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Ten turbidite myths

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Abstract

During the past 50 years, the turbidite paradigm has promoted many myths related to deep-water turbidite deposition. John E. Sanders (1926–1999), a pioneering process sedimentologist, first uncovered many of these turbidite myths. This paper provides a reality check by undoing 10 of these turbidite myths. Myth No. 1: turbidity currents are non-turbulent flows with multiple sediment-support mechanisms. Reality: turbidity currents are turbulent flows in which turbulence is the principal sediment-support mechanism. Myth No. 2: turbidites are deposits of debris flows, grain flows, fluidized flows, and turbidity currents. Reality: turbidites are the exclusive deposits of turbidity currents. Myth No. 3: turbidity currents are high-velocity flows and therefore they elude documentation. Reality: turbidity currents operate under a wide range of velocity conditions. Myth No. 4: high-density turbidity currents are true turbidity currents. Reality: Ph. H. Kuenen (1950) introduced the concept of “turbidity currents of high density” based on experimental debris flows, not turbidity currents. High-density turbidity currents are sandy debris flows. Myth No. 5: slurry flows are high-density turbidity currents. Reality: slurry-flows are debris flows. Myth No. 6: flute structures are indicative of turbidite deposition. Reality: flute structures are indicative only of flow erosion, not deposition. Myth No. 7: normal grading is a product of multiple depositional events. Reality: normal grading is the product of a single depositional event. Myth No. 8: cross-bedding is a product of turbidity currents. Reality: cross-bedding is a product of traction deposition from bottom currents. Myth No. 9: turbidite facies models are useful tools for interpreting deposits of turbidity currents. Reality: a reexamination of the Annot Sandstone in SE France, which served as the basis for developing the first turbidite facies model, suggests a complex depositional origin by plastic flows and bottom currents. Myth No. 10: turbidite facies can be interpreted using seismic facies and geometries. Reality: individual turbidity-current depositional events, commonly centimeters to decimeters in thickness, cannot be resolved in seismic data. All turbidite myths promote falsehood and should be abandoned.

Keywords: turbidites; inertia flows; turbidity currents; high-density turbidity currents; sandy debris flows; liquefied cohesionless coarse-particle flows; deep-water tidal bottom currents; Annot Sandstone

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1. Introduction

1.1. Turbidite controversy

The turbidite paradigm, which is based on the tenet that a vast majority of deep-water sediment is composed of turbidites (i.e., deposits of turbidity currents), has been the subject of controversy for nearly 50 years. The crux of the controversy revolves around disagreements concerning the hydrodynamic properties of turbidity currents and their deposits. Sanders (1965) was the first process sedimentologist to point out misuse of the term “turbidity currents” for processes that are clearly not turbidity currents (Fig. 1). For example, Sanders (1965, p. 218) did not consider

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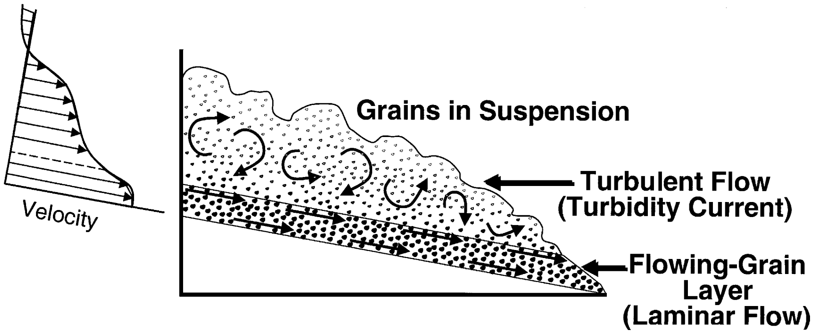


Fig. 1. A schematic profile through a density-stratified flow showing an upper turbulent turbidity current and a lower laminar flowing-grain layer. According to Sanders (1965, p. 218), only turbulent flows are turbidity currents and flowing-grain layers are not turbidity currents. The controversy began when Kuenen advocated the term "turbidity current" for flowing-grain layers that are non-turbulent (see Sanders, 1965, p. 218). Profile, based on experiments of Kuenen (1950), is modified after Sanders (1965).

laminar flowing-grain layers that occur beneath turbulent turbidity currents as turbidity currents (Fig. 1). In addition, field and experimental observations suggested that processes other than turbidity currents (e.g., slides, slumps, debris flows, grain flows, and bottom currents) could have played a major role in depositing deep-water sediment (e.g., Crowell, 1957; Wood and Smith, 1959; Ten Haaf, 1959; Murphy and Schlanger, 1962; Dott, 1963; Hubert, 1964; Sanders, 1965; Hollister, 1967; Stanley, 1967; Van der Lingen, 1969; Fisher, 1971; Jacobi, 1976; Shanmugam, 2000a). In incorporating these complex processes and their deposits into the family of "turbidites," sedimentologists began using the term "turbidite" euphemistically for deposits of deep-sea avalanches, slides, slumps, and debris flows (e.g., fluxoturbidite, megaturbidite, seismoturbidite, high-density turbidite etc.). As a consequence, the turbidite paradigm has reached a pinnacle of confusion and controversy.

Lowe and Guy (2000) claim that recent controversy concerning distinction between turbidity currents and debris flows is due to semantic differences in definitions of sediment–gravity flows. Because one group uses "rheological" definitions based on fluid rheology and the other group uses "sedimentological" definitions based on sediment-support mechanisms, Lowe and Guy (2000) claim that a rheological debris flow may actually be a sedimentological turbidity current. The problem with this dubious distinction between rheology and sedimentology is that any definition of fluids based on rheology, which is primarily controlled by sediment concentration, is also sedimentological! This is because sediment concentration controls not only fluid rheology but also flow turbulence, which is the principal sediment-support mechanism in turbidity currents. High sediment concentrations are known to suppress flow turbulence in sediment flows (Bagnold, 1954, 1956). Sediment flows with high-sediment concentration are not only plastic in rheology, but also laminar in state because of suppressed turbulence (see Shanmugam, 2000a, his Fig. 4).

The real reason for the recent controversy on deep-water processes is much more fundamental than definitions based on rheology vs. sedimentology. In the introduction to the SEPM Special Publication No. 2: Turbidity currents and the transportation of coarse sediments to deep-water, Russell (1951, p. 1) states, "Processes that are not directly observed are difficult to assess." Our inability to directly observe deep-water turbidity currents in modern environments and relate them to the rock record is the primary cause of our ignorance of turbidity currents and related controversies.

1.2. Previous work

My previous work on deep-water deposits forms the basis for this paper. My interest on the turbidite problem began in 1981 during a field trip, organized by Emiliano Mutti and his students, to examine the Eocene Hecho Group in Spain, and the Tertiary

Piedmont Basin in northwestern Italy. The examination of these two basins, considered to be classic examples of "turbidite" deposition, has led to our questioning the use of turbidite facies association schemes by Mutti and Ricci Lucchi (1972) for interpreting submarine fan environments (Shanmugam et al., 1985). Since then, we have discovered inherent problems with turbidite fan models (Shanmugam and Moiola, 1985, 1988, 1995, 1997), documented the disconnect between sequence-stratigraphic models and sedimentary facies based on calibration of core with seismic data (Shanmugam et al., 1995, 1997), challenged the flawed concept of high-density turbidity currents on theoretical grounds (Shanmugam, 1996), critiqued the Bouma Sequence and the turbidite mind set (Shanmugam, 1997), discovered that no one has ever documented an ideal turbidite bed with 16 divisions (Shanmugam, 2000a), discussed the importance of sandy debris flows based on experiments (Shanmugam, 2000a), and emphasized the significance of deep-water tidal bottom currents in submarine canyons (Shanmugam, 2001). Some of these publications have provoked responses. In particular, my recent paper on the turbidite paradigm (Shanmugam, 2000a) has prompted Mutti et al. (1999, p. 5) to comment that, "an extreme example of these problems can be found in a recent paper by Shanmugam (in press), who attempts to dismantle the turbidite paradigm."

1.3. Scope of this paper

A logical outcome of my previous work is the awareness that there are many myths, which form the underpinning of the turbidite paradigm. Therefore, the primary purpose of this paper is to critique 10 popular myths and attempt to undo each one by providing a reality check with relevant supporting data and arguments (Shanmugam, 2002). This paper is different from my previous publications in terms of both philosophy and content. For example, e.g., Sanders' (1963, 1965) pioneering insights into process sedimentology serve as the foundation for this paper (see Shanmugam, 2000b). In this paper, I trace the turbidite controversy back to the founding days of the turbidite paradigm, more than 50 years ago (Kuenen, 1950). More importantly, I present new field evidence that documents the disconnect between the turbidite facies model and the Annot Sandstone in SE France, which served as the basis for developing the turbidite facies model. Hopefully, this paper will stop geoscientists from further populating the scientific literature with "turbidite" falsehood based on myths.

2. Ten turbidite myths

2.1. Myth No. 1: turbidity currents are non-turbulent flows with multiple sediment-support mechanisms

According to Sanders (1965), turbidity currents are density currents caused by sediment in turbulent suspension (Fig. 1). Bagnold's (1954, 1956) experimental observations greatly influenced Sanders' (1965) theoretical analysis in distinguishing turbulent from laminar flows in density-stratified flows (Table 1). Bagnold (1954, 1956) first investigated aggregates of cohesionless grains in Newtonian fluid under shear and introduced the concepts of "inertia" and "viscous" regions based on grain inertia and fluid viscosity, respectively. In the grain–inertia region, the effects of grain concentration and related grain collision (i.e., dispersive pressure) dominate, whereas in the viscous region, the effects of fluid viscosity dominate. More importantly, in the grain–inertia region, high grain concentration tends to suppress fluid turbulence and promote laminar shear. In explaining the suppression of turbulence by grain concentration, Bagnold (1956, p. 288) stated, "At a certain stage the turbulence began to be suppressed, being damped out by the increasing overall shear resistance. And on a further increase in the grain population the turbulence vanished altogether... When the turbulence finally ceased, C was apparently uniform from top to bottom, at about 0.3... Having attained uniformity in the now laminar fluid flow, C could be increased nearly to the mobile limit of about 0.53. Ultimately the whole flow 'froze' simultaneously at all depths." Because a turbulent flow becomes laminar when grain concentration C reaches 30%, theoretically, turbidity currents cannot exist at high concentration values. In other words, high-concentration turbidity currents are not realistic processes.

In characterizing the "Bagnold Effect," Friedman et al. (1992, p. 232) stated, "The key point, which has emerged from studies of the shearing of aggregates of particles, is that almost nothing important about their behavior *en masse* (italics mine) can be predicted from analysis of how an individual particle behaves. Another significant point is that gravity shearing can transport particles even where no fluids are present." This concept of "mass transport" under laminar shear in the inertia region is controversial because it does not attribute sediment transport to the agency of turbulence (Bagnold, 1966, p. I37).

Sanders (1965) first pointed out that high-concentration, non-turbulent, granular layers (i.e., flowing-grain layers or inertia flows) that occur beneath some turbulent turbidity currents are not turbidity currents (Fig. 1). In other words, the basal laminar flows are not turbidity currents. The turbidite controversy erupted when Kuenen (see comment in Sanders, 1965, pp. 217–218) objected to Sanders' (1965) precise definition of turbidity currents using flow turbulence. Instead, Kuenen (see comment in Sanders, 1965, pp. 217–218) advocated a broad definition of "turbidity currents" that included both laminar flows and turbulent flows. This broad definition has been the root of the turbidite controversy (see Myth No. 4).

The generally accepted definition is that turbidity currents are a type of sediment–gravity flow with Newtonian rheology and turbulent state in which the principal sediment-support mechanism is the upward component of fluid turbulence (Dott, 1963; Sanders, 1965; Middleton and Hampton, 1973; Lowe, 1982; Stow et al., 1996; Shanmugam, 2000a). Middleton (1993, p. 93) clearly pointed out that if a flow is laminar or non-turbulent, it could no longer be considered as a turbidity current. However, following the approach of Kuenen (see comment in Sanders, 1965, p. 217–218), Kneller and Buckee (2000, p. 63) claim that turbidity currents can be non-turbulent (i.e., laminar) in state. McCave and Jones (1988, p. 250) also suggest "deposition of ungraded muds from high-density non-turbulent turbidity currents." This is confusing because fully turbulent flows (e.g., turbidity currents) and fully laminar flows (e.g., debris flows) are remarkably different from one another. The transition from laminar to turbulent flow takes place at a critical value of the Reynolds number (*Re*), which is defined as a measure of the ratio of the inertial force to the viscous force in the force balance (e.g., Shapiro, 1961). Turbulent flows develop at values greater than *Re*: 500, and fully turbulent flows occur at *Re*: 2000. This distinction is adequate for geological purposes because fully laminar and fully turbulent flows can be interpreted by examining depositional features of these flows in the rock record (e.g., Fisher, 1971, and Sanders, 1965), although we cannot interpret subtle variations in *Re* by examining core or outcrop.

Based on sediment-support mechanisms, Middleton and Hampton (1973) classified sediment–gravity flows into *debris flows* in which sediment is supported by matrix strength, *grain flows* in which sediment is supported by dispersive pressure, *fluidized flows* in which sediment is supported by fluid escape, and *turbidity currents* in which sediment is supported by fluid turbulence. Middleton and Hampton (1973, p. 2) also suggested the possibility of multiple sediment-support mechanisms in some transitional sediment–gravity flows. This does not negate an end-member turbidity current in which the principal sediment-support mechanism is turbulence. In nature, there are transitional flows in which multiple sediment support mechanisms may operate, but they are not true turbidity currents. These transitional flows and their deposits are poorly understood because of insufficient theoretical and experimental studies. However, Kneller and Buckee (2000, p. 63) misused the term "turbidity currents" for "transitional flows" with multiple sediment-support mechanisms. If we follow Kneller and Buckee's (2000) approach, we end up misinterpreting a wide spectrum of deep-water deposits formed from transitional flows under the catchall term "turbidites." In fact, Mutti et al. (1999) advocate such an imprecise use of the term "turbidite" for deposits of all sediment–gravity flows (see Myth No. 2 next).

2.2. Myth No. 2: turbidites are deposits of debris flows, grain flows, fluidized flows and turbidity currents

The term "turbidites" should refer strictly to those deposits that formed from turbulent suspension by turbidity currents (Sanders, 1965). Also, in the classification scheme of Middleton and Hampton (1973), only deposits of turbidity currents are considered turbidites. However, following the approach of Kuenen (see comment in Sanders, 1965, pp. 217–218), Mutti et al. (1999, p. 19) define "turbidites" as the deposits of all sediment–gravity flows, which include debris flows, grain flows, fluidized sediment flows, and turbidity currents (Fig. 2). In other words, Mutti et al. (1999) would classify deposits of debris flows as

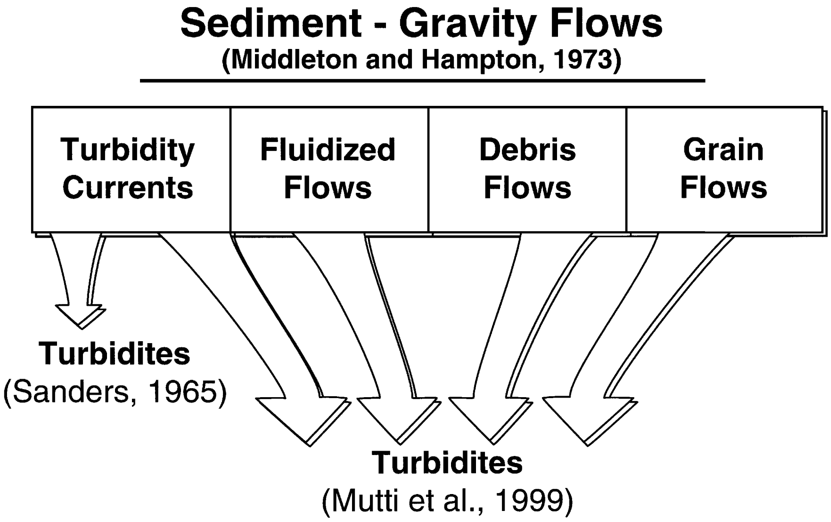


Fig. 2. Two differing definitions of the term "turbidites." According to Sanders (1965), turbidites are the exclusive deposits of turbidity currents. According to Mutti et al. (1999), deposits of all sediment–gravity flows are turbidites. In this study, I follow Sanders' (1965) definition.

turbidites. This approach by Mutti et al. (1999), if applied, would undo the progress made on process sedimentology during the past three decades in distinguishing deposits of debris flows, grain flows, fluidized/liquefied flows, and turbidity currents from one another.

The misuse of the term "turbidite" to deposits of flows that are not turbidity currents is common. For example, Hsu (1989, p. 85) pointed out that the term "fluxoturbidites" was first applied to "sand-avalanche deposits" in the Polish Carpathians by Dzulynski et al. (1959). Mutti et al. (1984) applied the term "seismoturbidites" for large-scale mass-flow deposits. Labaume et al. (1987) used the term "megaturbidite" for deposits of debris flows. Stanley et al. (1978) utilized the terms "atypical turbidites" and "problematica" for deposits of slumps, debris flows, and sand flows. In my view (Shanmugam, 1996), the high-density turbidites of Lowe (1982) are deposits of sandy debris flows.

Carter (1975, p. 147) offered an explanation for the popularity of turbidites by stating, "…the temptation is always to tailor field observations to presently *known* processes of sediment deposition, rather than to tie them to speculative theoretical possibilities; it is therefore not surprising that many published studies of flysch sequences place great emphasis on features explicable by turbidity current hypothesis, and tend to be somewhat skeptical regarding deposition of individual beds by other mass-transport processes." In short, the term "turbidite" is in danger of losing its original meaning.

Different authors use the term "turbidite systems" differently, but none of them make process sedimentological sense. For example, Normark et al. (1985, p. 342) used the term "turbidite systems" to represent *ancient* submarine fans. Mutti (1992) used the term to denote a genetic unit that is mappable. On the other hand, Stelting et al. (2000, p. 2) recently defined the term "turbidite systems" as the deposits of gravity flows. This is confusing because conventionally, the term "gravity flows" represents sediment–gravity flows composed of debris flows, grain flows, fluidized sediment flows, and turbidity currents (Middleton and Hampton, 1973), as well as other gravity-induced mass movements, such as slides and slumps. Because the term "turbidite" represents deposits of turbidity currents exclusively (Sanders, 1965; Middleton and Hampton, 1973), in preserving the original meaning of the term "turbidite," the term "turbidite systems" should also be used to represent deposits of turbidity currents. Otherwise, there is a danger of classifying deposits of debris flows and slumps under the catchall term, "turbidite systems."

2.3. Myth No. 3: turbidity currents are high-velocity flows in submarine canyons and therefore they elude documentation

A common myth is that turbidity currents are common in modern submarine canyons, but that these currents cannot be documented because of their high velocities (Shepard et al., 1979). Up- and down-canyon currents have been documented using current-meter records in modern submarine canyons, ranging in depths from 46 to 4200 m. These bottom currents commonly attain velocities of 25 cm/s and they have been attributed to tidal forces (Shepard et al., 1979). However, a velocity of 190 cm/s (i.e., 6.84 km/h) for a down-canyon current was measured by a current meter that was lost in the Scripps Canyon. Shepard et al. (1979) inferred that this event was a turbidity current because of its high-velocity. The problem with their inference is that turbidity currents are defined on the basis of fluid rheology and flow state, not on flow velocity. One cannot distinguish debris flows from turbidity currents based on flow velocity alone. For example, rapid debris flows are known to have traveled at a speed of 500 km/h (Martinsen, 1994, p. 142). The eruption of Colombia's Nevado del Ruiz volcano in 1985 triggered a subaerial mud flow that traveled at a speed of 320 km/h (The Learning Channel, 1997).

Hydroplaning, which develops only in subaqueous debris flows (Fig. 3), can dramatically reduce the bed drag, and thus increase head velocity (Mohrig et al., 1998). Therefore, subaqueous debris flows are expected to travel faster and farther than subaerial debris flows. For these reasons, I suggest that the flow with a 190 cm/s (i.e., 6.84 km/h) velocity in the Scripps Canyon could as well have been a debris flow.

Shepard and Dill (1966, their Figs. 55, 63, 139) published several underwater photographs of modern mass flows from various submarine canyons around the world. Shepard et al. (1969, their Figs. 6, 7, 9) also published photographs of modern debris flows from the La Jolla Canyon in California. Ironically, there are no photographs of turbidity currents from modern canyons. There is no geological reason why all turbidity currents should be high-velocity flows and should elude documentation. Like all other sediment–gravity flows, turbidity currents can operate under a wide range of velocity conditions based on sediment concentration, sea-floor gradient, etc. The reason we have been unable to photograph turbidity currents in submarine canyons is perhaps because turbidity currents are truly rare.

2.4. Myth No. 4: "high-density turbidity currents" are true turbidity currents

Kuenen (1950, p. 44) envisioned the concept of "high-density turbidity current" for subaqueous mud flows. With this false notion, Kuenen (1950) conducted three series of experiments using an aquarium, a ditch, and a tank. In his experiments using an aquarium of 2 m length and 50 cm depth and breadth, Kuenen (1950) used slurries of sand, clay, and gravel with flow densities of up to 2 g/cm^3 on a slope of 8.5°. Unfortunately, Kuenen (1950) used the wrong term, "turbidity currents of high density," for density-stratified flows with high densities of 2 g/cm^3 that are clearly debris flows or mud flows (e.g., Hampton, 1972). The clay content (23–33% of total solids by weight) in Kuenen's (1951) experiments was so high that these experimental flows are considered to be debris flows (e.g., Oakeshott, 1989). Furthermore, in Kuenen's (1951, p. 15) experiments, flows were observed to slide down the slope, move like a glacier, break up into slabs, crack on the surface, and come to rest, suggesting mechanisms of slides and debris flows rather than mechanisms of turbidity currents. As Sanders (1965, his Fig. 3) pointed out, Kuenen's (1950) experiments on "turbidity currents of high density" or "high-density turbidity currents" generated density-stratified flows with a lower laminar layer (i.e., flowing grain layer) and an upper turbulent layer (i.e., turbidity current) (see Fig. 1).

Sanders and Friedman (1997) preferred the term "liquefied cohesionless coarse-particle flow" for the basal laminar layer (see also Friedman and Sanders, 1978; Sanders, 1981; Friedman et al., 1992). The basal layer is characterized by: (1) shearing of cohesionless coarse particles, (2) grain collision and dispersive pressure, (3) laminar shearing, (4) dilation of the body of particles and liquefaction, (5) transportation of particles en masse, (7) movement of particles independent of overriding turbidity current, (8) different velocity than overriding turbidity current, and (9) deposition of structureless sand. John E. Sanders used several synonymous terms for the basal laminar flow:

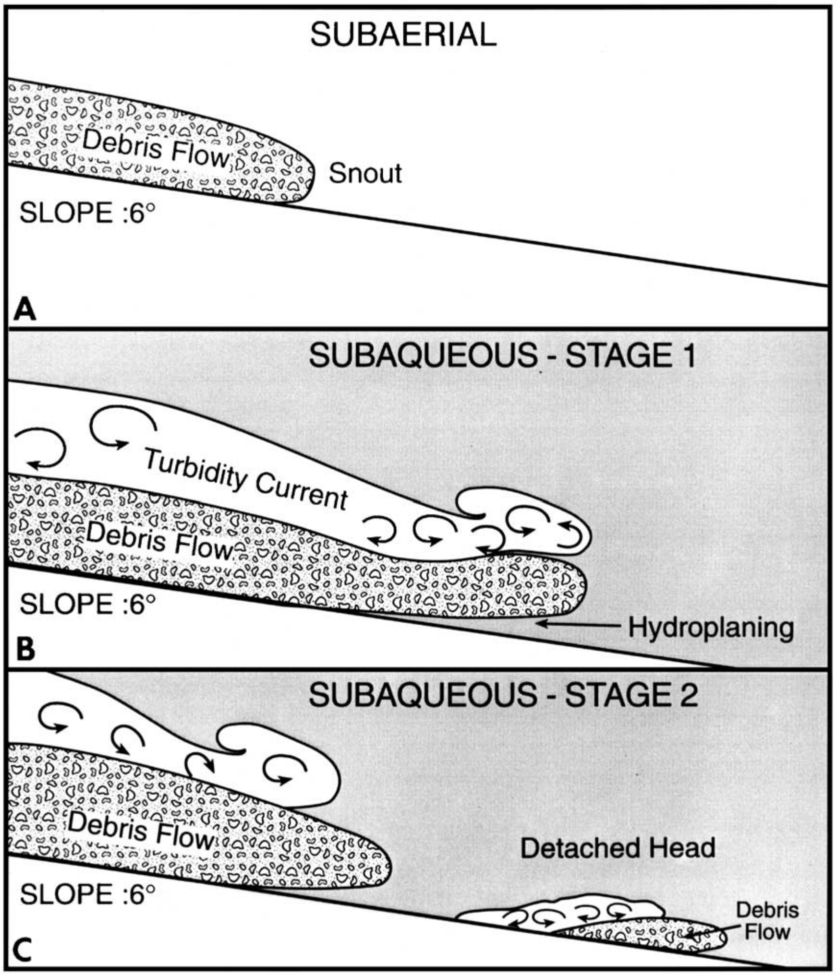
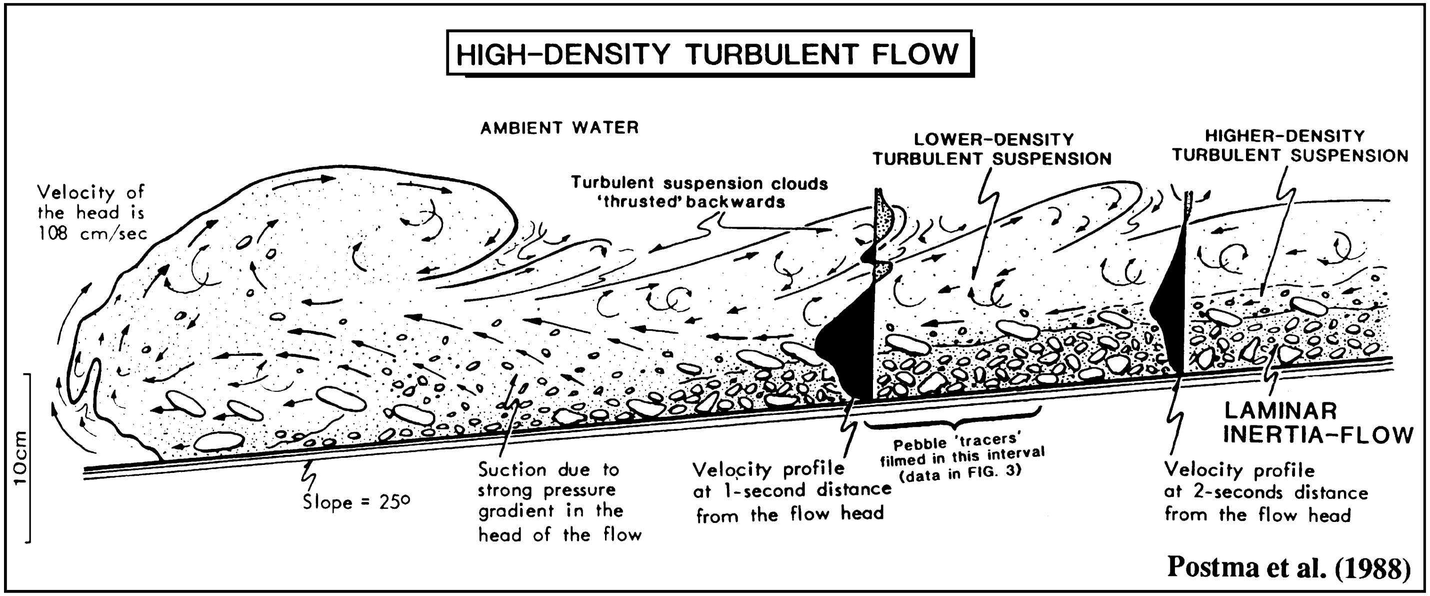


Fig. 3. Three profiles of experimental debris flows. (A) Slow-moving subaerial debris flow without hydroplaning. (B) Fast-moving subaqueous debris flow with hydroplaning (arrow) beneath the head of debris flow. Mohrig et al. (1998) discussed the concept of hydroplaning. (C) Subaqueous debris flow with hydroplaning and a detached head. Detached heads can travel long distances. Profiles are based on the author's observations of experiments by Mohrig et al. (1998) and Marr et al. (1997, 2001).

(1) traction carpet, (2) flowing-grain layer, (3) inertia flow, (4) fluidized flowing-grain layer, (5) inertia-flow layer, (6) avalanching flow, (7) inertial flow, (8) grain flow, (9) mass flow, (10) rheologic bed stage, and (11) fluidized cohesionless-particle flow (Table 1). I suggested the term sandy debris flow for the basal laminar layer (Shanmugam, 1996). The significance of this laminar flow is that it can be used to explain the origin of structureless (i.e., massive) coarse sandy and gravelly sediment in deep-water sequences.

Although Kuenen's (1950) experimental settings were primitive, Sander's (1965, his Fig. 3) perception of Kuenen's experiments is corroborated by later, more sophisticated, flume experiments. For example, Postma et al. (1988) produced density-stratified flows with a basal, high-concentration, laminar inertia-flow and an upper, low-concentration, turbulent flow (Fig. 4). In supporting Sanders' (1965) inertia-flow concept, Postma et al. (1988) used the term "laminar inertia flow" for the basal laminar flow (see Fig. 4).

Flume experiments by Marr et al. (1997, 2001) also developed density-stratified flows with a basal laminar sandy debris flow and an upper turbulent flow (Fig. 5). Depending on clay and water contents, they



Postma et al. (1988)

Fig. 4. A profile of experimental "high-density turbidity current" showing density stratification. Note a lower laminar inertia-flow and an upper turbulent flow. From Postma et al. (1988).

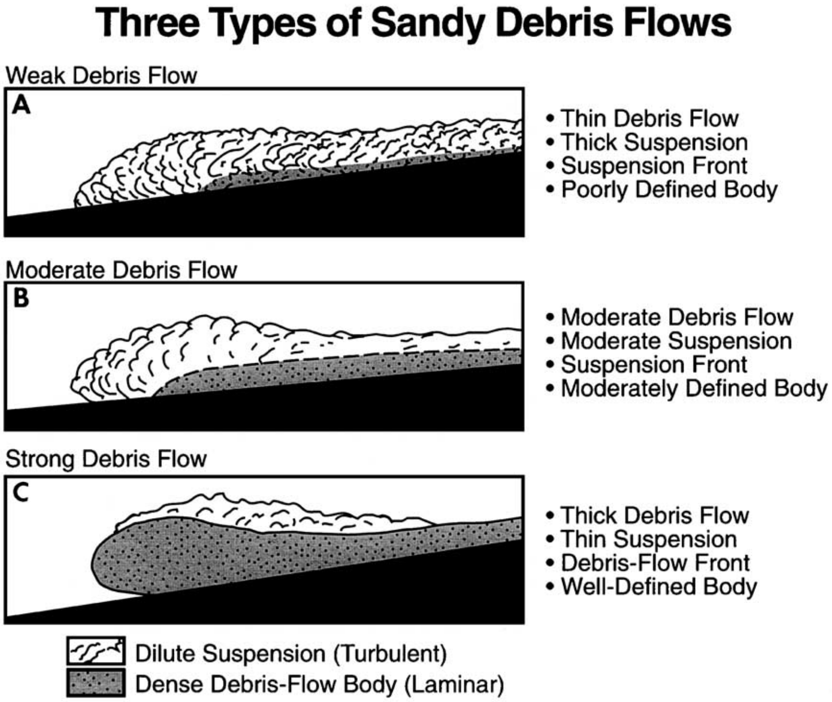


Fig. 5. Three profiles of experimental sandy debris flows showing density stratification in weak (A), moderate (B), and strong (C) types. Strong debris flows develop in slurries with high clay content and/or low water content (see Shanmugam, 2000a, his Fig. 14). Profiles are based on experiments of Marr et al. (1997, 2001).

developed three basic types of sandy debris flows, namely (1) weak, (2) moderate, and (3) strong types (Fig. 5). High clay content and/or low water content develop strong sandy debris flows (see Shanmugam, 2000a, his Fig. 14). Vrolijk and Southard (1997) reported the development of basal "laminar-sheared layers" beneath turbulent flows in their experiments. Table 1 summarizes Sanders' pioneering insights into density-stratified flows and his influence on subsequent studies.

During the founding days of the turbidite paradigm, Kuenen (1950) misused the term "turbidity currents of high density" for density-stratified flows with basal laminar debris flows. Many authors still continue to apply this flawed concept (e.g., Pickering et al., 1989; Mutti, 1992; Mutti et al., 1999). In justifying their continued use of the concept of "high-density turbidity currents," Mutti et al. (1999, p. 22) state, "The concept of basal granular layer coincides with that of 'high-density turbidity current' (cf. Lowe, 1982), the latter term being very popular among many sedimentologists and probably the easiest to use for general purposes of communication." We should use a concept because it is scientifically sound, not because it is popular.

The concept of "high-density turbidity currents" has been the epicenter of controversy for over 50 years. This is because the concept has been defined on the basis of five different properties, namely, (1) flow density (Kuenen, 1950) or grain concentration (Pickering et al., 2001), (2) driving force (Postma et al., 1988), (3) grain size (Lowe, 1982), (4) flow velocity (Kneller, 1995), and (5) rate of deposition (see Shanmugam, 2000a). These differing definitions are not consistent with one another in terms of Newtonian rheology, turbulent state and the principal sediment-support mechanism of turbulence, which define turbidity currents.

In my view, the concept of "high-density turbidity currents" is flawed because it represents sandy debris flows, not true turbidity currents (Shanmugam, 1996, 1997, 2000a). Other authors have also expressed

Table 1
Evolution of concepts on density-stratified flows with an emphasis on Sanders' pioneering insights

References	Upper, turbulent, low-concentration flow	Lower, laminar, high-concentration flow
Bagnold (1954, 1956) *	viscous region in which effects of fluid viscosity dominate	inertia region in which effects of grain inertia dominate
Dzulynski and Sanders (1962)	turbidity current	traction carpet
Sanders (1965)	turbidity current (Fig. 1)	*synonymous terms*: flowing-grain layer (p. 192); inertia flow (p. 194); fluidized flowing-grain layer (p. 210); inertia-flow layer (p. 211); avalanching flow (p. 213)
Friedman and Sanders (1978), Sanders (1981), Friedman et al. (1992, p. 335)	turbidity current (suspended load)	liquefied cohesionless-particle flow (bed load), *synonymous terms*: inertial flow; grain flow; mass flow; rheologic bed stage; fluidized cohesionless-particle flow
Sanders and Friedman (1997)	turbidity current	liquefied cohesionless coarse-particle flow
Kuenen (1951) *	turbidity current	slide
Dzulynski et al. (1959)	turbidity current	fluxoturbidity current
Carter (1975)	grain flow	slurry flow
Postma et al. (1988) *	turbulent suspension (Fig. 4)	laminar inertia-flow (Fig. 4)
Shanmugam (1996)	turbidity current	sandy debris flow
Marr et al. (1997, 2001) *	turbidity current	sandy debris flow
Vrolijk and Southard (1997) *	turbulent flow	laminar sheared layer
Kuenen (1950, 1951) *	turbidity currents of high density	
Bagnold (1956) *	grain flow	
Middleton (1967) *	high-concentration turbidity current	
Lowe (1982)	high-density turbidity current	
Postma et al. (1988) *	high-density turbidity current (Fig. 4)	
Mutti et al. (1999)	high-density turbidity current	
Lowe and Guy (2000)	slurry flow	

* Experimental studies.

doubts about the concept of "high-density turbidity currents." Hallworth and Huppert (1998, p. 1083), based on their experiments of high-concentration gravity flows with density stratification, stated that "...we are still unsure of the physical causes behind the effects we present here..." Kneller and Buckee (2000, p. 87) emphasized that "...existing theory seems inadequate to explain the behavior of some highly mobile dense dispersions, and arguments based solely on the geological interpretation of deposits may be inadequate to resolve issues of process."

Pickering and Hilton (1998, p. 89) concluded, "Of course, the precise hydrodynamic conditions and sediment concentrations of high-concentration turbidity currents remains unresolved." Disappointingly, these authors went on to apply the concept of "high-density turbidity currents" in their recent studies (e.g., Pickering et al., 2001). Our emotional attraction to the muddled concept of "high-density turbidity currents" is troubling.

2.5. Myth No. 5: slurry-flows are "high-density turbidity currents"

Conventionally, many authors (e.g., Carter, 1975; Stanley et al., 1978; Mutti et al., 1978; Hiscott and Middleton, 1979; Pierson and Costa, 1987) considered slurry-flows to be debris flows. Lowe and Guy (2000), however, equated slurry-flows with "high-density turbidity currents." Does this mean that slurry-flows, debris flows, and "high-density turbidity currents" are one and the same process? Clearly, the paper by Lowe and Guy (2000) has added another candidate to the lexicon of turbidite myths.

In justifying that slurry-flows are indeed "high-density turbidity currents," Lowe and Guy (2000, p.

65) state, "These cohesion dominated sublayers are analogous in many ways to friction-dominated traction carpets described previously from turbidity currents (Hiscott and Middleton, 1979; Lowe, 1982) and can be termed cohesive traction carpets." Traction carpets generally develop in mud-free or mud-poor basal granular layers due to dispersive pressure caused by grain collisions in gravity currents. In slurry-flows, however, high mud content should greatly reduce the chances of collision between grains and diminish the development of traction carpets. Lowe and Guy (2000) failed to explain this mechanical paradox.

Lowe and Guy (2000, p. 66) claim that slurry-flows underwent a number of flow transformations, however, they do not present physical evidence. This is because all we can infer from the depositional record is what happened during the final moments of deposition. Our inability to recognize flow transformations that occur during transport or just before deposition is the single most important, and yet unresolved, issue in deep-water process sedimentology (see Shanmugam, 2000a). We will never resolve this issue of flow transformation because it would be like attempting to establish the previous life history of a human being after reincarnation!

Lowe and Guy (2000) proposed a sequence of structures for "slurry-flow" deposits (M_1, M_2, M_3, M_4, M_5, M_6, and M_7). More importantly, Lowe and Guy (2000) suggested that these "slurry-flow" divisions are comparable to the vertical sequence of fine-grained turbidites (T_a, T_b, T_c, T_d, and T_e) proposed by Bouma (1962) and to the vertical sequence of coarse-grained turbidites or high-density turbidites (R_1, R_2, R_3, S_1, S_2, and S_3) proposed by Lowe (1982). The comparative analogy of these three facies models results in the following:

$M_1 = S_1$
M_2 and $M_3 = S_2$
$M_4 = S_3 = T_a$
$M_5 = T_b$, T_c, T_d, and T_e
M_6 and M_7 = post-depositional structures that have no equivalents with structures in the models of Bouma (1962) and Lowe (1982).

By comparing the vertical sequence of "slurry-flow" deposits with the "Bouma Sequence," Lowe and Guy (2000) implied that the "slurry-flow" sequence represents a single depositional event. Otherwise, it would be sedimentologically meaningless to propose a vertical sequence from multiple depositional events. Because slurry-flow "beds" are amalgamated units that represent multiple, random, depositional events (Lowe and Guy, 2000), the proposed vertical sequence of slurry-flow deposits is meaningless. Because Lowe and Guy (2000) attempt to manufacture an artificial order from natural chaos, their concepts of both "slurry-flows" and "high-density turbidity currents" are considered here as myths.

2.6. Myth No. 6: flute structures are indicative of turbidite deposition

It is a common practice to interpret deep-water sands that contain flutes as sole marks as turbidites (e.g., Hiscott and Middleton, 1979). The assumption is that the head of a turbidity current was turbulent and that the turbulence created the scour. The other assumption is that the scour was subsequently filled by the body of the same turbidity current. Care must be exercised in making these assumptions.

Flutes simply suggest that a turbulent state of the flow was responsible for creating the scour. However, flutes do not imply that the sand that rests on a scour surface was deposited by the same turbulent flow that created the scour surface (Sanders, 1965, p. 209). Scour surfaces, for example, can be created initially by turbulent flows and filled later by debris flows or other processes. Modern unfilled submarine channels and canyons are a testimony to the fact that the processes that created these erosional features in the past are probably not the same processes that will fill them in the future. Furthermore, scour surfaces can also be created by processes other than turbidity currents, such as geostrophic currents (Myrow and Southard, 1996) and bottom currents (Klein, 1966). In a modern tidal flat at Abu Dhabi, Friedman and Sanders (1974) observed positive-relief "bedforms" that resemble molds of flutes. These flutes are ascribed to sheet flow of incoming tide (Friedman and Sanders, 1974).

Because flutes can be formed by processes other than turbidity currents, the routine interpretation of flutes as evidence for turbidite deposition is wrong. The origin of deep-water sands should be based on their internal depositional features, not on their erosional basal contacts or sole marks.

2.7. Myth No. 7: normal grading is a product of multiple depositional events

Kuenen and Migliorini (1950, p. 99) and Kuenen (1967, p. 212) introduced the concept of normal grading for turbidites deposited by a single waning turbidity current. Many workers have adopted the concept of normal grading for turbidites (e.g., Bouma, 1962; Harms and Fahnestock 1965, p. 109; Sanders, 1965; Middleton, 1967). In a waning flow, velocity (u) decreases with time (t). As a result, a waning flow would deposit coarse-grained material first followed by fine-grained material, causing a normal grading (Fig. 6).

The AGI Glossary of Geology (Bates and Jackson, 1980, p. 269) also explained the origin of graded bedding (i.e., normal grading) by "deposition from a single short-lived turbidity current." The link between normal grading and its deposition from a single turbidity current event is the single most important concept in process sedimentology of turbidites. However, Lowe and Guy (2000) apply the concept of "normal grading" erroneously for an amalgamated unit (i.e., their type II slurry) deposited by multiple depositional events of slurry-flows. Lowe and Guy (2000, p. 59), who consider slurry-flows as a type of turbidity currents (i.e., high-density turbidity currents), state, "...types II, III, and IV, tend to show well-developed normal grading in both mean and max5 measures (their Figs. 24–26)." In describing the type II slurry, Lowe and Guy (2000) also state (see caption of their Fig. 24, p. 61), "...this bed is an amalgamated bed representing a succession of flows or flow surges."

Mulder et al. (2001) used the term "normal grading" for a unit that is composed of multiple sand and mud layers deposited from multiple events (see their Fig. 2). Furthermore, Mulder et al. (2001) included four subintervals of "inverse grading" as part of "normal grading" (Mulder et al., 2001, their Fig. 2). Clearly, the term "normal grading" has lost its original process-sedimentologic meaning for a single depositional event. In other words, one can manufacture normal grading in a depositional package, composed of multiple depositional events, by selectively designating a coarse bottom unit and a fine top unit in arriving at a desired outcome. Such a "normal grading" is sedimentologically meaningless.

A normally graded turbidite bed should represent a single depositional event. However, in the Annot Sandstone (Eocene–Oligocene) of the French Maritime Alps, sandstone units are amalgamated, representing multiple depositional events. This observation is critical because the Annot Sandstone served as the basis for developing the first turbidite facies model (Bouma, 1962). An important attribute of the Annot Sandstone is the claim that virtually every sandstone bed is normally graded (see Bouma, 1962, his measured sections K, ABC, and Q in Enclosures I, II, and III). Although, at first glance, the Annot Sandstone appears to show normal grading, detailed description offers a different story.

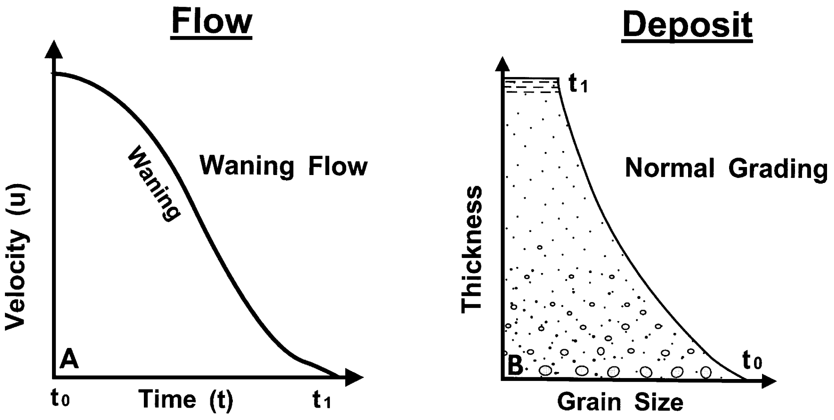


Fig. 6. (A) Waning flow in which velocity (u) decreases with time (t). (B) Normal grading is the product of a waning flow from which deposition of coarse-grained material is followed by fine-grained material. Normal grading is the product of a single depositional event. Normal grading does not contain complex features, such as sudden vertical increase in grain size or floating granules and floating mudstone clasts.

In understanding the nature of "normal grading" and related complexities, I selected 12 sandstone units of the Annot Sandstone, exposed along a road section in the Peira Cava area of French Maritime Alps (Fig. 7), for detailed field examination. Bouma (1962, p. 93, his Fig. 23) and Lanteaume et al. (1967) first used this road section in their studies of the Annot Sandstone. Unit 9 in this study corresponds to Bouma's (1962) Layer No. 1 in his measured section K (see Bouma, 1962, Enclosures I in inside pocket of back book cover). My study shows that these 12 sandstone units are amalgamated in nature and they represent products of multiple depositional events that include both sandy debris flows and bottom currents.

Although Unit 1 appears to show "normal grading" (i.e., vertical *decrease* in grain size), it exhibits a sudden vertical *increase* in grain size with lenticular layers (see 4.6–5 m, Fig. 8). This sudden jump in grain size cannot be considered as part of normal grading and it cannot be interpreted as a product of a single waning flow. Lenticular layers are lenses of granule-sized particles of quartz, feldspar and rock fragments in fine- to medium-grained sandstone. Long axes of lenticular layers are aligned parallel to bedding plane (Fig. 8). Unit 1 clearly represents an amalgamated sandstone unit deposited by multiple episodes of plastic flows and bottom currents.

Unit 8 shows pockets of gravel in what appears to be a "normally graded" fine-grained sandstone interval (Fig. 9). Gravel material in the pocket includes quartz, feldspar, rock fragments, and mudstone clasts. Although Bouma (1962) emphasized the normal grading in the Annot Sandstone, he did not report the presence of basal inverse grading, floating armored mud balls, lenticular layers, and pockets of gravels, observed in Unit 8 (Fig. 9). This unit clearly represents an amalgamated sandstone unit deposited by multiple episodes of plastic flows.

Depending on the degree of details observed in the field, the same unit could be described and interpreted differently by different workers. For example, with the least amount of detail (Level 1, Fig. 10), Unit 8 can be described as a simple "normally graded" bed, but with the most amount of detail (Level 3, Fig. 10) the same Unit 8 can also be described as "amalgamated." The significance of these differences in detail is that the level 1 description would ignore pockets of gravels and inverse grading, whereas the level 3 description would include pockets of gravels and inverse grading. Level 2 represents an intermediate degree of detail. As a result, the level 1 description would result in an interpretation of the unit as deposit of a single waning turbidity current, whereas the level 3 description would result in an interpretation of the unit as deposits of multiple depositional events by sandy debris flows and bottom currents.

Based on a careful evaluation of published field details of the Annot Sandstone (see Bouma, 1962, his measured sections K, ABC, and Q in Enclosures I, II, and III), I suggest that Bouma (1962) described the Annot Sandstone at levels 1 and 2 degree of detail. For example, published graphic logs of 157 layers in measured sections of K (38 layers), ABC (28 layers), and Q (91 layers) show level 1 degree of detail (Bouma, 1962, his Enclosures I, II, and III). In contrast, I described the same beds at level 3 degree of detail. This would explain why Bouma (1962) interpreted these units as "turbidites," whereas I interpret them as deposits of plastic debris flows and bottom currents. This difference in level of detail in field description would also explain the over population of "turbidites" in the published literature.

2.8. Myth No. 8: cross-bedding is a product of turbidity currents

The origin of cross-bedding by turbidity currents is controversial because the principal mode of deposition from turbidity current is suspension settling, whereas cross-beds are the result of traction deposition. Also, in laboratory experiments no one has ever generated cross-bedding by turbidity currents. In spite of these problems, turbidity currents of varying densities have been proposed in explaining the origin of cross-beds. These proposals are: (1) high-density turbidity currents (Lowe, 1982), (2) moderate- to low-density turbidity currents (Piper, 1970; Winn and Dott, 1979), and (3) low-density turbidity currents (Martinsen, 1994). Until we establish a genetic link between turbidity currents and cross-bedding either by direct observation in deep-water environments or by experimental studies in the laboratory, the origin of cross-bedding by turbidity currents would remain controversial.

Bouma and Coleman (1985) interpreted the deep-water Annot Sandstone with cross-bedding (Fig. 11), exposed in Peira Cava area in SE France (Fig. 7), as

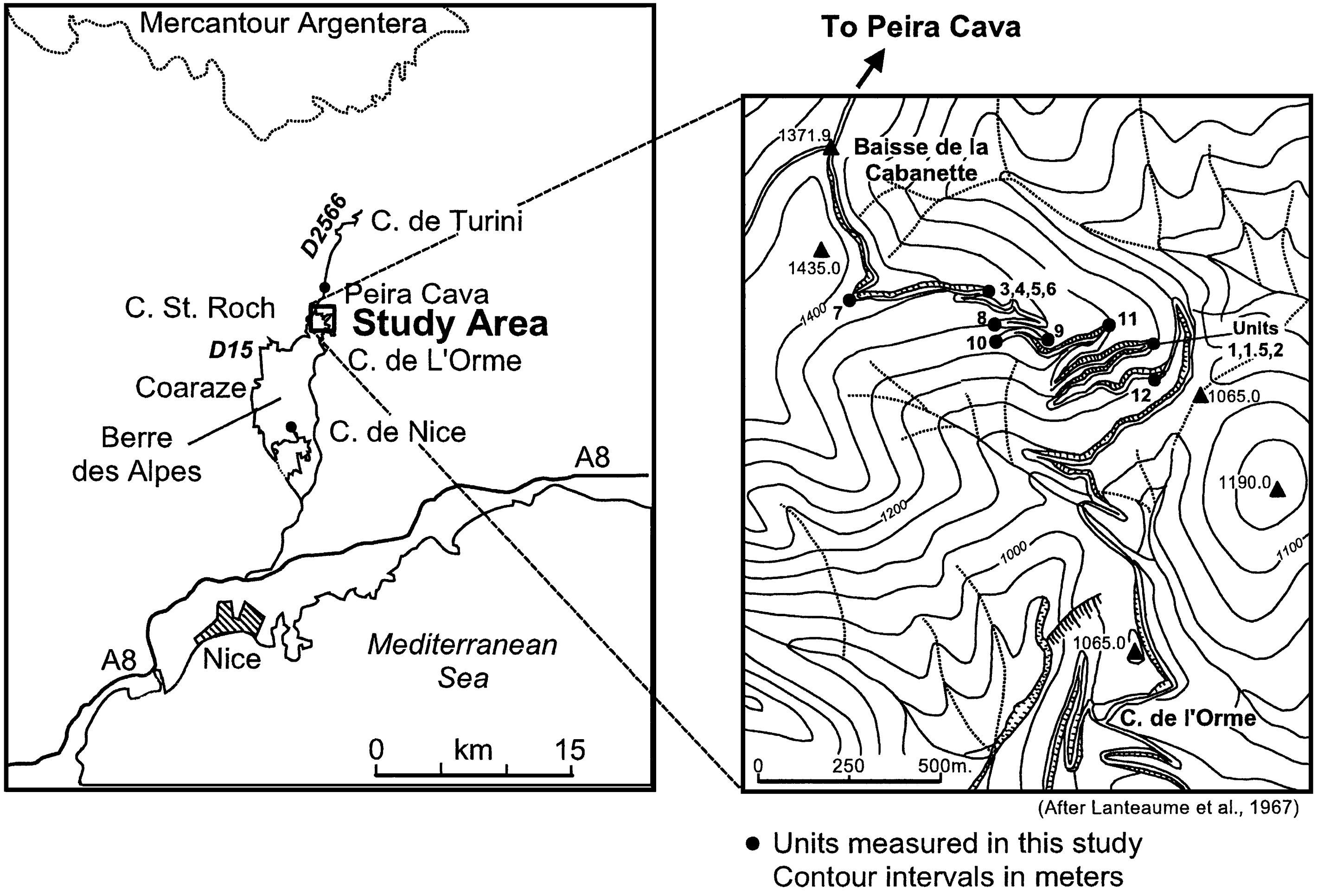


Fig. 7. Location map showing sites of 12 measured units of the Annot Sandstone (Eocene–Oligocene) along a road section, near Peira Cava area, French Maritime Alps. Bouma (1962, p. 93, his Fig. 23) used this road section, among others, in his study of the Annot Sandstone in developing the turbidite facies model. Unit 9 in this study corresponds to Bouma's Layer No. 1 in his measured section K (see Bouma, 1962, Enclosures I in inside pocket of back book cover). An outcrop photograph of Layer No. 1 is published by Bouma (1962, see Plate H1). Each unit in this study represents a major sandstone body and closely related minor sandstone and mudstone beds. Map is simplified after Lanteaume et al. (1967).

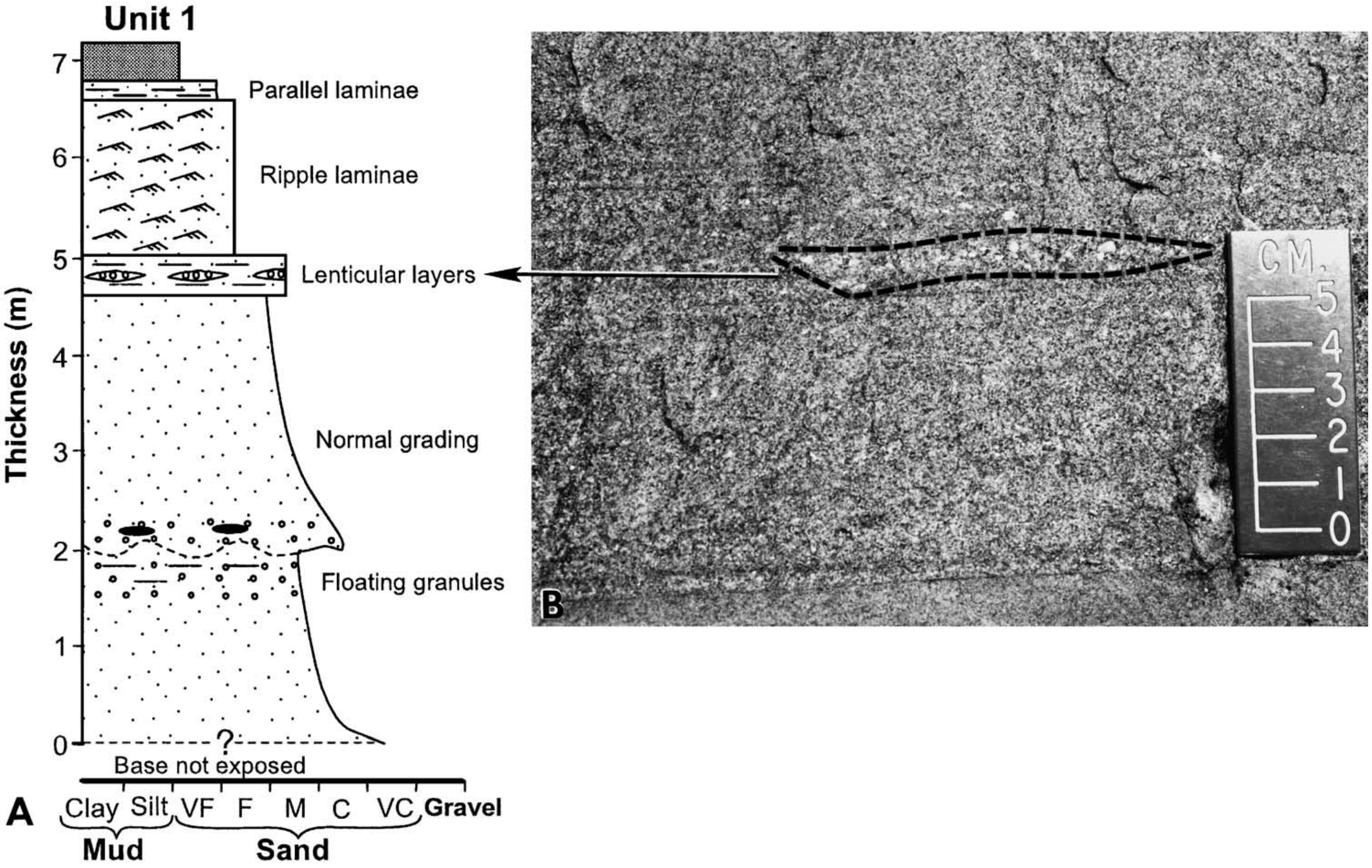


Fig. 8. (A) Sedimentological log of an amalgamated sandstone unit showing floating granules, a sudden increase in grain size (4.6–5 m) with lenticular layers, and a sudden decrease in grain size in the overlying division with ripple laminae. Although the entire unit appears to be normally graded, it is amalgamated and therefore it cannot be deposited from a single waning flow. (B) Outcrop photograph showing a lenticular layer, which is a lense (dashed line) of granule-sized particles of quartz, feldspar, and rock fragments in fine- to medium-grained sandstone. Long axes of lenticular layers are aligned parallel to bedding plane. Arrow shows stratigraphic position of photo. Unit 1 (see Fig. 7 for location), Annot Sandstone (Eocene–Oligocene), Peira Cava area, French Maritime Alps.

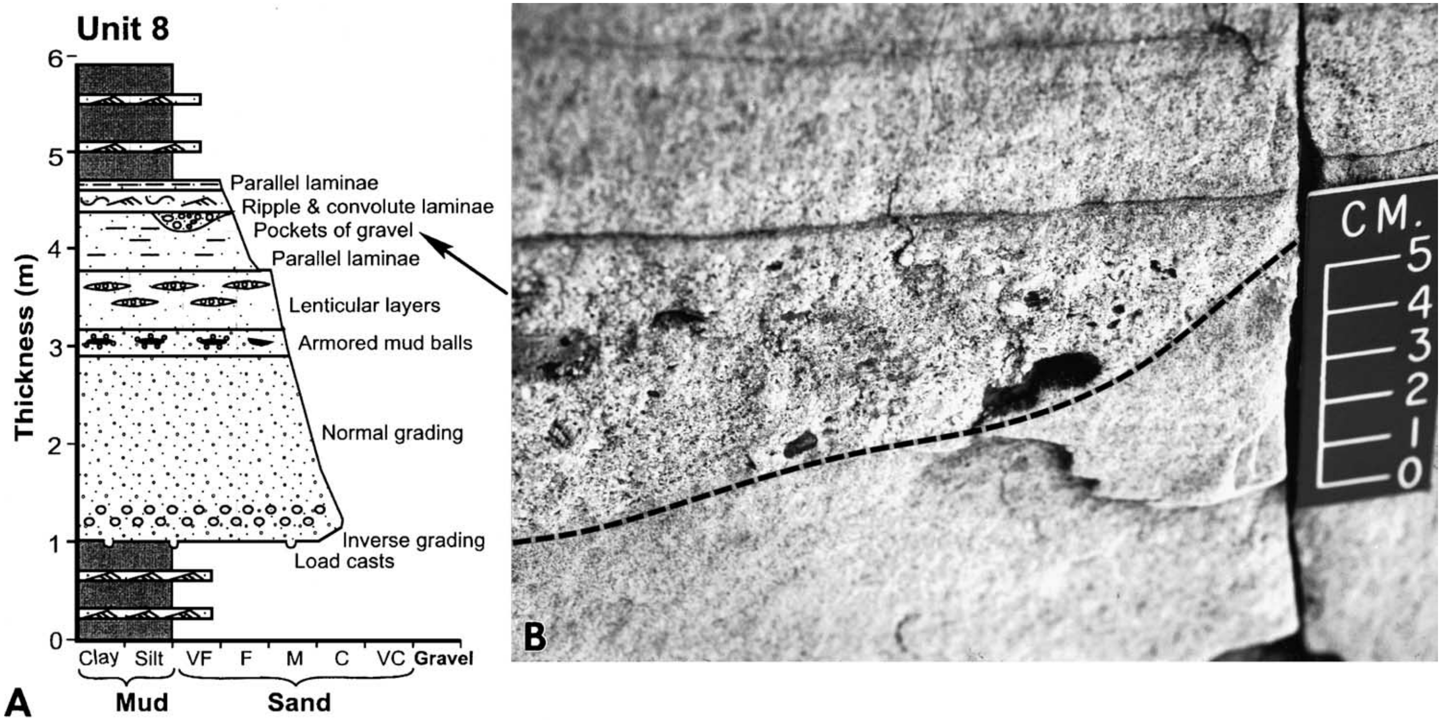


Fig. 9. (A) Sedimentological log of an amalgamated sandstone unit showing basal inverse grading, floating armored mud balls, lenticular layers, and pockets of gravel. Although the entire unit appears to be normally graded, it is amalgamated and therefore it cannot be deposited from a single waning flow. I suggest a complex origin by multiple events of plastic flows and bottom currents. (B) Outcrop photograph showing a pocket of gravel (dashed line). This pocket is composed of gravel-sized particles of quartz, feldspar, rock fragments, and mudstone clasts in fine-grained sandstone. Arrow shows stratigraphic position of photo. Unit 8 (see Fig. 7 for location), Annot Sandstone (Eocene–Oligocene), Peira Cava area, French Maritime Alps.

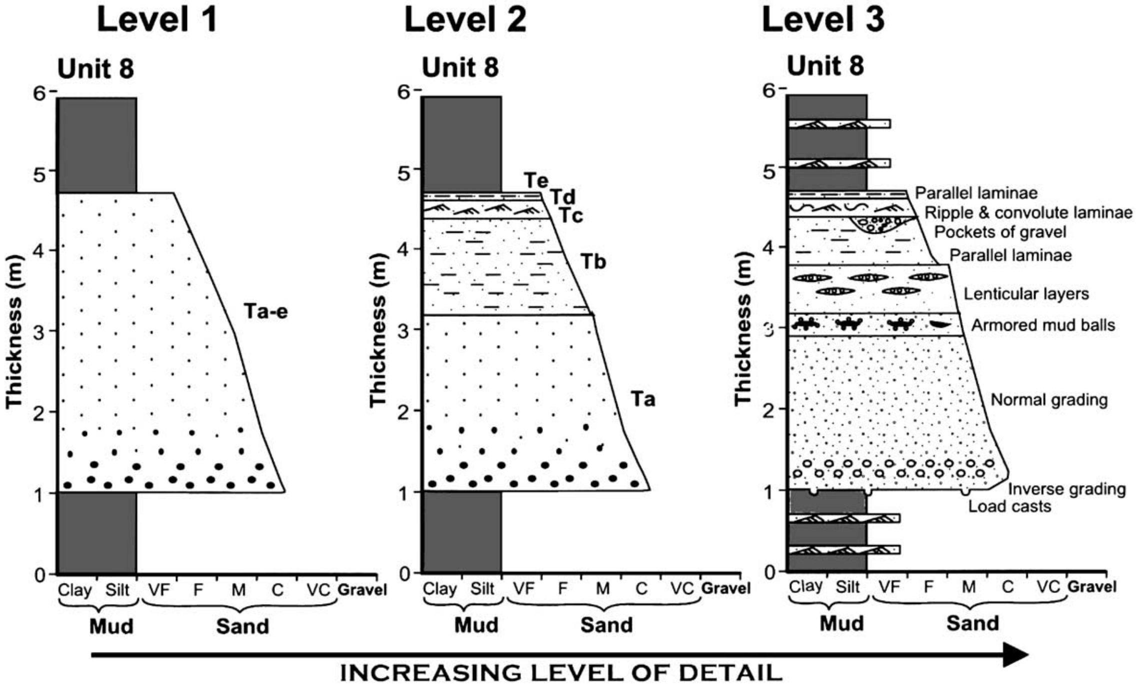


Fig. 10. Diagram showing three increasing levels of detail in the field description of Unit 8. Level 1: low degree of detail that shows a simple normally graded bed. Note the absence of basal inverse grading and other complex features. This level of detail would result in interpretation of the sandstone unit as the deposit of a single turbidity current. Bouma's (1962) published graphic logs of 157 layers in measured sections of K (38 layers), ABC (28 layers), and Q (91 layers), which include Unit 8 of this study, show level 1 degree of detail (see Bouma, 1962, his Enclosures I, II, and III). Level 2: moderate degree of detail that shows a normally graded bed with "Bouma" divisions. This level of detail would also result in a turbidity current interpretation. Level 3: high degree of detail showing basal inverse grading, armored mud balls, lenticular layers, and pockets of gravels. This level of detail would result in interpretation of the unit as the deposit of multiple depositional events by plastic flows and bottom currents. I described units of the Annot Sandstone at level 3. Unit 8 (see Fig. 7 for location), Annot Sandstone (Eocene–Oligocene), Peira Cava area, French Maritime Alps.

lateral accretionary channel–fill turbidites using fluvial point-bar analogy. My detailed examination of these same cross-beds shows mud/mica-draped tangential toesets (Fig. 12, also see Bouma and Coleman, 1985, their Fig. 5) and fanning (i.e., thickening) of the foresets in medium- to coarse-grade sandstone (Fig. 11). These structures exhibit an overall sigmoidal shape in outcrop (Fig. 11). The presence of tangential toesets, steeply dipping foresets, and fanning of the foresets may be equivalent to the full-vortex part of tidal bundles in the shallow-water mesotidal deposits of the North Sea (Terwindt, 1981). Tidal bundles represent a lateral succession of cross-strata deposited in one event by the dominant tide (Terwindt, 1981). In Unit 11 the sigmoidal cross-bedding is underlain by an inversely graded gravel layer and overlain by lenticular layers and mud-draped ripples in (Fig. 12). In deep-water environments, alternation of traction and suspension deposition (e.g., ripples and mud drapes) has been ascribed to tidal processes (Klein, 1975). Annot Sandstone has double mud layers, which are characteristic features of tidal deposits in shallow-water environments (Visser, 1980). I interpret these double mud layers as products of deep-marine tidal bottom currents. Deep-water tidal bottom currents and their deposits are common in modern submarine canyons (Shepard et al., 1979). Therefore, I suggest that deep-water tidal currents were responsible for forming sigmoidal cross-beds, mud-draped ripples, and double mud layers in the Annot Sand-

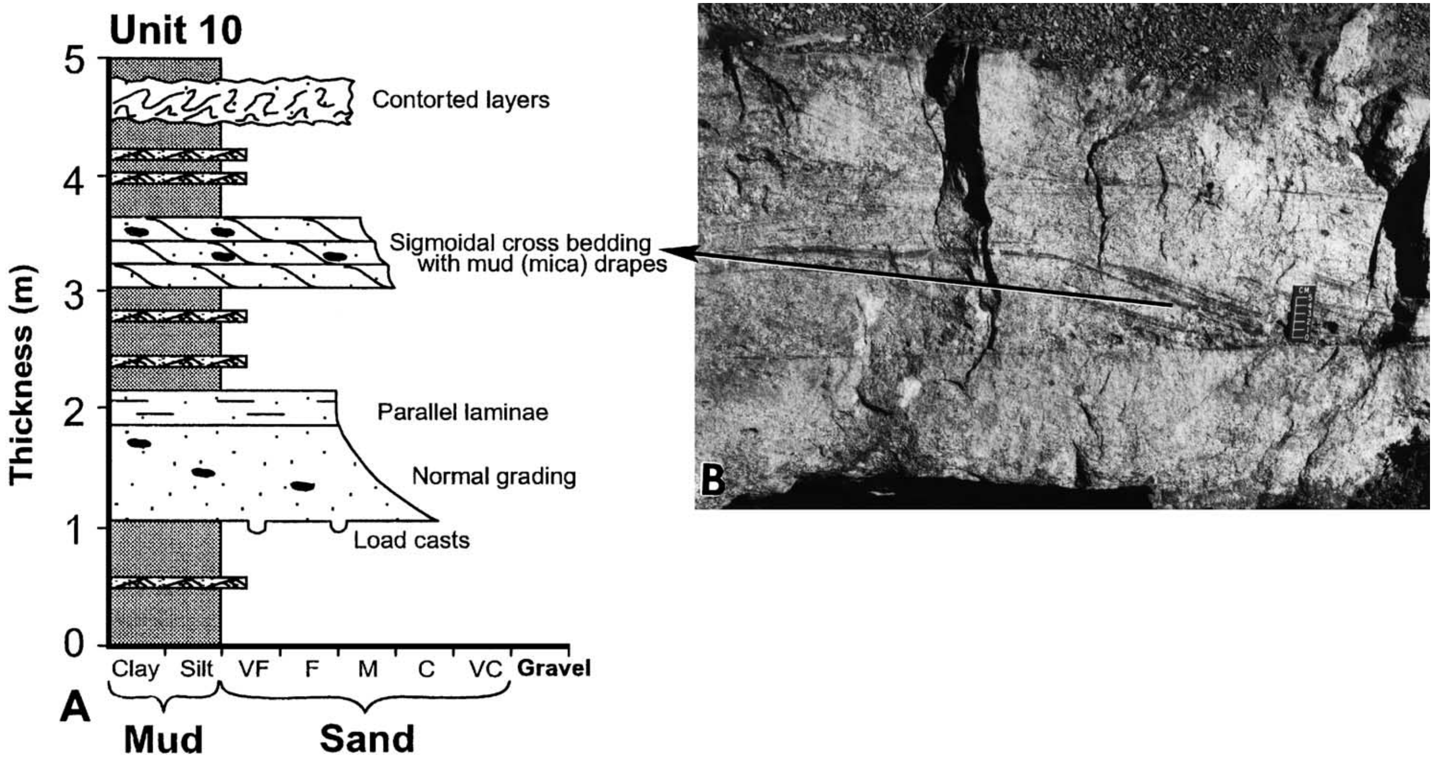


Fig. 11. (A) Sedimentological log of an amalgamated sandstone unit showing sigmoidal cross-bedding with mud (mica) drapes. Note a "normally graded" bed at 1–2 m interval with floating clasts. (B) Outcrop photograph showing sigmoidal cross-bedding in medium- to coarse-grade sandstone. Note mud/mica-draped (dark colored) stratification. Arrow shows stratigraphic position of photo. Pickering and Hilton (1998, their Fig. 4K) published a reverse view (i.e., foreset is dipping to the right in outcrop as shown in (B), but the authors published a view in which the foreset is dipping to the left, apparently a printing error!) of this cross-stratified sandstone unit and interpreted it as deposits of "high-density turbidity currents." Unit 10 (see Fig. 7 for location), Annot Sandstone (Eocene–Oligocene), Peira Cava area, French Maritime Alps.

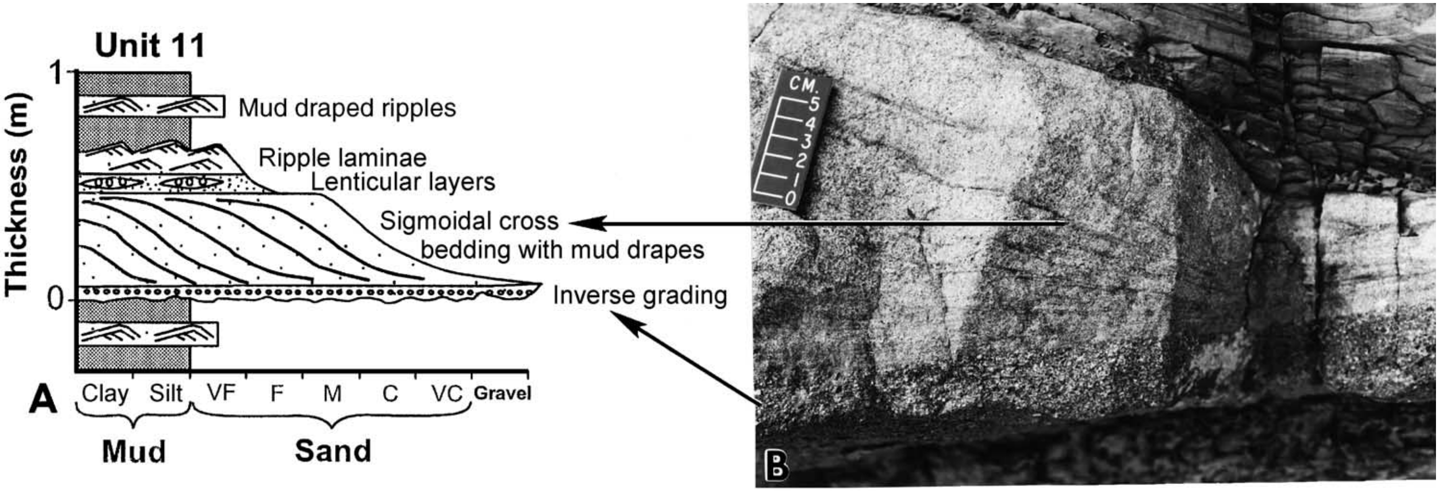


Fig. 12. (A) Sedimentological log of an amalgamated sandstone unit showing sigmoidal cross-bedding with tangential toeset. Note inverse grading below and lenticular layers above. (B) Outcrop photograph showing sigmoidal cross-bedding (top arrow) with tangential toeset in coarse- to granule-grade sandstone. Note mud/mica-draped (dark colored) stratification. Note inversely graded gravel layer below (bottom arrow). Arrows show stratigraphic position of photo. See Bouma and Coleman (1985, their Fig. 5) for an overall view of this unit. Unit 11 (see Fig. 7 for location), Annot Sandstone (Eocene–Oligocene), Peira Cava area, French Maritime Alps.

stone, perhaps in submarine canyon environments (Shanmugam, 2001). In my view, traction structures deposited by deep-water tidal bottom currents are commonly misinterpreted as "turbidites."

In attributing deep-water antidune "cross-bedding" to high-concentration turbidity currents (i.e., high-density turbidity currents), Pickering et al. (2001, p. 698) state, "The surface morphology and internal structure of the inclined sandy macroforms is inconsistent with well-constrained large-scale antidunes formed in fluvial environments. Although large-scale deep-water bedform fields interpreted as antidunes remain poorly studied, without clear contrary observations, it seems reasonable to assume that their architecture would be similar to fluvial examples." This comparison of deep-water bedforms to fluvial examples is ill founded for many reasons (see Shanmugam, 2000a). First, fluvial currents are low in suspended sediment (1–5% by volume; Galay, 1987), whereas Pickering et al. (2001) used the muddled concept of high-concentration turbidity currents. Second, fluvial currents are *fluid*–gravity flows, whereas turbidity currents are *sediment*–gravity flows (Middleton, 1993). Third, in fluvial currents sand and gravel fractions are transported primarily by bed load (traction) mechanism and therefore fluvial deposits are characterized by dune bedforms or cross-bedding, whereas in turbidity currents sand is transported by suspended load and therefore their deposits are characterized by normal grading. The problem here is that Pickering et al. (2001) did not cite any flume studies in explaining the origin of "inclined sandy macroforms" from high-concentration turbidity currents. Nor did Pickering et al. (2001) discuss any theoretical basis for explaining the origin of antidunes from high-concentration turbidity currents. Until we develop objective criteria, based on meaningful theories, realistic experiments and direct observations, for interpreting deposits of complex deep-water processes, studies like this (i.e., Pickering et al., 2001) promote only complacency, not clarity.

2.9. Myth No. 9: turbidite facies models are useful tools for interpreting deposits of turbidity currents

As I pointed out earlier, the Annot Sandstone (Eocene–Oligocene) of the French Maritime Alps served as the basis for developing the first turbidite facies model. This model, known as the "Bouma Sequence," is composed of five divisions (T_a, T_b, T_c, T_d, and T_e) in an orderly vertical manner. This is conventionally considered to be the product of a single, waning, turbidity current. This model has been influential in interpreting deep-water sands as turbidites in a submarine fan setting (Bouma, 1962; Mutti and Ricci Lucchi, 1972; Walker, 1984). However, several authors have critiqued the "Bouma Sequence" based on theoretical and experimental grounds (e.g., Sanders, 1965; Van der Lingen, 1969; Hsu, 1989; Shanmugam, 1997). This critique is aimed in particular at the disconnect that exists between experimental structures and the "Bouma Sequence."

Simons et al. (1965, p. 35) conducted flume experiments under equilibrium flow conditions and developed traction structures (i.e., T_b, T_c, and T_d). Although Walker (1965) used these experimental structures as analogs in his hydrodynamic interpretation of the "Bouma Sequence," he also cautioned "...the flume experiments were conducted under conditions of non-deposition, whereas many of the sedimentary structures of turbidites are formed under conditions of net deposition" (Walker, 1965, p. 22–23).

In flume experiments, the origin of traction structures requires the establishment of hydrodynamic equilibrium. The duration required for establishing hydrodynamic equilibrium is greater than the time required for sedimentation (Allen, 1973). Because natural turbidity currents are waning flows, and because waning flows may never attain equilibrium (Allen, 1973), the origin of equilibrium traction structures (e.g., horizontal laminae and ripples) in flume experiments cannot be compared to the origin of structures by natural waning flows. In most natural flows, changes in bed configurations tend to lag behind changes in flow conditions, and there have been almost no flume experiments on disequilibrium bed configurations (Southard 1975, p. 33). Also, no one has ever generated the complete "Bouma Sequence" in laboratory experiments. Therefore, traction structures formed in flume experiments are not appropriate analogs for interpreting structures formed by natural turbidity currents.

In addition, the following field evidence from the Annot Sandstone raises serious questions about using the "Bouma Sequence" as the basis for interpreting deep-water deposits as "turbidites." For example, in Unit 7, pebbles and granules constitute the basal inverse grading (Fig. 13). Such inverse grading does not have a comparable division in the "Bouma Sequence." More importantly, none of the published graphic logs of 157 layers, which includes Unit 7, shows inverse grading (Bouma, 1962, his Enclosures I, II, and III). Other authors have seldom described the common occurrence of inverse grading in the Peira Cava area (e.g., Pickering and Hilton, 1998). The origin of inverse grading by turbidity currents is problematic because inverse grading cannot be explained by suspension settling from turbidity currents (Sanders, 1965, p. 199). As a result, other mechanisms have been proposed. For example, inverse grading is commonly interpreted as traction carpets in "high-density turbidity currents" (Lowe, 1982). The problem is that traction carpets are sup-

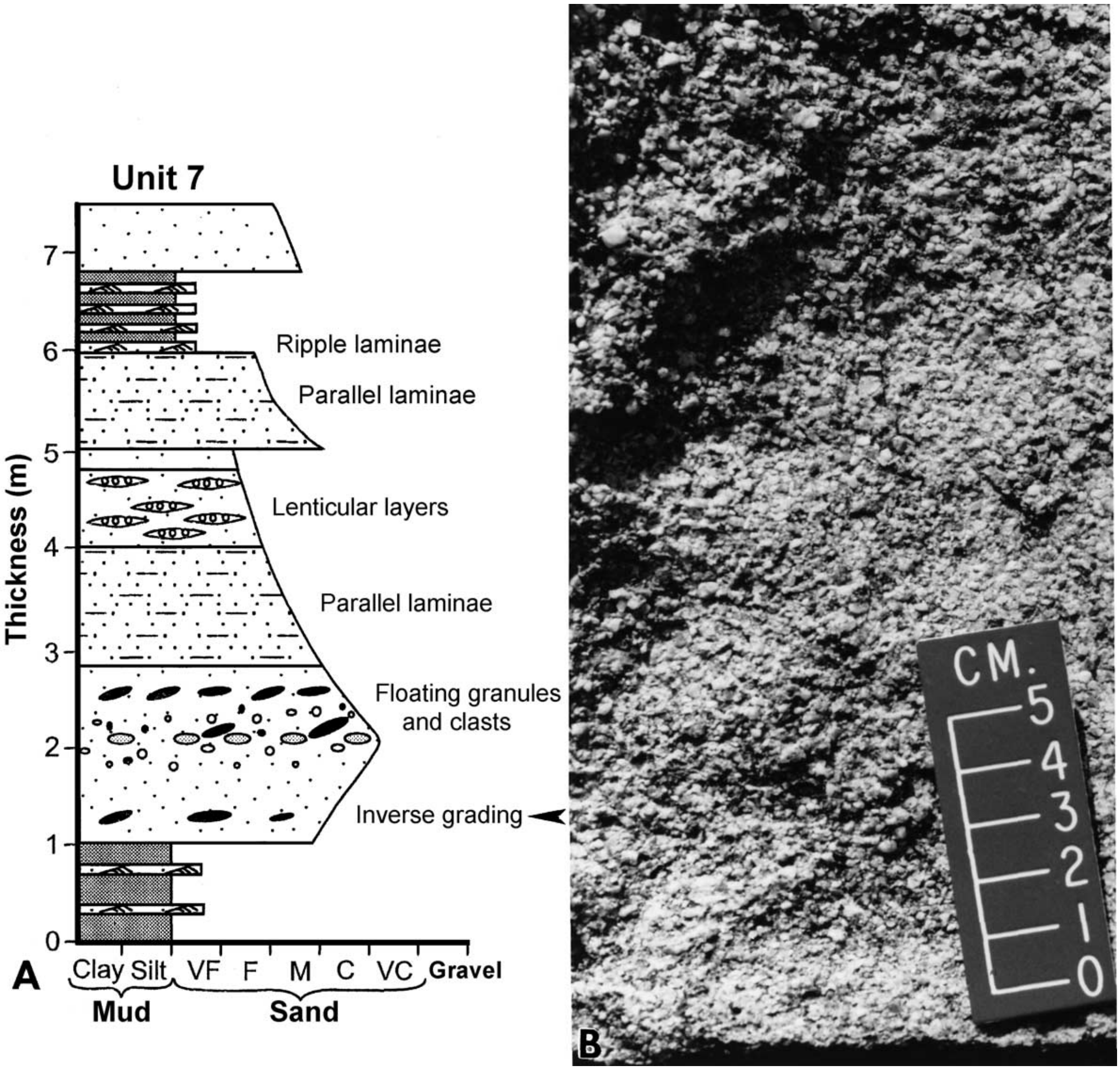


Fig. 13. (A) Sedimentological log of an amalgamated sandstone unit showing basal inverse grading overlain by an interval with floating granules and clasts, parallel laminae, and lenticular layers. (B) Outcrop photograph showing basal inversely graded interval in coarse- to granule-grade sandstone. Arrow shows stratigraphic position of photo. See Bouma and Coleman (1985, their Fig. 3) for an overall view of this unit. Unit 7 (see Fig. 7 for location), Annot Sandstone (Eocene–Oligocene), Peira Cava area, French Maritime Alps.

posed to be less than 5 cm thick (Lowe, 1982), but inverse grading in the Annot Sandstone is up to 2 m thick (Fig. 13).

Mechanisms that explain inverse grading are: (1) dispersive pressure, caused by grain-to-grain collision that tends to force larger particles toward the zone of least rate of shear (Bagnold, 1954), (2) kinetic sieving by which smaller particles tend to fall into the gaps between larger particles (Middleton, 1967), and (3) the lift of individual grains toward the top of flow with lower pressures (Fisher and Mattinson, 1968). Of these, the kinetic sieving mechanism may not be applicable because many of the examples of inverse grading are composed mostly of pebbles and granules. I propose a combination of dispersive pressure, matrix strength, hindered settling, and buoyant lift in plastic–laminar flow for development of inverse grading.

The "Bouma Sequence" does not take into account large floating mudstone clasts, but the Annot Sandstone has units with large floating mudstone clasts and quartz granules in medium- to coarse grade sandstone (Fig. 14). We have observed large clasts up to 60 cm in length and 25 cm in width. Clasts are randomly distributed, imbricated, or show planar (i.e., long axes of clasts are aligned parallel to bedding) fabric. Although Bouma (1962, p. 66) reported clay pebbles with planar fabric in the Annot Sandstone, he did not discuss their position in the "Bouma Sequence."

Large pockets of mudstone clasts, which are common in the Annot Sandstone, may be attributed to rigid-plug deposition in debris flows (e.g., Johnson, 1970). Planar clast fabric in the Annot sandstone supports the view that these sands were deposited by laminar flow (see Fisher, 1971). Postma et al. (1988) explained the origin of floating clasts by freezing near the top of inertia-flow layer (Fig. 4). In spite of their differences in terminology, all these flows are plastic in rheology and laminar in state. Therefore, they are debris flows, not turbidity currents.

Bouma and Coleman (1985) interpreted Unit 7 as lateral accretionary channel–fill turbidites using fluvial point bar analogy. They used the presence of pebble nests, foreset bedding, and paleocurrent directions in support of their interpretation. However, this analogy is inappropriate for the following reasons. First, the Annot Sandstone example used in the study does not show channel geometry, but does show sheet geometry (Fig. 15), which is an unlikely geometry for lateral-accretion deposits of a meandering channel. Second, logged sequences of the Annot Sandstone in Peira Cava do not contain sedimentary facies in support of the lateral accretion model (Oakeshott, 1989, p. 307). Third, the pebble nests in the Annot Sandstone are analogous to slurried beds, and slurried beds have been interpreted to be deposits of debris flows (Mutti et al., 1978, p. 219). In addition to slurried beds, Unit 7 exhibits inverse grading at the base (Fig. 13), and contains floating granules and clasts (Fig. 14), and floating armored mud balls (Fig. 16). I would suggest that these features are the product of plastic debris flows, which are not a viable mechanism to explain lateral accretion deposits in a meandering channel (Fig. 17). The origin of point bars in meandering channels by unsteady turbidity currents in deep-marine environments is an unresolved issue. As pointed out earlier, cross-bedding in the Annot Sandstone can be better explained by deep-water tidal bottom currents in canyons or channels.

The Annot Sandstone exhibits a characteristic basal inverse grading and an upper interval that appears to be normally graded (Figs. 9, 12, 13, 16)). Most studies tend to ignore the basal inverse grading and overemphasize the upper "normal grading" (e.g., Bouma, 1962). The "Bouma Sequence" not only ignores the basal inverse grading, but also fails to represent important sedimentological features that are present in the upper "normally graded" interval (e.g., floating mudstone clasts and quartz granules, armored mud balls, pockets of gravels, and lenticular layers). Ironically, these ignored features are the key to understanding the complex depositional origin of the Annot Sandstone. Floating quartz granules, for example, cannot be explained by suspension settling of turbidity currents; they must be explained by plastic flows (Fig. 17). Because these complex features of the Annot Sandstone occur in amalgamated units (Figs. 8–16), it is unclear what the observational basis is for the five divisions of the ideal "Bouma Sequence." Furthermore, in amalgamated sandstone units, such as the ones in the Annot, the upper interval of "normal grading" is a manifestation of multiple depositional events by plastic flows and bottom currents. In short, there is no observational basis for attributing the origin of the "Bouma Sequence" to turbidity currents. Neither is there any theoretical or experimental basis for linking the "Bouma Sequence" to turbidity currents.

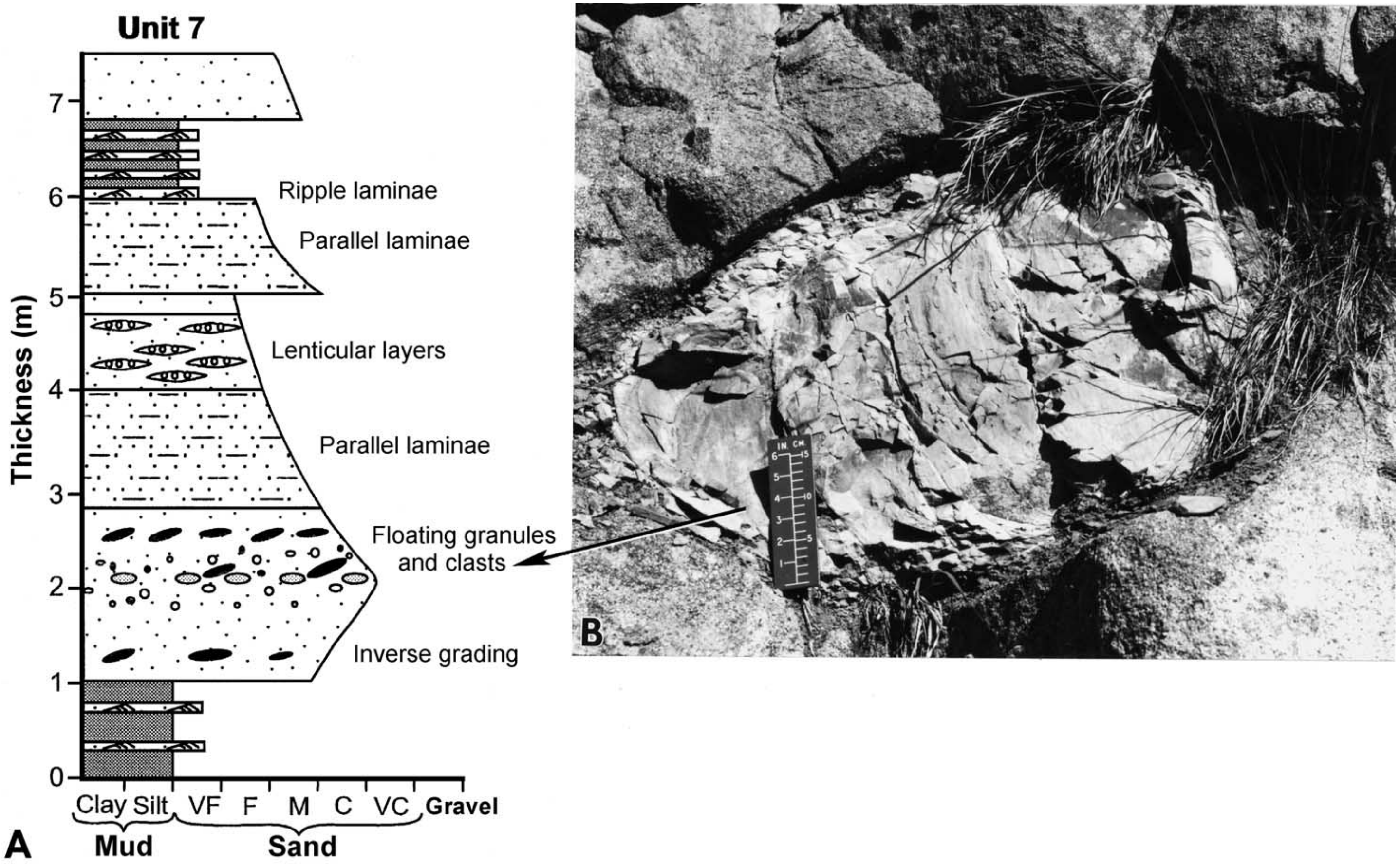


Fig. 14. (A) Sedimentological log of an amalgamated sandstone unit showing basal inverse grading overlain by an interval with floating granules and clasts, parallel laminae, and lenticular layers. (B) Outcrop photograph showing a large floating mudstone clast in medium- to coarse-grade sandstone. Arrow shows stratigraphic position of photo. See Bouma and Coleman (1985, their Fig. 3) for an overall view of this unit. Unit 7 (see Fig. 7 for location), Annot Sandstone (Eocene–Oligocene), Peira Cava area, French Maritime Alps.

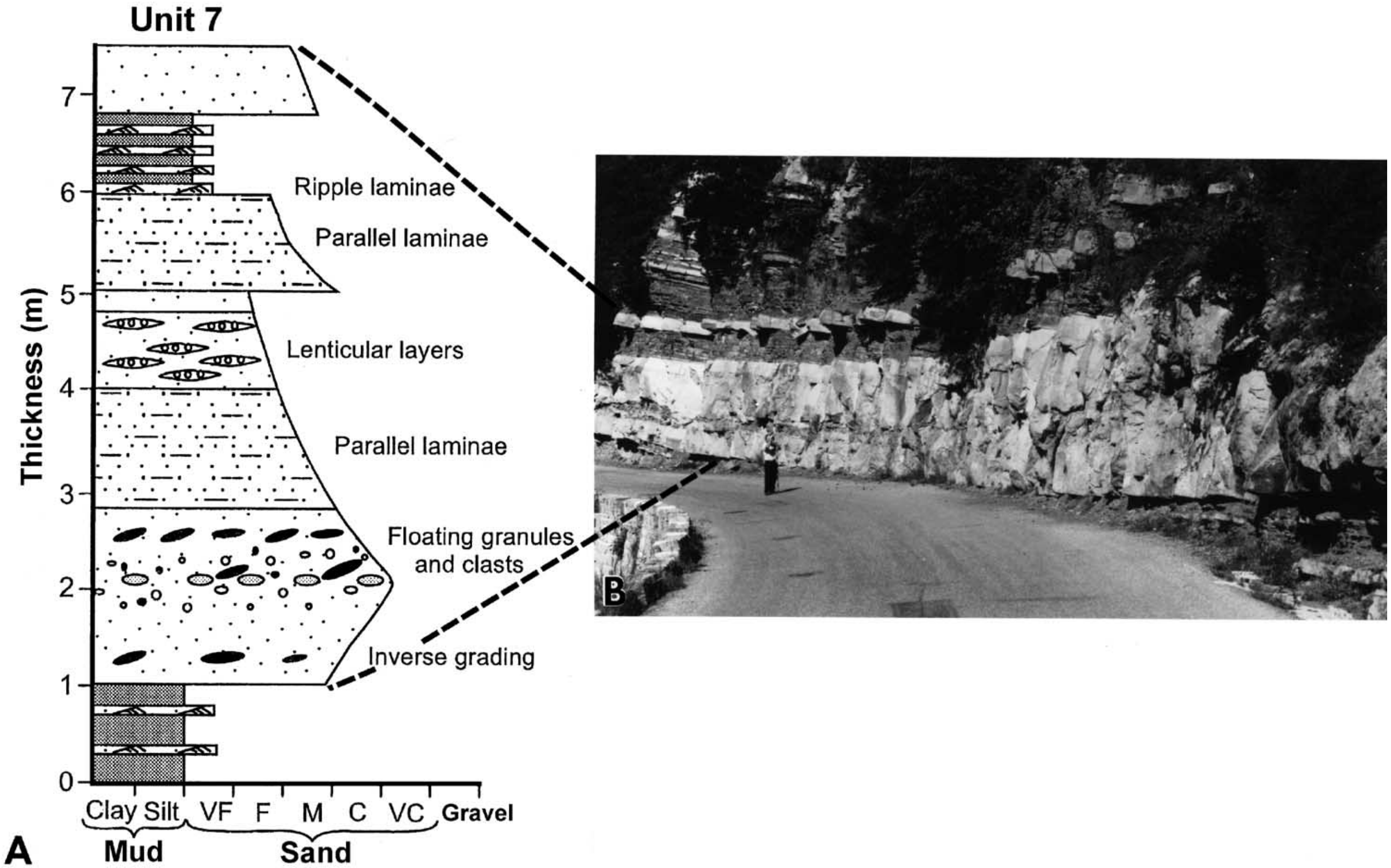


Fig. 15. (A) Sedimentological log of an amalgamated sandstone unit showing basal inverse grading overlain by an interval with floating granules and clasts, parallel laminae, and lenticular layers. Sedimentological log of Unit 7 varies in space because of amalgamation. For example, at extreme left of outcrop Unit 7 is composed of a basal sandstone, a middle pebble nest, and an upper sandstone, but as we move to the right of outcrop, the middle pebble nest gradually thins out. (B) Outcrop photograph showing sheet-like geometry of Unit 7. Dashed lines shows stratigraphic position of the unit. See Bouma and Coleman (1985, their Fig. 3) for a similar view of this unit. Bouma and Coleman (1985) interpreted the sandstone interval (1–6 m in A) as lateral accretionary channel-fill turbidites and interbedded sandstone and mudstone interval (6–7 m in A) as overbank turbidites (see Fig. 17). Unit 7 (see Fig. 7 for location), Annot Sandstone (Eocene–Oligocene), Peira Cava area, French Maritime Alps.

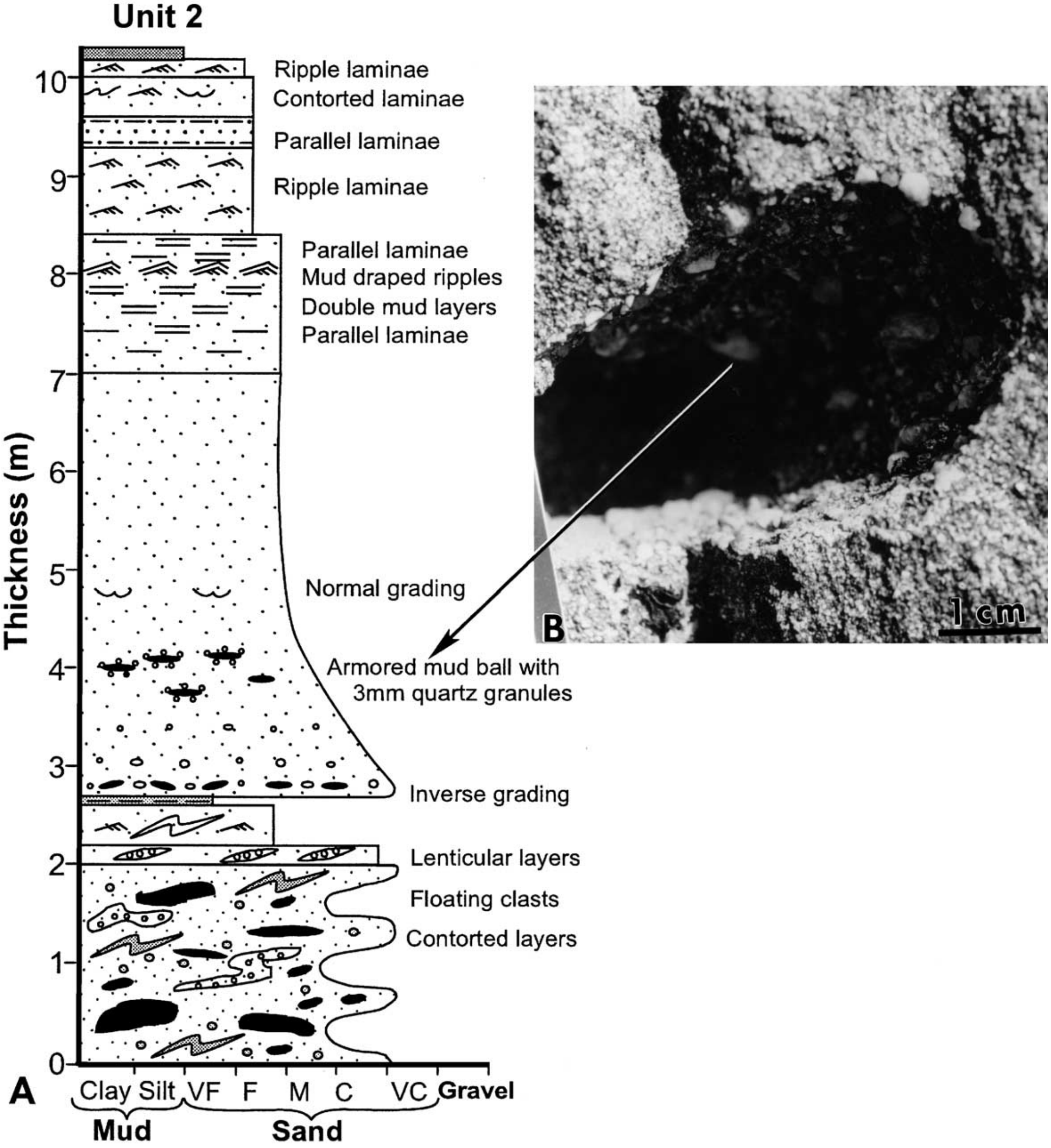


Fig. 16. (A) Sedimentological log of an amalgamated sandstone unit showing basal inverse grading overlain by an interval with floating armored mud balls with 3 mm quartz granules, parallel laminae, double mud layers, mud draped ripples, and parallel laminae. Double mud layers are indicative of deposition from deep-marine tidal bottom currents. (B) Outcrop photograph showing a hollow created by weathering away of a mudstone clast in medium- to coarse-grade sandstone. Note quartz granules at the outer rim of the hollow. In other cases, remnants of mudstone clasts armored with quartz granules are present in hollows. Therefore, hollows with quartz granules at their rims represent areas of armored mudstone clasts. Arrow shows stratigraphic position of photo. Unit 2 (see Fig. 7 for location), Annot Sandstone (Eocene–Oligocene), Peira Cava area, French Maritime Alps.

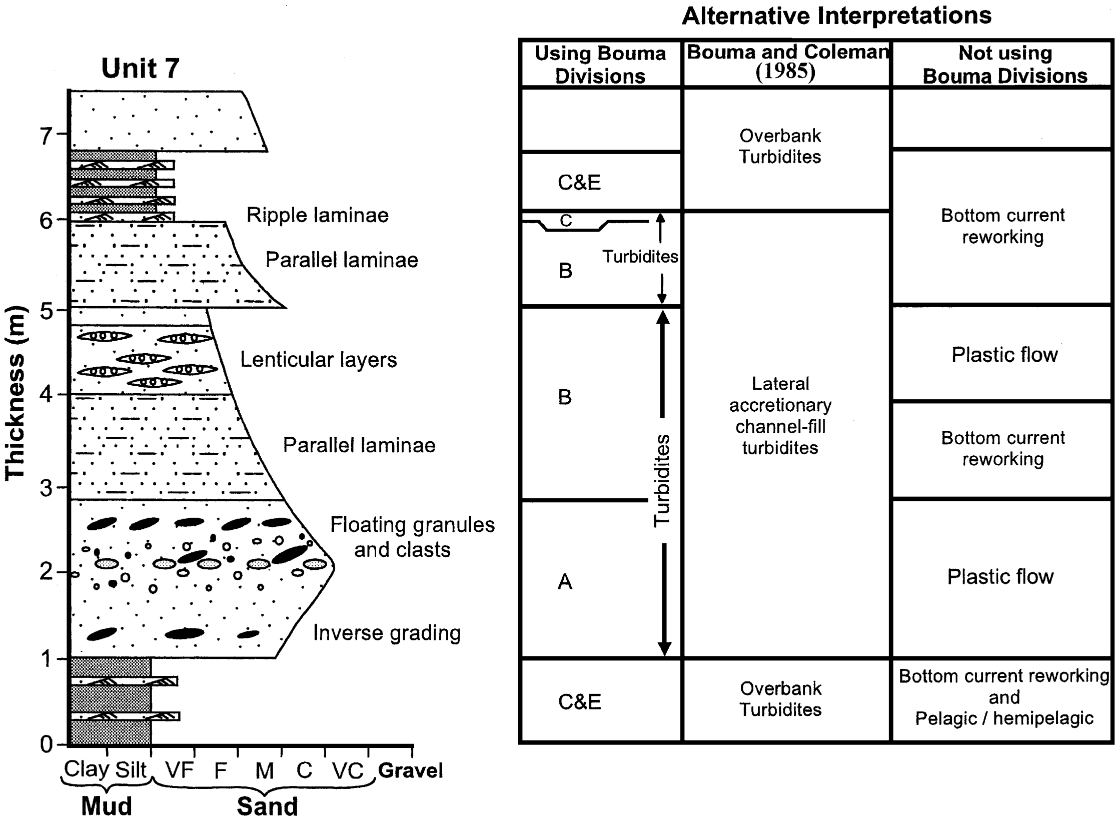


Fig. 17. Left column: field description of amalgamated Unit 7 (see Fig. 7 for location) showing complex internal features, such as basal inverse grading (Fig. 13), floating mudstone clasts (Fig. 14), and lenticular layers. Unit 7 shows a sheet-like external geometry (see Fig. 15). Right columns: three alternative interpretations of field description. (1) By using Bouma divisions (Bouma, 1962), the entire unit could be interpreted as turbidites. (2) Bouma and Coleman (1985) interpreted this unit as lateral accretionary channel-fill turbidites and associated overbank turbidites. (3) By not using Bouma divisions, I interpret each layer of the unit individually either as deposits of plastic flows or bottom currents. Plastic flows represent sandy debris flows in this case.

2.10. Myth No. 10: turbidite facies can be interpreted using seismic facies and geometries

Vail et al. (1991) used seismic facies and geometries to classify deep-water systems into basin-floor fans and slope fans in a sequence-stratigraphic framework, and in turn, they used fan models to predict specific depositional facies composed of turbidites (i.e., deposits of turbidity currents). However, as discussed above, the term “turbidity current” has precise meanings in terms of fluid rheology (i.e., Newtonian), flow state and sediment-support mechanism (i.e., turbulence). Evidence for Newtonian rheology and flow turbulence cannot be established directly from seismic-reflection profiles or wireline-log motifs; rather, these properties can only be ascertained from actual sediment facies in cores or outcrops.

The practice of interpreting depositional facies or processes from seismic data is meaningless for the following reasons: (1) interpretation of complex deep-water processes requires conventional core or outcrop because centimeter to decimeter thick depositional facies cannot be resolved in seismic data, (2) seismically resolvable, thicker, packages are composed commonly of more than a single depositional facies, (3) a single depositional facies can generate more than one seismic geometry, (4) more than one depositional facies can generate similar seismic geometry, and (5) post-depositional compaction can change seismic geometry through time.

Calibration of cored intervals with seismic reflection profiles suggests that a single depositional facies (e.g., sandy debris flow) can return a variety of seismic facies or geometries. For example, in the Faeroe Basin, west of Shetlands, conventional cores recovered from mounded seismic facies and geometries with bidirectional downlap are composed of deposits of sandy debris flows and slumps (Shanmugam et al., 1995). In the Agat area in the Norwegian North Sea, conventional cores recovered from mounded seismic facies with chaotic internal reflections are documented to be composed of deposits of sandy debris flows and slumps (Shanmugam et al., 1994). In the Gulf of Mexico, sheet seismic facies and geometries with parallel and continuous reflections are also composed of deposits of sandy debris flows (Shanmugam and Zimbrick, 1996). In the Gryphon Field, North Sea, conventional cores recovered from lateral pinch out geometries with irregular and continuous reflections are composed of deposits of sandy debris flows (Shanmugam et al., 1995). In the Ewing Bank 826 Field of the Gulf of Mexico, Plio–Pleistocene sands were cored and interpreted to be deposited primarily by bottom currents (Shanmugam et al., 1993). Calibration of these cores with seismic profiles suggests that there are no differences in seismic reflection patterns between these reworked sands and associated channel turbidites.

At present, our understanding of the sedimentary facies that form different seismic facies and geometries is poor because of insufficient “ground truthing” by core data. Seismic facies of deep-water sequences can be deceptive, and therefore, mapping of seismic facies in deep-water sequences should be done with the realization that these patterns may not represent distinct depositional facies. Until we systematically calibrate seismic facies with process sedimentology using long cores, any process interpretation of seismic data in seismic stratigraphy and seismic geomorphology is only an exercise of our imagination without scientific basis.

3. A personal perspective

Only deposits of turbidity currents should be called turbidites. Turbidity currents are a type of sediment–gravity flow with Newtonian rheology and turbulent state. The principal sediment-support mechanism in turbidity currents is flow turbulence. Deposition from waning turbidity currents occurs via suspension settling. Therefore, turbidites are characterized by simple normal grading without complications of floating granules and floating clasts. Turbidites do not develop inverse grading. Origin of traction structures (e.g., cross-bedding and mud-draped ripples) may be better explained by deep-water bottom currents, in particular by tidal bottom currents in submarine canyons. Deviation from these basic principles is a common source of confusion and controversy. Yet turbidite facies models deviate from these principles, as the reexamination of the Annot Sandstone shows. After 50 years of the turbidite paradigm, it’s time to end the practice of nurturing turbidite falsehoods based on myths.

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I dedicate this paper to John Essington Sanders (1926–1999) who pioneered the science of undoing turbidite myths. This paper is a modified version of my oral presentation (Shanmugam, 2000b) entitled “John E. Sanders and the turbidite controversy” that was given at the “Conference of the History of Geologic Pioneers” held at the Rensselaer Polytechnic Institute, Troy, NY (August 3–5, 2000). I am very grateful to R.J. Moiola and R.B. Bloch for valuable discussions in the field. I thank the journal editor, Professor G.M. Friedman, for constructive comments, two journal reviewers for their critical reviews, D.W. Kirkland for helpful suggestions, and Jean Shanmugam for editorial comments.

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