 2006) has published his very alternative view of both downslope and alongslope processes, which is not followed here, although it does serve to emphasize the complex nature of any single flow event.

With regard to this complexity, it is important to recognize that turbidity currents are part of a process continuum across the spectrum of processes illustrated in Table 1 (Stow et al., 1996). Mass transport events in proximal slope regions may evolve downslope into debris flows and then into turbidity currents. Low-concentration turbidity currents can feed material into semipermanent bottom currents or, through a process of dilution and reverse buoyancy, lead to a process of hemiturbiditic settling (Stow and Wetzel, 1990; Sparks et al., 1993). This sort of evolution is part of downslope flow transformation. In addition, gravitational transformation within individual flow events, especially those that are coarse-grained and high-concentration, leads to internal stratification. Both types of transformation can result in composite beds with abrupt textural breaks (Houghton et al., 2009; Talling et al., 2013; Pickering and Hiscott, 2016; Strachan et al., 2016; Bozetti et al., 2018) or separation of the flow into two parts yielding spatially separated deposits.

Turbidity Currents

Within this spectrum of processes, turbidity currents are one of the most important ways by which fine-, medium-, and coarse-grained material is transferred from shallow to deep-water. They are one of a family of downslope and related processes as illustrated in Figure 2 (Stow et al., 1996; Hüeneke and Mulder, 2011; Talling et al., 2012; Hansen et al., 2015; Pickering and Hiscott, 2016). They are turbulent suspensions of mud and sand (and gravel in some cases) in water, which are propelled by the downslope component of gravity acting on the excess density. They may occur as short-lived surge events that travel for only a matter

of kilometers (a few miles) downslope or go through a process of flow ignition such that an autosuspension process is generated in the flow. This permits very long distance transport over tens to several thousands of kilometers (tens to hundreds of miles), both downslope and across flat abyssal plains. They can even travel a certain distance in an upslope direction before they come to a halt by a combination of frictional resistance, loss of sediment from the base of the flow, and reverse gravitation pull.

Individual turbidity currents are discrete events with very variable recurrence intervals (10^0 – 10^5 yr) and of very different sizes. The largest flows are known to overtop channel margins of 850 m (2800 ft) in height. These are likely to be several kilometers (~1 mi) in width and probably tens of kilometers (<10 mi) in length. Much smaller turbidity currents also occur. Such currents can be channel confined or flow across open slopes with little apparent confinement. They can deposit beds between less than 0.01 m and greater than 10 m (0.5 in.–33 ft) in thickness. Mean accumulation rates, therefore, are also very variable, typically from 0.1 m/ky to greater than 1 m/ky (0.3–3 ft/ky). The frequency of occurrence of turbidity currents ranges from approximately one every thousand years for the distal Bengal fan to one every few years for parts of the Amazon and Congo fan systems or more frequently still offshore active rivers and in some lacustrine environments.

Flow Concentration

Turbidity currents occur at a range of sediment concentrations, from those that are considered high-concentration flows (or high-density turbidity currents, HDTs) at around 50–250 kg/m³ (3–16 lb/ft³) to low-concentration flows (or low-density turbidity currents, LDTs) of around 0.25–50 kg/m³ (0.02–3 lb/ft³; Stow and Bowen, 1980; Stow et al., 1996; Pickering and Hiscott, 2016). There is some debate around the upper and lower limits of turbidity current concentration, such that hyperconcentrated flows are taken as ranging upward from around 450 kg/m³ (28 lb/ft³) and debris flows upward from around 800 kg/m³ (50 lb/ft³). Hyperpycnal underflows from rivers in flood typically have concentrations in the upper range of low-concentration turbidity currents, whereas bottom current concentrations (depositing contourites) are several orders of magnitude lower—around 0.0002 to 0.002 kg/m³ (0.02–2 mg/l).

The high-concentration flows are typically bipartite, having a lower traction carpet with very high concentration (hyperconcentration), grain interaction and

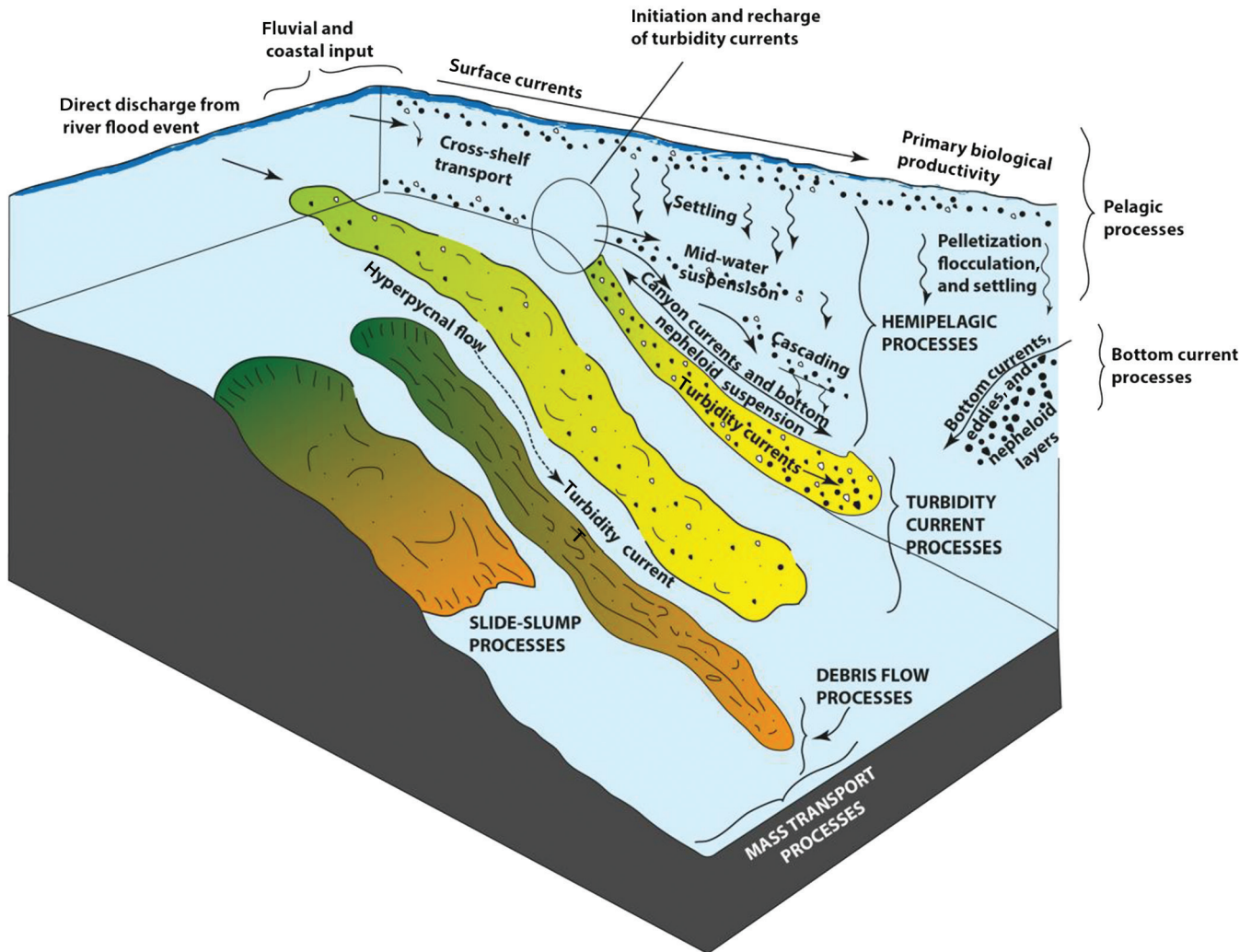


Figure 2. Deep-water process family including mass transport, sediment gravity flow (debris flows and turbidity currents), bottom-current, pelagic and hemipelagic processes.

quasi-viscous flow behavior especially near the base of the flow, and a fully turbulent more dilute upper part. These HDTs are highly competent and can transport coarse grain sizes (coarse sand and gravel) and give rise to *coarse-grained turbidites*, including thick sandy turbidites, mega-turbidites, hybrid beds, and deep-water massive sands (Kneller and Branney, 1995; Stow and Johansson, 2000; Haughton et al., 2009). Such deposits are mostly thick and very thick bedded and are discussed by Cronin (2018).

Low-concentration flows are, for the most part, fully turbulent Newtonian flows and capable of carrying sand, silt, and clay-sized material (Hansen et al., 2015). The largest grain size transported is a reflection of the flow competency, density, and velocity. These LDTs deposit *medium-grained turbidites* and *fine-grained turbidites*, which are mostly medium and thin bedded. These are the subject of the present chapter.

Turbidity currents become progressively more dilute as more and more of the suspended sediment load is deposited. In its final stages, the turbidity current and any remaining suspension begins to mix upward into the water column forming a very dilute suspension cloud many hundreds of meters above the seafloor (Stow and Wetzel, 1990; Stow et al., 1990). This process has been termed reversing buoyancy (Sparks et al., 1993) and the deposits are called *hemiturbidites* (Stow and Wetzel, 1990).

Flow Velocity and Deposition

Flow velocity of turbidity currents has been measured directly in only very few cases (Pickering and Hiscott, 2016). It has been calculated more commonly by measuring the time between sequential cable breaks that lie

across the seafloor in the path of such currents. Indirect determination of flow velocity is more readily made from the nature of bedforms generated by the passing current and from the maximum clast size present in the deposited turbidite beds. Summarizing these data yields the velocity and grain size matrix for turbidity currents, illustrated in Figure 3. Whereas the high-concentration flows depositing coarse-grained turbidites can reach velocities in excess of 20 m/s (65 ft/s), those that are in the depositional phase for medium- and fine-grained turbidites have slowed to around 0.5 m/s (1.6 ft/s) and 0.15 m/s (0.5 ft/s), respectively. Figure 3 also shows our best estimates of the time taken for individual turbidite beds to be deposited—from minutes to days.

Deposition occurs from the base of the turbidity current as the flow loses its carrying capacity (or competence). This is the result of (a) a decrease in flow velocity, (b) a reduction in flow density, (c) interaction with a bottom current flow across the path of the turbidity current,

or (d) progressive loss of sediment due to deposition. In reality, deposition is most likely due to a combination and interaction of these different factors, influenced by topographic change and frictional resistance of the seafloor. A gradual decrease in flow competence at any one location results in the deposition of a normally graded bed.

Deposition occurs through a boundary layer in which there is locally increased shear stress caused by the friction between the flow and the seabed. This affects the final characteristic of the grading and sedimentary structures within the turbidite. Stow and Bowen (1978, 1980) showed how the shear sorting mechanism yields silt-mud lamination in TBTs. We here propose that the same mechanism is involved in the production of normal parallel lamination in fine sandstones and siltstones. In this case the shear sorting through the boundary layer separates sand and silt grains of very slightly different shape or composition and hence allows the deposition of individual parallel laminae with very subtle differences.

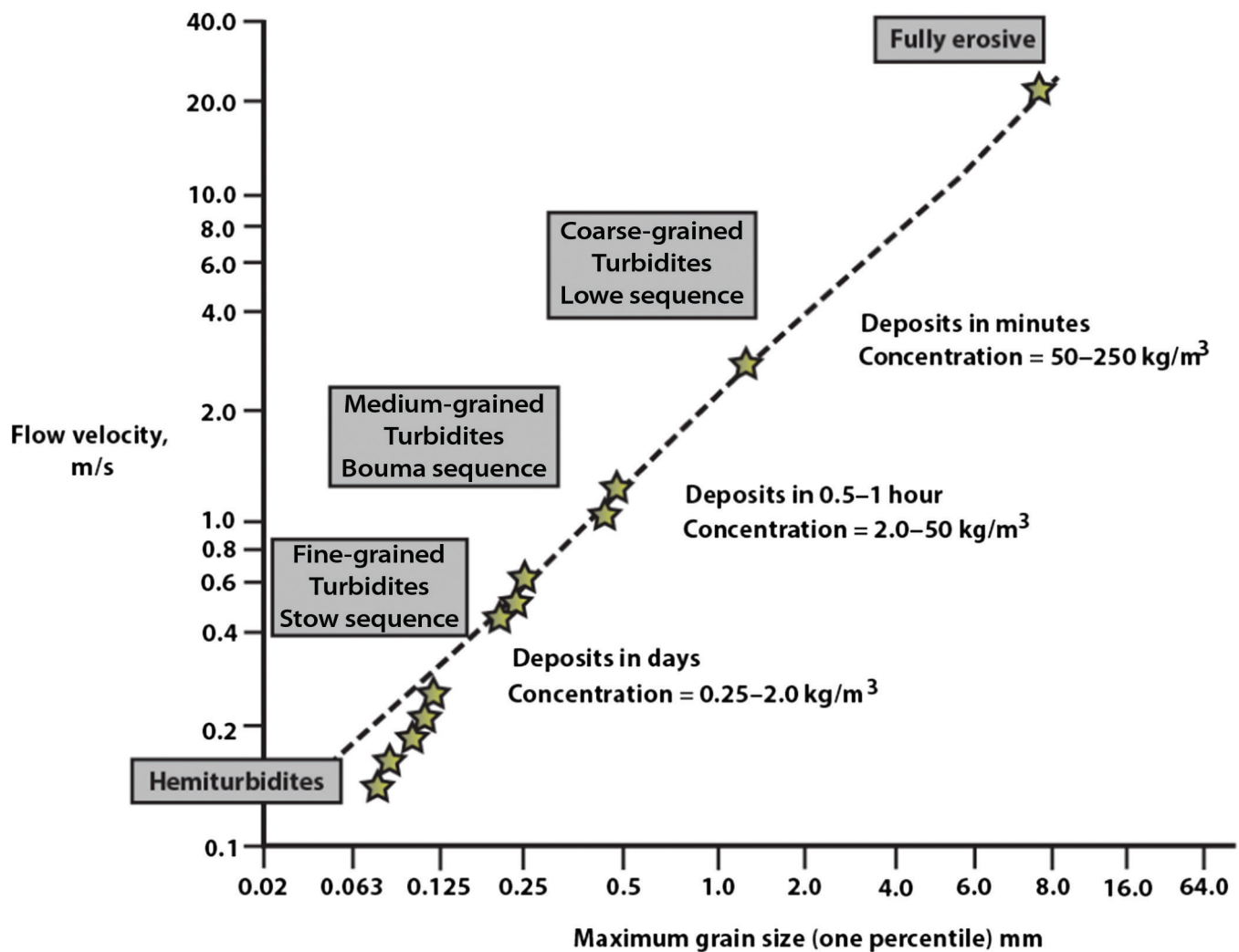


Figure 3. Velocity-grain size matrix for turbidity currents (after Stow et al., 2012).

Flow Initiation

The causal mechanisms for the origin of turbidity currents are widespread and varied. One principal cause is the failure of submarine slopes leading to sliding, slumping, or debris flow processes. These may evolve through ingestion of ambient seawater into turbidity currents. Slope failure, commonly linked with development of excess pore water pressure within the sediment pile, can be caused by (a) seismic activity, (b) sea-level rise and fall, (c) excessive sediment loading, (d) gas hydrate instability and release, and (e) changes in groundwater flow conditions within the slope and shelf (Lee, 2009; Twichell et al., 2009; Hüneke and Mulder, 2011; Talling, 2014; Pickering and Hiscott, 2016).

Other factors more specific to the generation of low-concentration turbidity currents include (a) sudden excess sediment supply by rivers in flood (i.e.,

their generation from hyperpycnal flows), (b) rapid glacial discharge events, (c) resuspension of shelf edge to upper slope sediment as a result of storm stirring and the incidence of internal tides or waves, and (d) storm build-up of water across a continental shelf and its rapid discharge down submarine canyons. It is worth noting that in addition to a mechanism for generating low-concentration turbidity currents (and hence depositing turbidites), hyperpycnal flows may also deposit their flood-charged sediment load directly as hyperpycnites (Soyinka and Slatt, 2008). Although generally thin bedded, these distinctive inverse-to-normally graded deposits are quite different from the TBTs and VTBTs that we describe in the following sections.

The principal modes of initiation, remolding, transport, and deposition by turbidity currents are summarized in Figure 4.

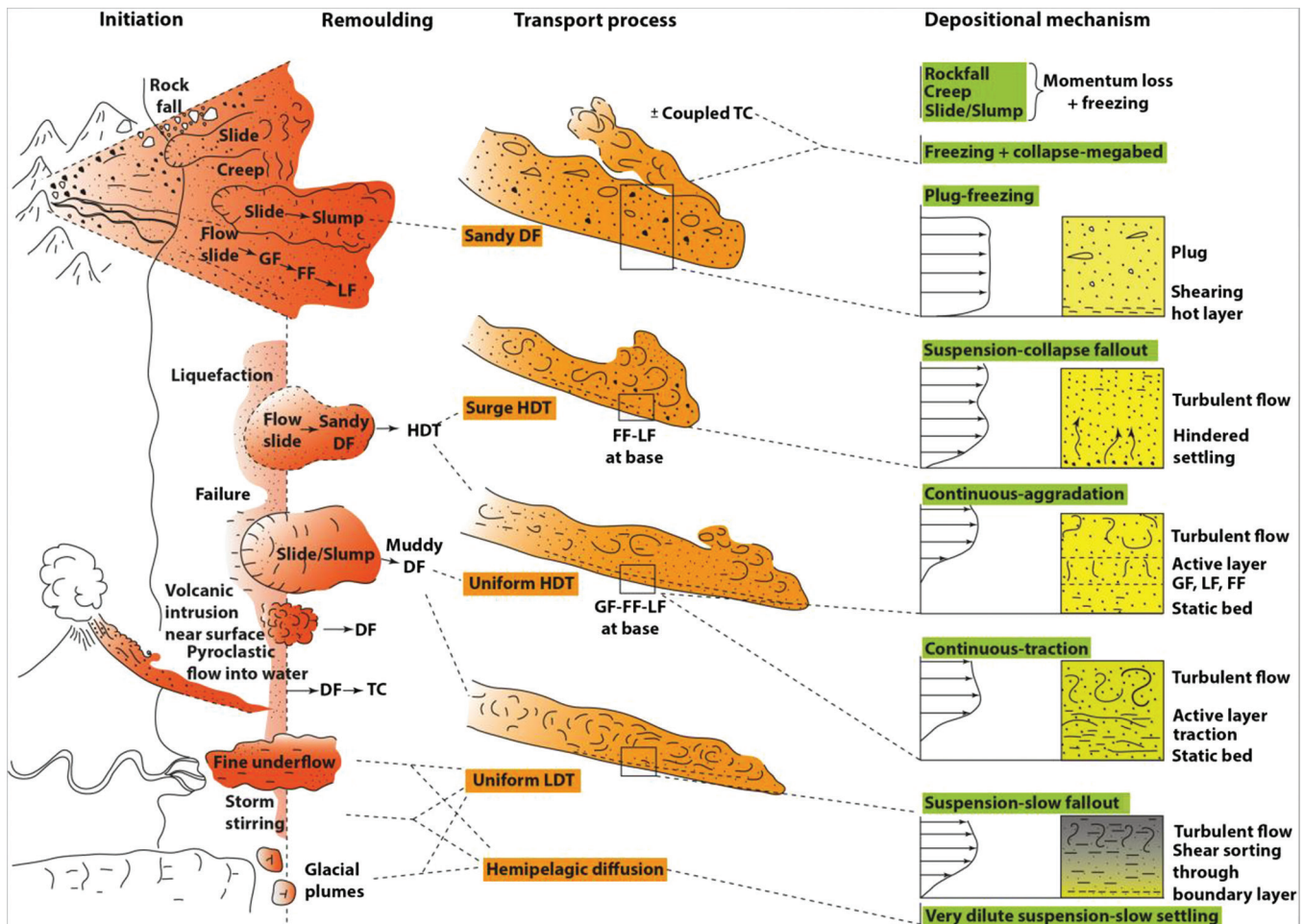


Figure 4. Turbidity current and related downslope processes: initiation, remolding, transport, and depositional phases. DF = debris flow; FF = fluidized flow; GF = grain flow; HDT = high-density turbidity current; LDT = low-concentration turbidity current; LF = liquefied flow; TC = turbidity current. After Stow and Johansson, 2000.

FACIES AND FACIES MODELS

Turbidites have been one of the better known and most intensively studied deep-water sediment facies since they were first recognized in the 1950s (Kuenen and Migliorini, 1950) and the first facies model developed by Bouma (1962). They are now very well-known from sediment cores recovered from modern deep-water systems, subsurface (hydrocarbon) boreholes, and ancient outcrops now exposed on land. Each new study of a particular turbidite system reveals specific deposit characteristics and facies for that system. The most commonly observed facies have been variously synthesized into a range of facies schemes proposed by Mutti (1992), Ghilardo (1992), Stow (1986, 1994), Stow et al. (1996), Pickering et al. (1995), Mulder and Cochonat (1996), Hüeneke and Mulder (2011), and Pickering and Hiscott (2016), among others.

These composite characteristics and multiple data sets have been synthesized into facies models for coarse-grained turbidites (Lowe, 1982; Stow and Johansson, 2000; Houghton et al., 2009; Cronin, 2018), medium-grained turbidites (Bouma, 1962; Walker, 1965), and fine-grained turbidites (Stow, 1977; Piper, 1978; Stow and Shanmugam, 1980). For convenience, these are referred to as the Lowe, Bouma, and Stow sequences or facies models, after the authors who first established the respective scheme. Each of these facies models shows a characteristic sequence of sedimentary structures and grading, which reflects deposition from

a single turbidity current event. They are event deposits. The different structures are referred to as divisions within the sequence. The Stow sequence is more or less equivalent to the DE divisions of the Bouma sequence or to the E1–3 divisions of Piper (1978).

The complete sequences are present in less than 10% of turbidites. More common are partial sequences in which the same order of divisions is preserved but not all are present in any one bed. For each sequence, the lower divisions represent deposition from the current when it is more energetic and the upper divisions when it is less energetic. For a single turbidity current, this can be achieved from more proximal to more distal, respectively, and also from channel axis to overbank. The same high to low energy regime applies to Lowe, Bouma, and Stow turbidites. In some cases, Lowe divisions are overlain by Bouma divisions in a single bed, or Bouma divisions by Stow divisions. Rarely, all three can occur in megaturbidites.

Thin-bedded and medium-bedded turbidites are best characterized by the Stow and Bouma models. These are shown together with the typical range of partial sequences in Figures 5 and 6. They represent deposition from uniform turbidity currents in the depletive regime of the Kneller and Branney (1995) matrix. They are the most abundant and widespread types of turbidite in both marine and lacustrine settings. Modern and ancient examples of TBTs and VTBTs are shown in Figure 7. Thick-bedded and coarse-grained turbidites and associated deep-water facies are discussed by Cronin (2018).

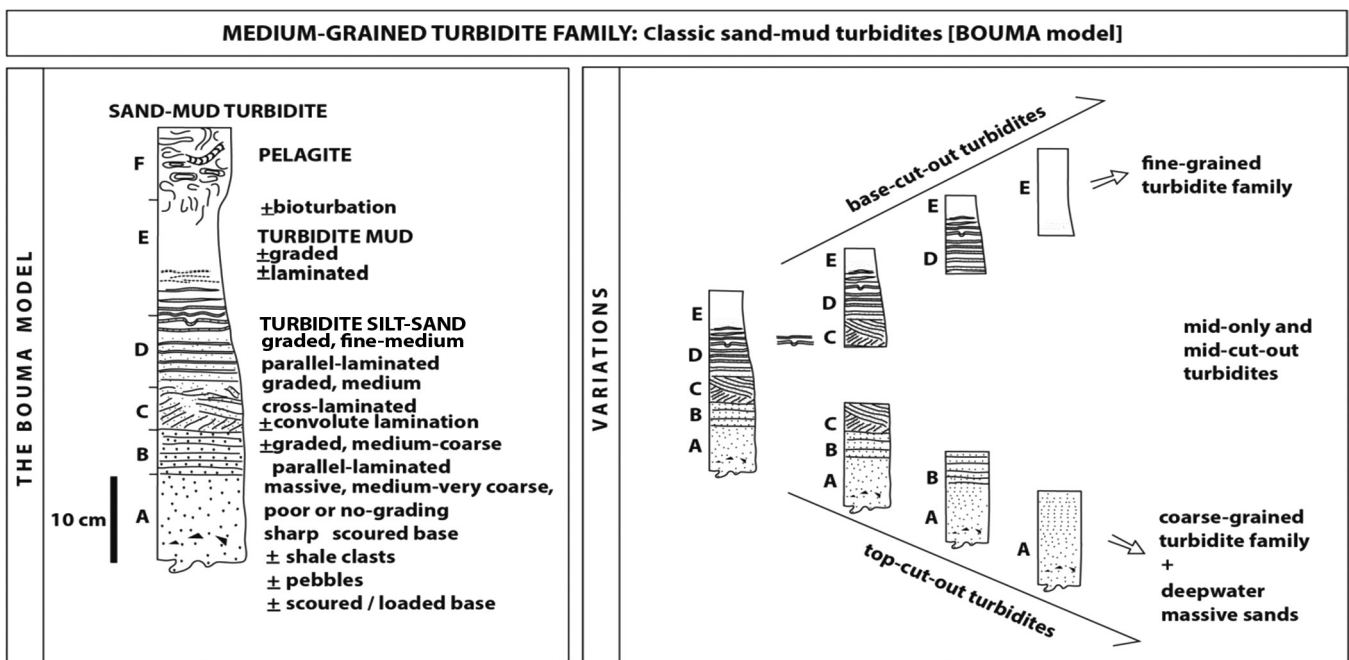


Figure 5. Facies model for medium-grained (Bouma) turbidites and partial-sequence variations. Typical of thin-bedded turbidites.

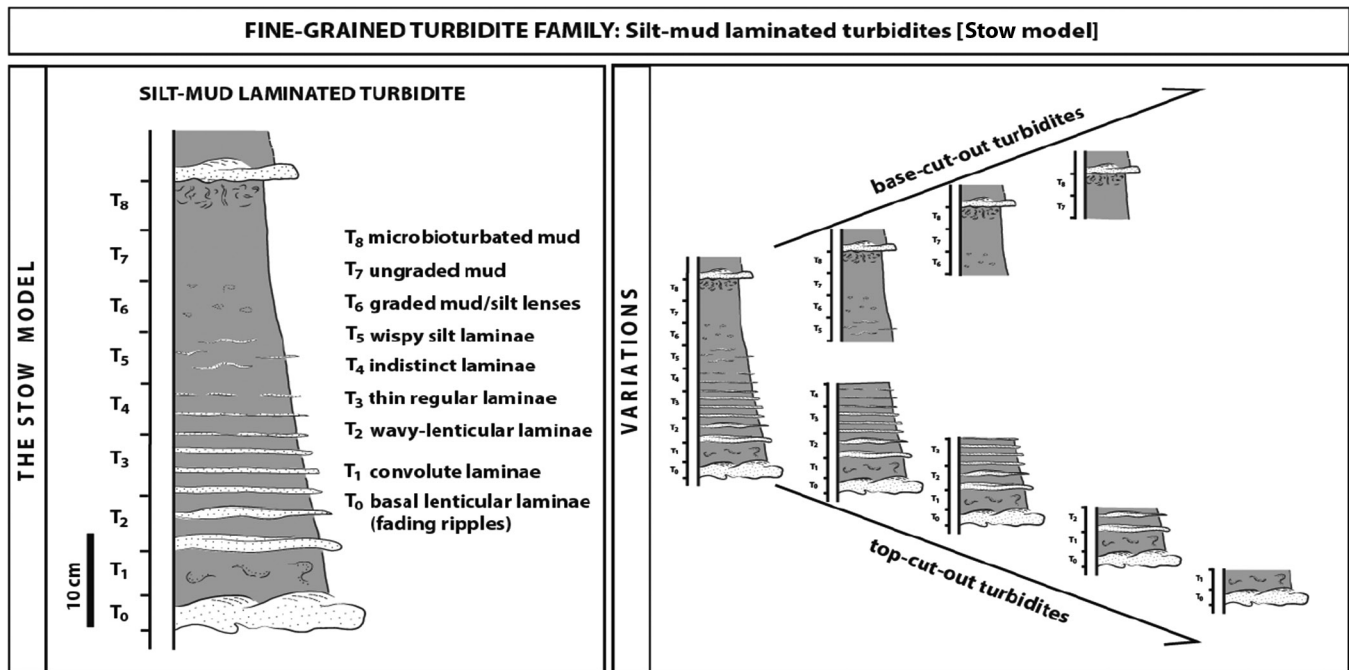


Figure 6. Facies model for fine-grained (Stow) turbidites and partial-sequence variations. Typical of very thin-bedded turbidites.

Variations from the Standard Models

There is some dissent as might be expected, and this helps us better refine and establish what we do know. In particular, Shanmugam (2000, 2006) questions our understanding of the turbidity current process and hence of turbidite facies models. One of his key concerns is that turbidite has become a bucket term for a wide range of processes and facies and that some, especially the coarse-grained facies, might be more accurately attributable to debris flows. This issue is discussed by Cronin (2018). We would make three observations here: (a) downslope processes, including turbidity currents, evolve during a single event, from debris flow to high- and then low-concentration turbidity current via a process of flow transformation; (b) the process of deposition through the traction carpet or boundary layer will markedly affect the nature of the deposit; (c) the well-documented range of turbidite facies we observe can be clearly attributed to a process-facies continuum of turbidity currents and turbidites, as outlined previously.

In terms of composition, turbidites can comprise siliciclastic, bioclastic, volcanoclastic, and chemoclastic types, as well as mixtures of these different components. Both the Bouma and Stow models were developed from siliciclastic systems but have been shown to apply equally to bioclastic and volcanoclastic turbidites (Stow et al., 1984b, 1998; Eberli, 1991). Some

differences have been documented for calcareous bioclastic turbidites (Figure 8). For example, calcarenite (sand-grade) turbidites in some cases have a large-scale dune cross-bedded division, which is typically missing from siliciclastic turbidites. Calcilutite (mud-grade) turbidites show a less distinct silt-laminated division than siliciclastics and a more gradual, often reverse-graded, upward transition into hemipelagic or pelagic ooze (Stow et al., 1984b; Piper and Stow, 1991). Too few examples of chemoclastic turbidites have been described to establish what differences they may display (Stow et al., 1995).

In distal turbidite environments and in channel levee-overbank settings, silt beds (>70% silt-sized particles) are more abundant than sands and commonly occur as thin- or medium-bedded turbidites. These silt beds exhibit the same suite of structures (the Bouma sequence) as sand-mud turbidites. Ungraded structureless silts are found more proximally and can be attributed to AE-division Bouma turbidites. Strachan et al. (2016) describe other variations of silt and silty-sand turbidites with a wide ranging of grading styles, including ungraded-, reverse-, and normal-graded silt turbidites from proximal settings (Figure 8).

Medium- to very thick-bedded mud turbidites, with and without a thin basal silt division (Figure 7), are known from a variety of environments including ponded basins (Blanpied and Stanley, 1981; McCave and Jones, 1988; Wynn et al., 2000; Tripsanas et al.,

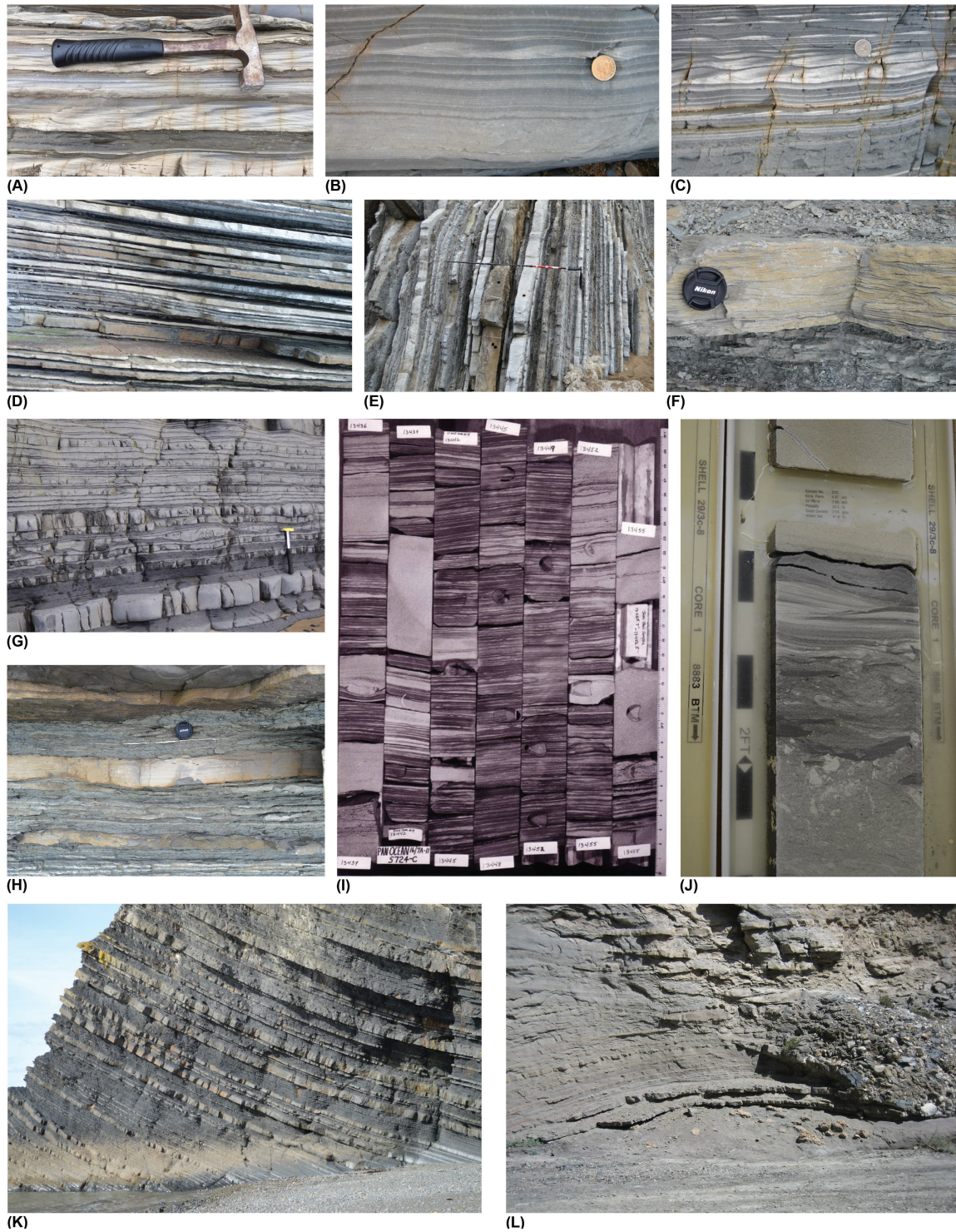


Figure 7. Selected photographs of thin-bedded turbidite (TBT) and very thin-bedded turbidite (VTBT) facies from core and outcrop. (A–D) Very thin-bedded turbidites (VTBTs, various outcrop). Note distinctive faded-ripple basal divisions (Stow T0). Lower bed in “B” is a disorganized VTBT. Width of view in D is 0.75 m (2.4 ft). (E–H) Thin-bedded turbidites (TBTs, various outcrop), interbedded with VTBTs and some medium-bedded turbidites. (I) Typical Brae field core, North Sea, Upper Jurassic, with TBTs, VTBTs, and some medium-bedded turbidites. (J) Typical Forties Formation core, North Sea, Paleocene, showing sandy base of TBT (upper), VTBT with T0–2 divisions (middle), and disorganized TBT (lower). (K) Aberystwyth Grits turbidite formation, West Wales, Silurian, showing typical basinal succession of TBTs, VTBTs, and medium-bedded turbidites. Vertical variation of bed thickness characterized by oscillation sequences of around 2–3 m (6.5–10 ft) thickness. Cliff section 16 m (50 ft). (L) Tabernas Basin succession, Miocene, southeast Spain, with TBTs and VTBTs (middle left) within a submarine channel, incised by conglomeratic debrite and medium- to thick-bedded sandstone turbidites. Section above dry riverbed (foreground) is approximately 3 m (10 ft).

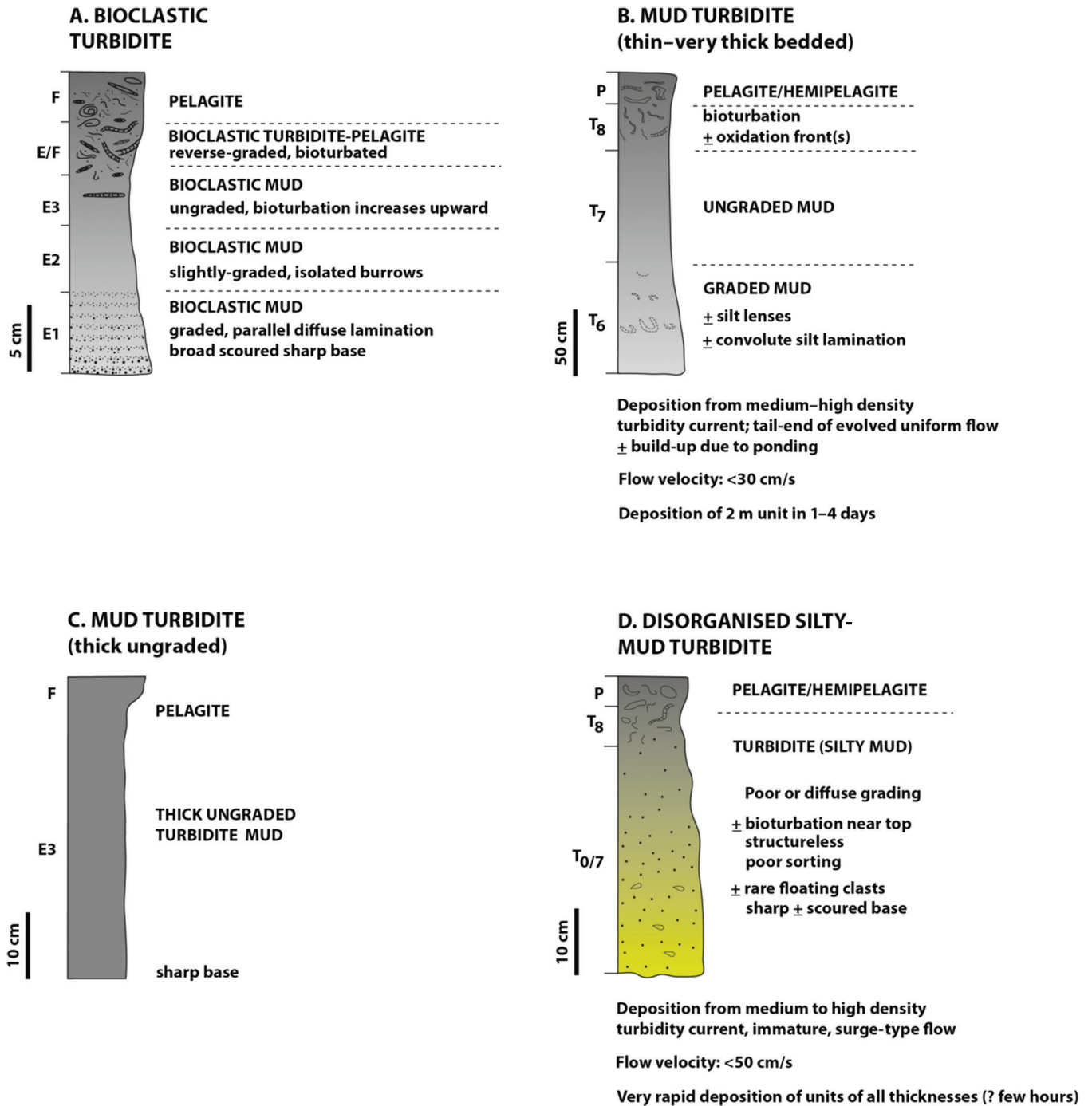


Figure 8. Facies models for associated turbidite facies. Typical of medium- and thin-bedded turbidites (after Piper and Stow, 1991, and Strachan et al., 2016).

2004), channel-fill successions (Stow et al., 1996), open-slope and base-of-slope settings (Tabrez, 1995), and distal fan lobes (Stow et al., 1990). Such thick mud turbidites in distal and basin plain settings may be associated with hemiturbidites, the result of very slow deposition from the suspension cloud that develops

above and beyond the feather edge of true turbidite deposition (Stow and Wetzel, 1990; Sparks et al., 1993). Hemiturbidites have the same composition as the associated mud turbidites but are structureless, ungraded, very fine grained, and bioturbated throughout (Figure 9).

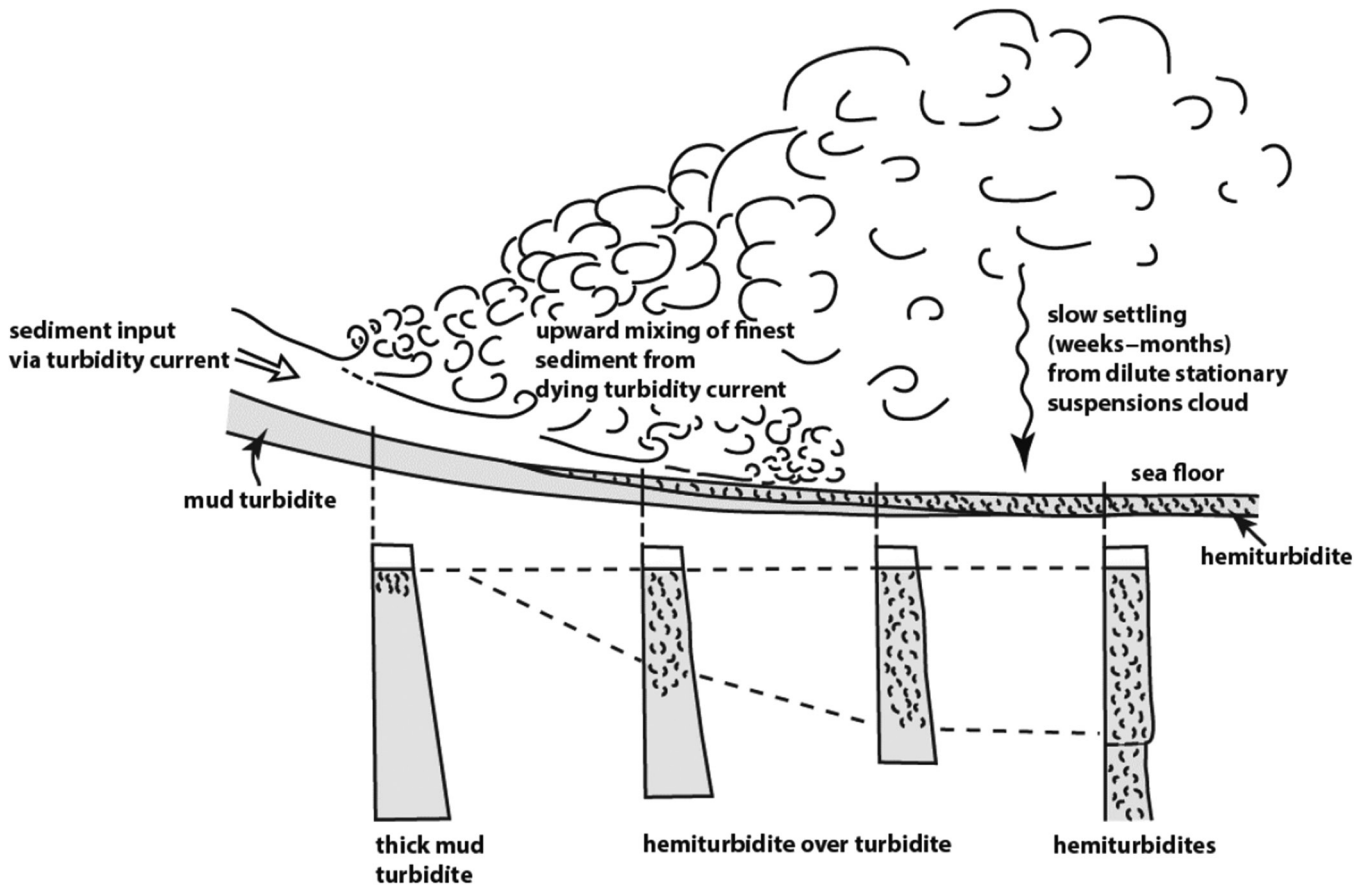


Figure 9. Schematic diagram of the hemiturbidites depositional process and facies (after Stow and Wetzel, 1990).

Disorganized Turbidites

There is a group of thin-, medium-, and thick-bedded turbidites that do not show clear Stow or Bouma sequences, have absent or very indistinct lamination, and do not have a clear separation between the sand or silt and mud fractions. Some show distinctive normal grading, whereas others have poor grading and abundant small mudstone clasts (Figure 8). We interpret these as the deposits of immature, surge-type turbidity currents. They may have developed from debris flows but never developed into uniform turbidity currents.

FACIES ASSOCIATIONS

TBTs and VTBTs occur in close association with a variety of other deep-water facies depending on the different depositional settings and sediment supply (Mutti and Ricci Lucchi, 1978; Stow et al., 1996). In turbidite-dominated systems, such as downslope channels, pro-delta slopes, submarine fans, depositional lobes,

and small, well-supplied basins, the interbedding of a range of different turbidite facies is commonplace. Where TBT and VTBT facies are most abundant, the turbidite *facies associations* most commonly observed include the following:

- (a) Closely spaced, sand-rich TBTs with repeated Bouma CD mid-divisions;
- (b) Separated sand-mud TBTs with Bouma CDE divisions, interbedded with minor VTBTs and hemipelagites;
- (c) Widely spaced TBTs with a range of mid-upper Bouma divisions, interbedded with common VTBTs and minor hemipelagites;
- (d) Closely spaced sand- and silt-rich VTBTs with repeated Stow T0–2 basal divisions, interbedded with rare Bouma TBTs;
- (e) Silt-mud VTBTs with a range of mid-upper Stow divisions, interbedded with some lower division Stow turbidites and Bouma TBTs;

- (f) Mud-rich VTBTs with mainly upper Stow T4–8 divisions and some interbedded thicker mud turbidites and hemipelagites.

These six turbidite facies associations represent a continuum of deposition from more energetic (a) to less energetic (f) turbidity currents. They may occur in more proximal to distal settings, across a fan-levee system away from the channel axis, or vertically superimposed as the result of channel abandonment.

Other facies associations also occur together with the TBT and VTBT suite. In many slope apron settings, they are interbedded with more abundant and thicker hemipelagite or pelagites, ranging from slowly accumulated biogenic-rich facies at low latitudes to rapidly deposited terrigenous (including glaciogenic) facies at high latitudes. Such facies are often referred to as the *background* sediment in turbidite systems. They are not always easy to distinguish from turbidite mud divisions unless there are clear compositional and bioturbation differences.

Slumps, slides, debrites, and disorganized turbidites are especially common at high latitudes, on active margins and wherever slope gradients are high. This association is also typical of many channel-fill successions, which further include a range of thicker bedded and coarser grained turbidites.

Where bottom currents sweep across the turbidite system, contourites occur as interbedded facies and characteristic modification and reworking is typical, yielding hybrid turbidite-contourite facies. In open basin plains, they are associated with pelagites and hemipelagites, whereas in closed basins, there may be thick mud and sand turbidites, megabeds, and debrites.

VERTICAL SEQUENCES

Vertical sequences of bed thickness in turbidite successions are commonly used to infer depositional environments and architectural elements for ancient examples. Early work focused on thinning-upward sequences as characteristic of channel fill and thickening-upward successions as representing lobe progradation (Walker and Mutti, 1973). The sequences, typically 10–40 m thick, also showed fining-upward and coarsening-upward trends of turbidite grain size, respectively. More recent work recognizes a greater variety of types and scales of sequences (Piper and Stow, 1991; Stow et al., 1996; Pickering and Hiscott, 2016) as outlined later.

Whereas many studies rely on visual inspection and estimation of bed-thickness trends, Hiscott (1981) has demonstrated that such sequences are typically not statistically significant. A variety of statistical

techniques—including autocorrelation, trend series analysis, runs test, Fourier analysis, and Markov chain analysis—have, therefore, been applied to turbidite successions (Forster, 1995; Chen and Hiscott, 1999; Awadallah et al., 2001; Talling, 2001; Pickering and Bayliss, 2009; Pickering and Hiscott, 2016). These studies have had some success in characterizing small-scale sequences of less than 10 m (33 ft) but more difficulty with the medium- and large-scale sequences. There is much work still to do on the statistical data and analyses that are required to determine sequence types and significance.

The following summary focuses on sequences that contain wholly or mainly TBT and VTBT beds. We use a slightly modified terminology from Piper and Stow (1991) in subdividing sequences into mega-sequences (>100 m [328 ft] thick), meso-sequences (10–100 m [33–328 ft] thick), and micro-sequences (<10 m [33 ft] thick).

Mega-Sequences (>100 m [328 ft])

Over a few hundred meters of succession, turbidite systems commonly evolve from thick to thin bedded (coarse to fine grained) and vice versa. This can be at the scale of a basin-fill episode or within large-scale turbidite systems (Bouma et al., 1986; Manley and Flood, 1988) and is generally attributed to allogenic controls, such as sea-level fluctuation or tectonic cyclicity (Shanmugam and Muiola, 1982; Klein, 1985). Such sequences are observable on seismic reflection profiles.

Meso-Sequences (10–100 m [33–328 ft])

It is at the scale of good outcrops and subsurface boreholes (with cores or wireline logs) that most debate has centered on the recognition and interpretation of turbidite sequences. A considerable database now exists from 50 years of scientific drilling into deep-water systems and exploration and production drilling of turbidite reservoirs (Forster, 1995; Stow et al., 1996; Stow and Mayall, 2000; Shanmugam, 2006; Pickering and Hiscott, 2016).

- (a) Thinning-up (fining-up) sequences are common in coarse-grained turbidite systems, where they are widely interpreted as channel-fill deposits. The upper parts of these sequences comprise TBTs and VTBTs. Channel migration and abandonment are invoked as causal mechanisms, as well as tectonic pulsing and lateral migration of the supply system over time.

- (b) Thickening-up (coarsening-up) sequences are observed in coarse-, medium-, and fine-grained turbidite systems and are classically interpreted as representing basinward progradation of fan lobes, although this is not the only sequence type representative of lobes. Tectonic pulsing, sea-level oscillation, and variation of sediment input can yield similar cyclicity.
- (c) Symmetrical and partially asymmetrical sequences—thickening- then thinning-up, for example—are one of the most common style of thickness variation in medium- and thin-bedded turbidite systems, although in visual assessment the eye is often drawn preferentially to either thinning-up or thickening-up packets. Such sequences can be caused by the progradation of lobes followed by lateral migration or by temporal variation in sediment input.
- (d) Block-like packets of thicker (coarser) beds, showing relatively abrupt transitions with the encasing thin-bedded and finer-grained succession, are another common indication of channel-fill deposits, from large-scale mid-fan or feeder channels to small-scale lobe-cutting distal channels. They may also represent sudden influx of coarse-grained turbidites into a basin plain.
- (e) Random non-cyclic successions are another very common sequence type, especially in TBT and VTBT series. Many of the slope apron and basin-plain systems are of this type, as also are levees and interchannel deposits.

Micro-Sequences (<10 m [33 ft])

The patterns recognized as meso-sequences also appear to be present in micro-sequences, although grain size is not always so closely linked with bed thickness (Piper and Stow, 1991; Forster, 1995). Mutti (1977) related micro-sequences to specific depositional environments. Thickening-up and symmetrical micro-sequences were linked to lobe-fringe and fan-fringe environments; block-like sandy TBTs separated by mud-rich units to interchannel areas; random, irregular, noncyclic series to channel mouth and channel margin areas; and random but regular, noncyclic series to basin plain environments. Drilling on modern systems has shown a certain degree of accuracy in these inferences, although more statistical work is needed in this area. Mutti (1977) proposed wholly autogenic controls on this cyclicity, whereas Lash (1988) ascribed similar micro-sequences to allogenic controls.

Compensation cycles were first described by Mutti and Sonnino (1981) as repeated thinning-up sequences, each just a few beds in thickness. They ascribed this variation as due to the influence of the slight positive relief of the previous turbidite on the next turbidity current. Both theoretical and observational evidence now shows that compensation cycles can be thinning-up, thickening-up, or, more commonly, symmetrical (Stow and Piper, 1984; Melvin, 1986; Piper and Stow, 1991; Forster, 1995). They are especially characteristic of lobes and basin plains.

TURBIDITE ATTRIBUTES AND THEIR QUANTIFICATION

The foregoing synthesis of sediment facies, facies associations, and vertical sequences is mainly descriptive in nature. It allows a first-order interpretation of the processes and general environments of deposition. However, we suggest that the wealth of detailed information on sedimentary attributes, which can be derived from TBTs and VTBTs in particular, should be subjected to more rigorous quantification. We have, therefore, established a methodology of measuring sediment attributes and deriving quantifiable attribute indices from their combination. These will allow us to better understand turbidity current processes, more effectively characterize depositional environments, and input directly into models for reservoir simulation.

Turbidite Attributes

The principal sedimentary attributes used to characterize and discriminate between different TBT and VTBT systems are listed in this section. The first five of these we have already discussed in more detail in previous sections.

- (a) Facies: nature of turbidite facies present including standard and nonstandard turbidites; quantification of the relative proportion of TBTs with Bouma sequences and VTBTs with Stow sequences.
- (b) Sedimentary structures: recognition of full and partial sequence types and top, mid, and basal divisions present.
- (c) Facies associations: the grouping of TBT and VTBT facies to represent the succession (and parts of the succession) more succinctly than through individual facies; also the associated facies present in succession and their relative proportion.
- (d) Bed thickness: examination of bed thickness, including full turbidites (i.e., sand-mud graded

beds); quantification of the mean thicknesses of sand and mud parts of beds.

- (e) Vertical sequences of bed thickness: a broader perspective of the turbidite succession within mega- and meso-sequences, either from visual inspection or determined from statistical analysis; particular focus on the micro-sequences within the TBT and VTBT package.
- (f) Sand-shale or sand-mud ratio: quantification of the relative proportion of sand and mud within a given interval; this is a derivative measurement of the standard net-to-gross ratio used in the petroleum industry.
- (g) Connectivity: characterization and measurement of the sand and shale geometry, sand and shale lengths, and number of sands or silts in direct contact with one or more other sands or silts.
- (h) Sediment texture: determination of the mean grain size of sands, mean grain size of silts, and mean grain size of the interbedded mud divisions; other textural attributes (e.g., sorting and skewness) can also be quantified.
- (i) Sediment composition: mineralogical or geochemical makeup of the different sediment fractions (sand or mud); siliciclastic, bioclastic, volcanoclastic, chemoclastic, or mixed turbidite types.
- (j) Sediment fabric: the alignment and disposition of individual grains and particles with respect to each other; applicable to both sand and mud fractions.

Attribute Indices

The measurement and quantification of these attributes are discussed in another chapter in this volume (Omoniyi et al., 2018), with application to the North Brae field reservoir. In that chapter we also derive a series of four fundamental variables, which we call *attribute indices*, from a combination of individual attributes. These indices are as follows:

- (a) The facies net-to-gross index (NGI) is aligned closely with the standard net to gross sand value commonly used to evaluate reservoir intervals but is calculated specifically for the section of core and specific facies association present. It provides a clear indication of the relative proximity of deposition or turbidity current energy and competence.
- (b) The sand connectivity index (SCI) indicates the proportion of sand that is in vertical connection with other sand in a specific facies association and is derived from the nature of bed and lamination cross-cutting relationships. It is calculated as a

product of facies NGI (above) and a vertical connectivity factor and provides a more rigorous predictor of TBT–VTBT sand reservoir potential than conventional sand net to gross.

- (c) The facies ratio index (FRI) is derived from the proportion of TBT beds to the sum of TBT and VTBT beds in a characteristic facies association. It is, therefore, distinctive of different depositional environments, proximal to distal relationships, or near-to-far channel location.
- (d) The sediment textural index (STI) is derived from the mean grain-size property of all the TBT–VTBT facies in the specific facies association being considered. In particular, it is a measure of the difference in mean grain size between the coarser grained (sand-silt) beds and the finer grained (mud-rich) interbeds. It, therefore, takes into account the relative ease with which fluid can migrate through and be stored within the mudstone interbeds compared with the sandstone beds. It can provide insight into sediment transport, depositional history, and sediment maturity.

Each index has a numerical value of between 0 and 1 and is calculated either for average 1 m (3 ft) sections of core or, to yield more precise characterization, for specific facies associations within the cored section. A full calculation of the attribute indices is given in Omoniyi et al. (2018) together with an explanation of how they can be applied in a reservoir context. Further work is in progress on a lateral connectivity index and on the application of all indices to reservoir simulation models.

ARCHITECTURAL ELEMENTS AND ENVIRONMENT

Both TBTs and VTBTs occur throughout the spectrum of architectural elements in a variety of deep-water environments (Figure 10). The principal features of these facies within the different elements are summarized in this section. A fuller quantification of each with our new attribute indices is work in progress so that the following contains only a qualitative indication of attribute index values.

- (a) Sheets and drapes on nonchannelized slope aprons, delta-front slopes, and seamount flanks are dominated by TBTs and VTBTs, together with variable amounts of background hemipelagites. These occur in association with thick silt-mud turbidites, disorganized turbidites, and debrites, especially where deposition is rapid, slope angles are high, or seismic activity is prevalent. The bed thickness

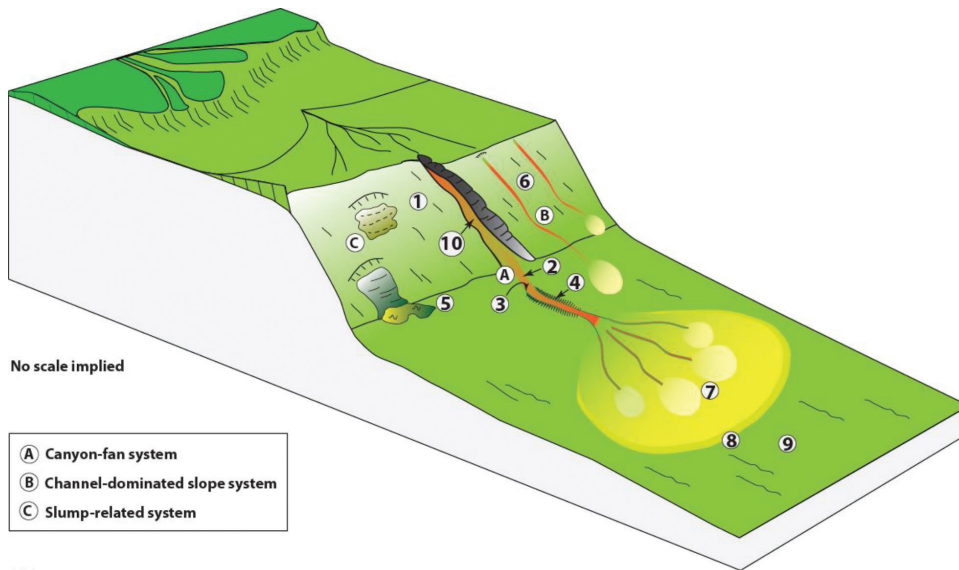
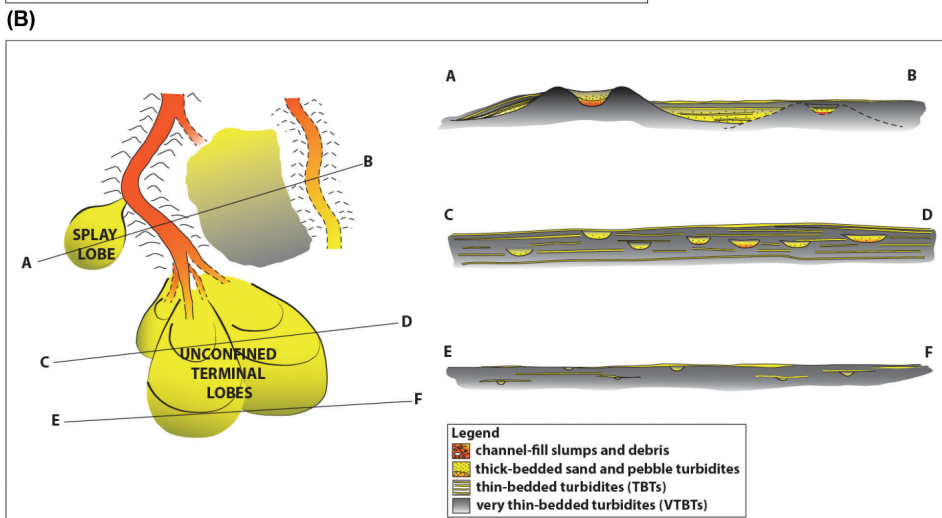
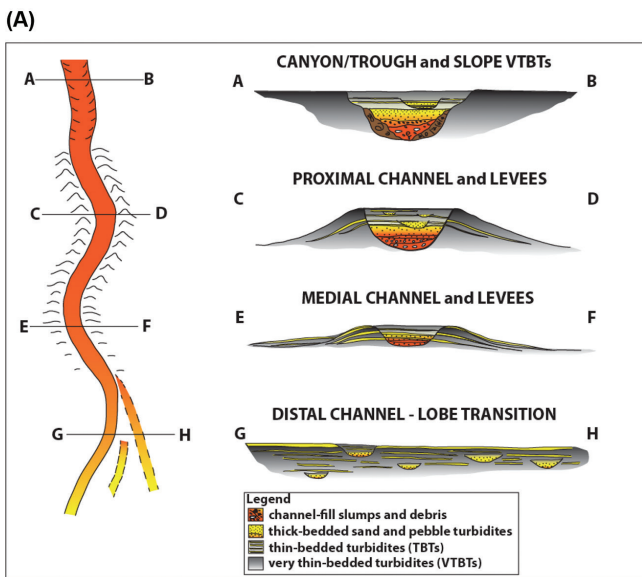


Figure 10. (A) Distribution of TBTs and VTBTs within different deep-water architectural elements. (B) Expanded plan view and cross sections for channel, levee, and channel-lobe transition zones. (C) Expanded plan view and cross sections for channel and different lobe types. In Figure A, numbers shown represent subenvironments: 1 = Nonchannelized slope aprons; 2 = Channel-fill erosional, mixed, and constructional channels; 3 = Channel margin; 4 = Levee and overbanks; 5 = Slide and slump masses; 6 = Interchannel area; 7 = Isolated and clustered lobes, splay lobes, and interchannel lobes; 8 = Lobe fringe; 9 = Basin plain; 10 = Canyon.



(C)

variation is generally random and noncyclic. Sand-shale ratio is relatively low and mean grain size is fine. Each of the attribute indices (NGI, SCI, FRI, and STI) are low or very low.

- (b) Channel-fill in erosional, mixed, and constructional channels is characterized by coarse-grained facies, slumps, and debrites in the lower parts, overlain by medium-bedded turbidites and then TBTs and VTBTs. There is considerable variation between erosional and depositional channels, larger troughs and canyons, smaller gullies and distributaries, and abandoned channel segments so that our generalizations must be treated with caution. The general pattern is one of Bouma TBTs passing upward into Stow VTBTs within an overall thinning-up meso-sequence. Block-like sequences are also common. Disorganized and thick mud turbidites, slumps, and debrites are common, especially in the channel margin region. Thick structureless silt turbidites may be common. Hemipelagites are rare, except toward the very topmost fill. Erosive features and shale clasts may be common. Sand-shale ratio and mean grain size vary from high to low upward through the thin-bedded channel fill section. The lower parts of this show relatively good NGI, SCI, FRI, and STI indices, decreasing in value upward.
- (c) Levee and back-levee deposits flanking constructional channels, and channel over-bank deposits adjacent to more erosional channels, are all dominated by TBTs and VTBTs. Both meso- and micro-sequences are mostly random and noncyclic. They show systematic variation in properties in both down-channel and away-from-channel direction. The near-channel locations comprise the more sand- and silt-rich facies (i.e., more Bouma TBTs, more Stow VTBTs with base-only divisions, higher sand-shale ratios, and greater mean grain size). They also show more chaotic and convolute-laminated silt-mud structures and distinctive thin-bedded silt-rich turbidites. However, in a down-channel direction, there is commonly an increase in sand-rich facies in the more distal regions where the levee height has diminished. In the more sand- and silt-rich deposits, the NGI, SCI, FRI, and STI indices are all intermediate in value, becoming low to very low away-from-channel and in high proximal levees.
- (d) Isolated and clustered lobes in channel-terminal locations, splay lobes, interchannel lobes, and ponded lobes comprise a high proportion of TBTs in a proximal lobe position and more VTBTs in a distal lobe position. The relative proportion of these and of medium-bedded and silt turbidite

facies depends on the size and scale of the depositional system and of how far down-system the lobe occurs. Symmetrical and thickening-up sequences are both common as well as compensation cycles. The proximal parts of lobes have some of the highest values for NGI, SCI, FRI, and STI indices, decreasing distally. Proximal lobes and the channel-lobe transition zone can show more chaotic and convolute sedimentary structures, a greater lenticularity of beds (large and small scale), and marked erosive features and shale clasts.

- (e) Sheet turbidites in basin systems, including small, confined, and large, open basin types, typically comprise abundant TBTs and VTBTs. These are associated with medium- and thick-bedded turbidites and with thick silt and mud turbidites, especially in the smaller basins of tectonically active regions. The large, open basins comprise a greater proportion of VTBTs and hemipelagite and pelagite facies. The intercalation of megaturbidites and turbidites of markedly different compositions is also typical of basin deposits. Both symmetrical meso-sequences and random noncyclic patterns of bed thickness are common, as also are small-scale compensation cycles. Small basins may show moderate to good values of NGI, SCI, FRI, and STI indices, whereas large, open basins may show very low values.

SUMMARY AND SIGNIFICANCE

There is a dominance of TBT and VTBT facies in deep-water systems, occurring throughout the spectrum of architectural elements in deep-water environments. Although previously somewhat neglected, recent studies have begun to focus on these systems, including scientific drilling into modern deposits, industrial exploration in ancient subsurface successions, and detailed fieldwork on ancient outcrops. Oil and gas are already being successfully produced from TBTs in several fields from the Gulf of Mexico (Clemenceau et al., 2000), offshore New Zealand (Browne and Slatt, 2002), off northwest Sabah (Karimi et al., 1997), and the Nile Delta offshore Egypt (Cross et al., 2009).

However, TBTs still represent a relatively neglected potential for deep-water turbidite exploration and production. Large volumes of hydrocarbons are trapped in these systems and difficult to extract without detailed understanding of the sedimentary characteristics. They, therefore, have huge significance as both principal and marginal reservoirs, and for optimizing values of existing reservoirs, particularly in

deep-water systems where investments are high and challenges severe. VTBTs have equally great potential as deep-water source rocks, as unconventional reservoirs, and, in some cases, as good sealing rocks.

When such a large proportion of the world's hydrocarbon reservoirs occur in deep-water turbidite systems the study of the thinner bedded turbidites is of paramount importance (Pettingill, 1998; Stow, 2000; Stow and Mayall, 2000; Browne and Slatt, 2002; Khain and Polyakova, 2004; Gluyas and Garrett, 2005; Hurst et al., 2005).

From this growing data set, we have been able to synthesize the principal characteristics of these fine-grained and thin-bedded facies and present a state-of-the-art review. There is much work still required. In particular, we are developing a more rigorous approach to measuring TBT and VTBT attributes and their combinations to yield quantifiable attribute indices. This then provides quantitative data that can be used to inform our understanding of depositional processes, to distinguish between architectural elements and depositional settings, and to input as a predictive tool in hydrocarbon exploration and production.

Attribute combinations can be used to model fluid flow through TBT and VTBT reservoirs, unconventional reservoirs, source rocks, and seals. Further work will include flow simulation models for different combinations of variable. The different run simulations are expected to yield very significant differences in vertical and horizontal flow behavior for different turbidite settings that we suggest are a valuable predictor for reservoir performance. The next step will be to validate these models against actual reservoir production histories. The nature of fluid flow through or its impedance by various TBT and VTBT associations is critical in assessing reservoir performance and developing reservoir management strategies.

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