From Turbid to Lucid:

A Straightforward Approach to Sediment Gravity Flows and Their Deposits

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ABSTRACT

Deepwater sediment gravity flows are categorized on the basis of a combination of four parameters – sediment concentration, sediment-support mechanism, flow state (laminar or turbulent), and rheology. Because there is no agreement among sedimentologists about which of these parameters should be the decisive one, one school's turbidites become another school's debrites, and vice-versa. Except for rheology, all of these parameters change gradationally from one end member to another. Therefore, rheological classification of sediment gravity flows should be the most straightforward and the least controversial. These flows can be either Newtonian (i.e., turbidity currents), or non-Newtonian (i.e., debris flows). However, identification of flow rheology by examining the deposits may not be easy. Although we may confidently identify some rocks as turbidites and others as debrites, there are some transitional deposits, here called densites, that share both the characteristics of turbidites and debrites. Densites are the deposits of dense flows, which are rheologically stratified flows having a composite rheology of Newtonian fluids and non-Newtonian fluids. Moreover, the absence of a general term for all types of sediment gravity flow deposits has resulted in overuse and misuse of the term turbidite. The term 'gravite' is proposed here for deposits of any kind of sediment gravity flow, irrespective of their depositional environment.

INTRODUCTION

The term 'turbidity current' was introduced by Johnson (1938) and applied to a current generated due to turbid or muddy water. Later, Kuenen (1957) introduced the term 'turbidite' for the deposit of a turbidity current, and Bouma (1962) introduced a classic five-fold vertical facies model for turbidites. Soon, the terms 'turbidites,' 'Bouma sequences,' and 'deepwater deposits' became almost synonymous in many published accounts. Although the overuse and misuse of the terms 'turbidity current' and 'turbidite' was first indicated by Sanders (1965), the turbidite controversy has recently caught wide attention (e.g., Shanmugam, 2000; Lowe and Guy, 2000; Kneller and Buckee, 2000; Mulder and Alexander, 2001).

Sediment gravity flows play a major role in transporting and depositing sediments in deepwater environments, and can be defined as a complex mixture of sediment and fluid that flows down slope due to the action of gravity. Sediment gravity flows are different from fluid gravity flows, because in the latter, fluid is moved by gravity dragging the sediment along, whereas in former gravity moves the sediment, which drags the fluid along. A turbidity current is only one type of sediment gravity flow. The center point of the turbidite controversy lies in the classification scheme of sediment gravity flows, which is so far poorly constrained and a bit ambiguous. This controversy can lead to erroneous numerical modeling of sediment gravity flows frequently used in submarine construction and hydrocarbon exploration because specific mathematical formulae govern specific types of sediment gravity flows. Therefore, it is felt that this classification scheme needs to be reviewed to clarify the controversy. In this paper, I take a simple and straightforward approach to classifying sediment gravity flows. I also suggest some key depositional features on which flow types can be interpreted least equivocally. Although the suggestions made here are applicable irrespective of depositional environments, this paper mainly deals with deepwater sediment gravity flows and their deposits.

CLASSIFICATION OF SEDIMENT GRAVITY FLOWS: BACKGROUND AND REVIEW

The initial definitions of turbidity currents and debris flows were purely descriptive, without being specific about the physical properties of the current. Therefore, from the beginning, questions revolved around what should be the main basis of classification of sediment gravity flows. Different authors emphasized different parameters in their classification schemes (sediment concentration: Bagnold, 1962; rheology: Dott, 1963; fluid turbulence: Sanders, 1965; sediment-support mechanisms: Middleton and Hampton, 1973; combination of rheology and sediment-support mechanism: Lowe, 1982; combination of physical flow properties and sediment-support mechanism: Mulder and Alexander, 2001). Among the four most important parameters (sediment concentration, sediment-support mechanism, flow state, and rheology) of sediment gravity flows, sediment concentration (by volume) directly affects other three parameters. Therefore, sediment concentration appears to be the most pragmatic parameter for defining the various types. Unfortunately, we can not establish specific threshold values for various types of sediment gravity flows (Shanmugam, 1996) because grain size and concentration of clay minerals offset these threshold values.

Sediment-support mechanisms include matrix strength, dispersive grain pressure, escaping pore fluid, and fluid turbulence. These mechanisms may change gradationally with increasing fluid content, and more than one support mechanism may operate simultaneously for a specific type of sediment gravity flow. Similarly, the flow state may change gradationally and back-and-forth between a laminar state and a turbulent state with the change of sediment concentrations or basin slopes. On the other hand, the rheology of sediment gravity flows is expressible in a straightforward and simplified mathematical way in a 2-D graph (Fig. 1). Most importantly, the rheological types do not vary gradationally among each other. Therefore, rheology may be the one parameter that can be used least ambiguously to define various types of sediment gravity flows.

According to Figure 1, there are only two basic types of rheology in sediment gravity flows – Newtonian and non-Newtonian. If a sediment gravity flow deforms instantly with applied stress and develops a linear relationship between shear stress and strain rate, it is called a Newtonian fluid. Any deviation from this characteristic results in non-Newtonian

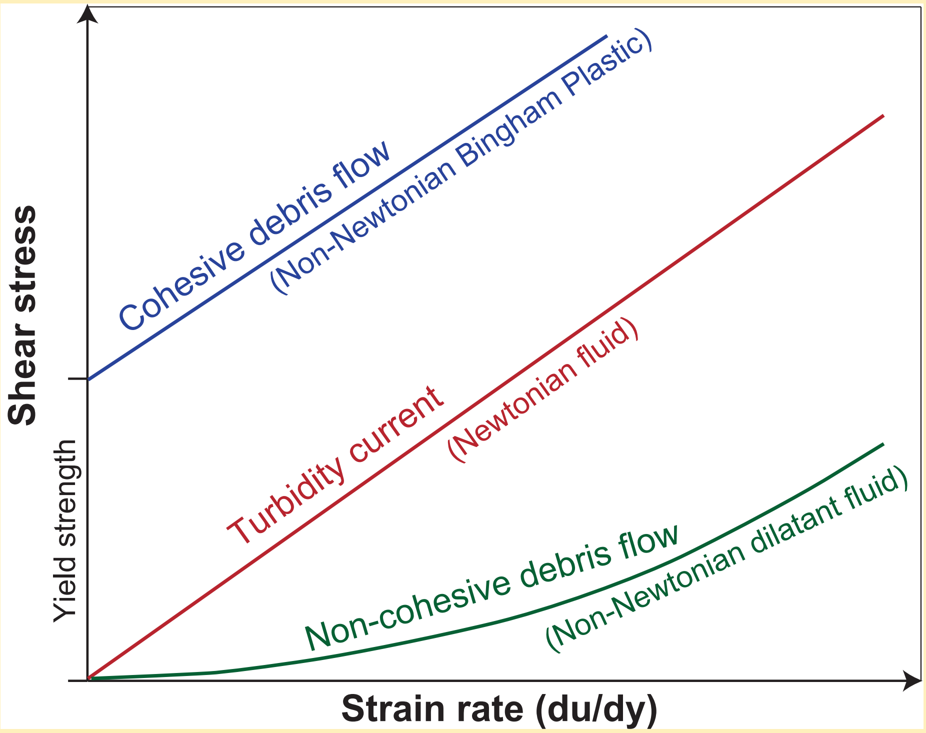

Figure 1. Basic types of rheology in sediment gravity flows. According to this diagram, turbidity currents are Newtonian fluids, whereas debris flows are not. Debris flows can be either non-Newtonian Bingham plastics (cohesive debris flows; e.g., mud flows) with a certain yield strength, or non-Newtonian dilatant fluids (non-cohesive debris flows; e.g., grain flow) without any yield strength.

rheology. Sediment gravity flows can show two types of non-Newtonian rheology (Fig. 1). In a non-Newtonian Bingham plastic, a critical value of shear stress (called yield stress) has to be crossed before there is any deformation, after which the deformation is linear (i.e., a Bingham plastic is a combination of an ideal plastic and a Newtonian fluid). In a non-Newtonian dilatant fluid there is no yield strength, but the deformation is nonlinear with applied stress in such a way that it becomes progressively harder to deform the fluid (Fig. 1). Applying the above concepts, I recommend that sediment gravity flows with Newtonian rheology should be called 'turbidity currents,' and those with non-Newtonian rheology should be called 'debris flows' (Fig. 1). Debris flows can be divided further into 'cohesive debris flows' (non-Newtonian Bingham plastics), and 'non-cohesive debris flows' (non-Newtonian dilatant fluids) (Fig. 1). This 'cohesiveness' of debris flows generally depends on the clay concentration of the flows. Although some workers (e.g., Hampton, 1975; Baas and Best, 2002) showed that as little as 2-4% clay (by volume) can generate yield strength in the flows, further research is needed to clarify the matter. So far, we know the least about the numerical and experimental modeling of non-Newtonian dilatant sediment gravity flows (e.g., grain flows) and their deposits. I suspect that it is a critical loophole in understanding the evolution of sediment gravity flows; hence it is an issue of turbidite controversy.

It may be easy to determine the rheology of flows in the laboratory. However, interpreting the flow rheology of a deposit by examining its depositional features may be challenging. There are sediment gravity flow deposits that share both the characters of turbidites and debrites (deposits of debris flows). If we follow the turbidite controversy for the last ten years, it becomes obvious that these hybrid deposits are the main issue of debate. A plethora of terminology (e.g., high density turbidity currents, sandy debris flows, slurry flows, concentrated density flows) has been applied to these rocks. Most of these deposits originate from rheologically stratified (or bipartite) sediment gravity flows (e.g., Sanders, 1965; Tinterri et al., 2003) with commonly a lower zone of non-Newtonian dilatant fluid (non-cohesive debris flow) overlain by a Newtonian fluid (turbidity current). Because these types of flows can frequently change the intra-flow rheological boundaries, and can generate a single event bed, a separate name is needed for these flows and their deposits. In this study, these flows are called 'dense flows' (after Allen, 1997), as they show an intermediate density (due to intermediate sediment concentration) between turbidity currents and debris flows (Fig. 2A), and their deposits are named 'densites.' However, it is emphasized that according to rheology there are only two basic types

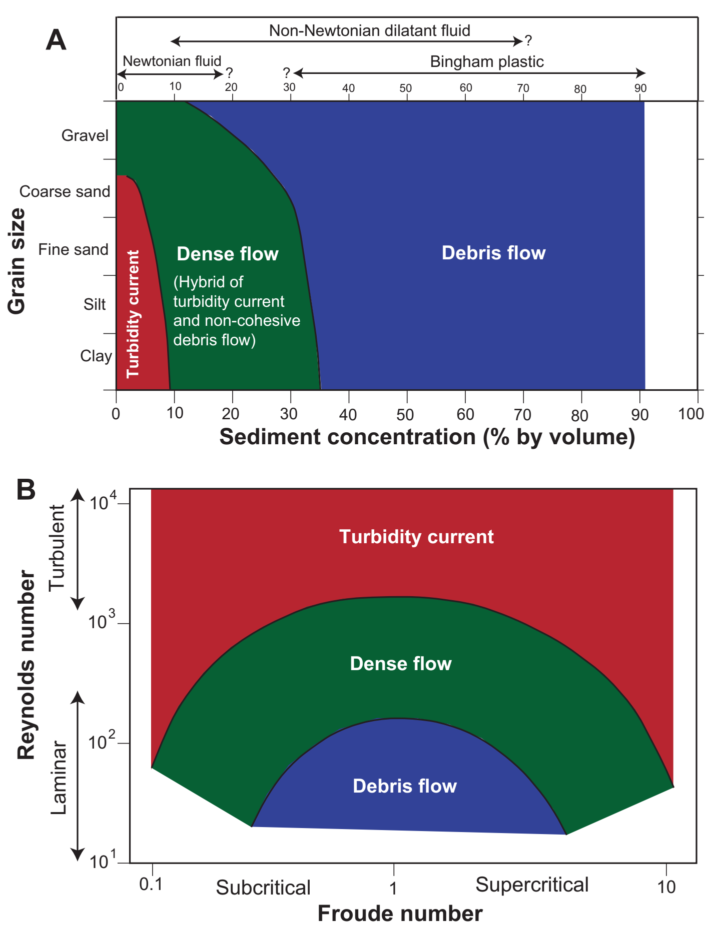

Figure 2. Distribution of different types of sediment gravity flows in 2-D space of sediment concentration vs. grain size (A), and Reynolds number vs. Froude number (B). Note that dense flows (rheologically stratified sediment gravity flows) occupy an intermediate position between turbidity currents and debris flows. For convenience, rheological types are shown for possible operational ranges of sediment concentrations; however, the percentage of clay within the bulk sediments (not shown in Fig. 2A) is an important factor controlling the flow rheology (after Allen, 1997).

Increasing fluid content

Rheology	Flow Type		Deposits		Dominant sediment-support mechanism
Newtonian fluid	**Turbidity current** (mostly turbulent)	Subcatagories: - Low-concentration (<1%) & muddy (e.g., fluid mud ?) - Low-concentration (0.2-3%) & medium-grained (Hyperpycnal flow: Mulder et al., 2003) - Low-concentration & fine-grained (Stow & Shanmugam, 1980) - Medium-grained classic (Bouma, 1962)	**Turbidite**	**Gravite** (Gani, 2003)	Fluid turbulence
Variable (Partly non-Newtonian fluid, partly Newtonian fluid)	**Dense flow** (partly laminar, partly turbulent)	Variously named as: - High-density turbidity currents (Lowe, 1982) - Sandy debris flows (Shanmugam, 1996) - Slurry flows (Lowe & Guy, 2000) - Concentrated density flows (Mulder & Alexander, 2001) - Liquified flows /fluidized flows	**Densite** (This study)		Dispersive grain pressure, fluid turbulence, escaping pore fluid, matrix strength
Non-Newtonian dilatant fluid	**Debris flow** (mostly laminar)	Non-cohesive debris flow (e.g., grain flow)	**Debrite**		Dispersive grain pressure
Bingham plastic		Cohesive debris flow			Matrix strength
Bingham plastic	Slide and slump		Slide and slump depostis		Matrix strength

Figure 3. Classification of sediment gravity flows with a simplified nomenclature for the flow types as well as their deposits. Flow rheology is the basis of this classification (Fig. 1). Direction of increasing fluid content is roughly analogous to the down-slope evolution of sediment gravity flows. Flow states and sediment-support mechanisms are incorporated to give a comprehensive picture of the nature of these flows. For the range of sediment concentrations of these flows, see Fig. 2A.

of sediment gravity flows – turbidity currents and debris flows.

As mentioned earlier, there are no threshold values of sediment concentration (by volume) in constraining the types of sediment gravity flows. A range of sediment concentration values, which can vary according to grain size, is suggested for turbidity currents, dense flows, and debris flows (Fig. 2A). In general, with increasing sediment concentration, a turbidity current can transform into a dense flow, and then into a debris flow. Similarly, depending on the Froude numbers, these three flows can be both turbulent and laminar (Fig. 2B). However, turbidity currents are mostly turbulent, whereas debris flows are mostly laminar.

Based on flow rheology and incorporating the concept of dense flows, a simplified tabular classification of sediment gravity flows is generated (Fig. 3). Because most of the sediment gravity flows originate from slides and slumps, these are included at the bottom of this classification. The classification also shows the dominant sediment-support mechanism and flow state for each of the types to give a comprehensive picture about the nature of these flows.

DIAGNOSTIC FEATURES OF DIFFERENT SEDIMENT GRAVITY FLOW DEPOSITS

One reason for the turbidite controversy is the lack of consensus among sedimentologists about which depositional features are the key in determining the types of sediment gravity flows. While dealing with rocks, sedimentologists deduce the processes of depositions based on observable criteria of the deposits. Therefore, successful interpretation of sediment gravity flow deposits depends on how accurately we can establish a link between physics (of the process) and sedimentology (of the product). Rheology and sediment-support

Figure 4. Links between physics (of processes) and sedimentology (of products) of sediment gravity flows. Different rheological properties and sediment support mechanisms can generate depositional features diagnostic to specific types of sediment gravity flows.

Physics (of flows)		**Link**	**Sedimentology** (of products)
Rheology	Newtonian fluid	No yield strength; no freezing	Well sorting with no 'floating' clasts; top part always shows normal distribution grading
	Non-Newtonian dilatant fluid	Frictional freezing but no yield strength; freezes from the bottom up	No normal distribution grading; layer by layer accretion
	Bingham plastic	*En masse* freezing due to yield strength; plug flow; freezes from the top down	Poor sorting; preserved flow morphology; sharp upper boundary; boulder projecting through the top
Sediment-support mechanism	Fluid turbulence	Differential grain settling from suspension	Normal distribution grading; well sorting
	Escaping pore fluid	Leaves escape marks	Dish and pillar structures; convolution
	Dispersive grain pressure	Larger the grain, greater the liftoff	Inverse grading
	Matrix strength	Supports large/outsized clasts	Matrix-supported 'floating' clasts; poor sorting

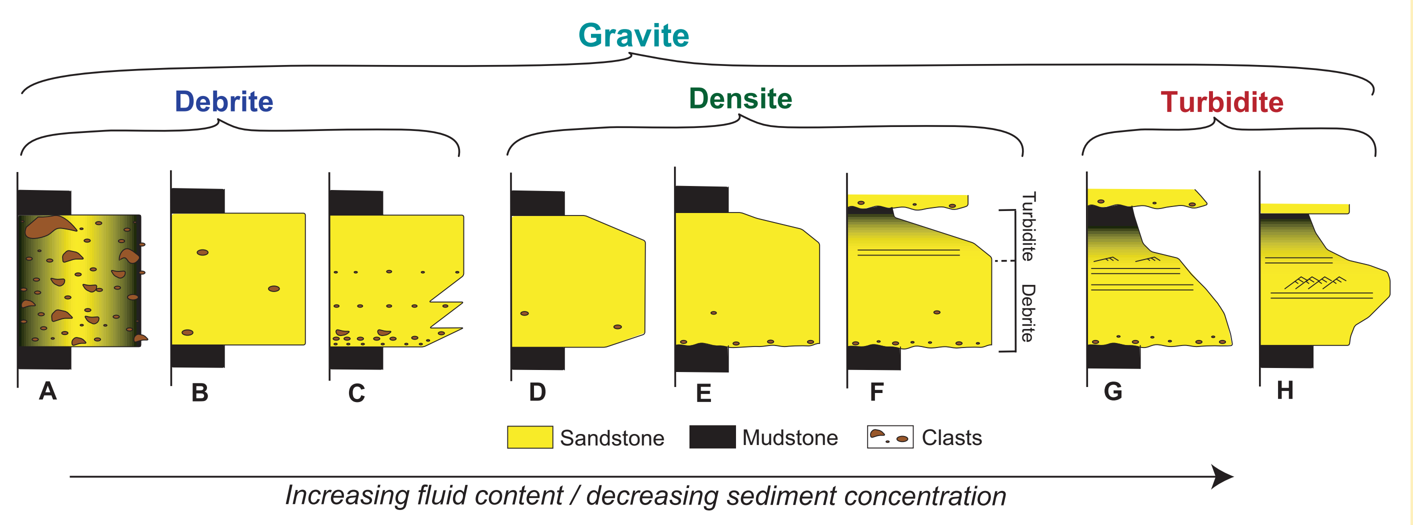

Figure 5. Simplified lithologic models for gravites (deposits of sediment gravity flows). A: cohesive debrite; B-C: non-cohesive debrites; D-F: densites (deposits of bipartite sediment gravity flows); G: turbidite (Bouma sequence); H: turbidite (deposit of hyperpycnal flow). Note that the arrowed direction is analogous to the down-slope evolution of sediment gravity flows. See text for discussion.

mechanisms of flows suggest a number of links, which, in turn, point to a set of key depositional features for each type of sediment gravity flow deposits (Fig. 4). Based on these diagnostic features, the concepts described in the previous section, and on numerous published works, I suggest the following terminology be applied for the deposits of different sediment gravity flows.

Gravite

Gravite is defined as a sediment or rock deposited from a sediment gravity flow (Gani, 2003). It is an umbrella term that incorporates all sediment gravity flow deposits (including slide and slump deposits) irrespective of their depositional environment (Fig. 5). The absence of such a concise, general term resulted in overuse and misuse of the term 'turbidite' in geological literature. For example, although submarine fans consist of different types of sediment gravity flow deposits, the term 'turbidite systems' has been used interchangeably with 'submarine fan systems' (e.g., Bouma and Stone, 2000). When the assignment of sediment gravity flow deposits to any particular types is either problematic (due to preservational bias, poor outcrop quality, etc.) or unnecessary, the term gravite can be used conveniently without creating any debate of the recent kind. Gravites exclude deposits of fluid gravity flows.

Debrite

Debrites, a class of gravites, are deposits of debris flows. Traditionally, debris flows are regarded as moving mass of rock clasts, clay minerals, and water. Although debris flows are commonly regarded as plastic flows (e.g., Lowe, 1982), there are other views that support non-Newtonian fluid rheology (e.g., Allen, 1997). In this study, for the sake of simplicity, I consider debris flows as sediment gravity flows whose rheology is not Newtonian (Fig. 1). Therefore, debrites can include both cohesive debrites (Bingham plastic rheology) and non-cohesive debrites (non-Newtonian dilatant fluid rheology). In general, a gravite bed that does not show any distribution grading even in the uppermost part is a debrite (Fig. 5). Cohesive debrites are relatively easy to identify. Most importantly, because of the yield strength of the flow, they contain 'floating,' outsized clasts in a muddy matrix (Figs. 5A, 6A). These deposits show poor sorting with rare, if any, coarse-tail grading. On the other hand, non-cohesive debrites are relatively mud-free sandstones (e.g., grain flow deposits) that show inverse grading because of the dispersive grain pressure (Fig. 5C). Generally, non-cohesive debrites aggrade layer by layer (~ <few cm) because they do not freeze en masse due to lack of yield strength (Fig. 5C). If we accept the notion that it takes little clay (~2%) for debris flows to develop yield strength, then debrites like Figure 5B are hard to classify further.

Densite

In this study, the term 'densite' is introduced for deposits of dense flows (Fig. 2). A densite is a hybrid gravite, consisting commonly of a lower debrite (mostly non-cohesive) layer and an upper turbidite layer without developing any bedding plane between these two layers (Figs. 5D-F, 6B). In geologic literature, these deposits have been identified frequently as turbidites with Bouma T_a or $T_{a\text{-}b}$ divisions. However, these beds show distribution grading only at the top parts, and the rest of these beds are either massive or inversely graded (Fig. 5D-F). As part of the turbidite controversy, various flow names have been proposed in explaining the depositional mechanism of these deposits (Fig. 3). The features of these beds are diagnostic of rheologically stratified/bipartite sediment gravity flows (i.e., dense flows) and are here called densites.

Turbidite

When the term 'turbidite' was introduced (Kuenen, 1957) for deposits of turbidity currents, it became popular in geological literature. I propose using turbidity currents only for sediment gravity flows with Newtonian rheology. Therefore, I recommend restricting the term turbidites to only those gravites that suggest a Newtonian rheology of the depositing currents. Turbidity currents have long been regarded as surge-type waning currents. These types of currents with Newtonian rheology, unlike other currents, should produce a diagnostic distribution grading (due to differential grain settling) from the bottom to the top of the deposits (i.e., Bouma sequence; Figs. 5G, 6C). However, Kneller and Branney (1995) introduced the concept of waxing, steady, and waning turbidity currents, which may produce reverse grading, non-grading, and normal grading, respectively. To explain the depositional mechanism of ungraded, massive sandstones Kneller and Branney (1995) advocated sustained 'high-density turbidity currents,' with a lower non-Newtonian rheology and an upper Newtonian rheology. Therefore, according to this study, the deposits of these 'high-density turbidity cur-

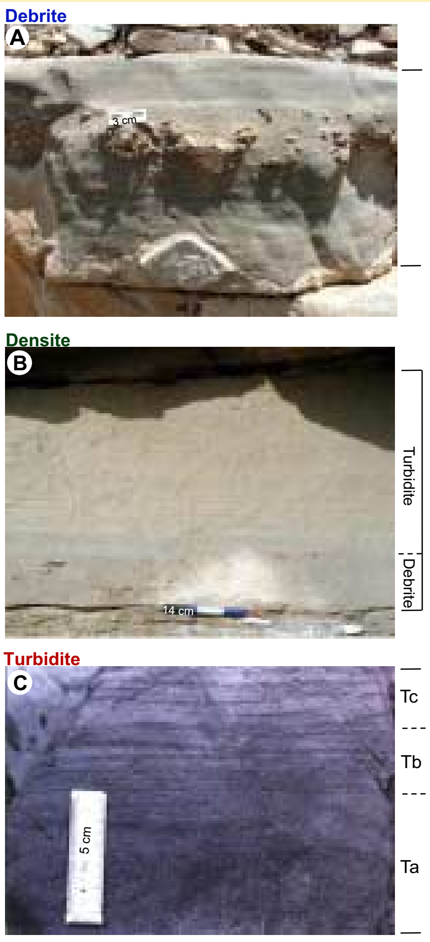

Figure 6. (A) Wackestone cohesive debrite in the base-of-slope deposits of Permian Lamar Limestone Member, Guadalupe Mountains, west Texas. Poorly sorted skeletal grains floating within matrix mud along with ungraded and sharp upper boundary indicate a Bingham plastic rheology of the depositing flow. Compare with Fig. 5A. (B) Delta front densite in the Upper Cretaceous Wall Creek Formation of central Wyoming. The lower layer of this bed is ungraded with floating mud clasts, hence indicates non-Newtonian flow rheology. The upper layer shows distribution grading with flat stratification indicating Newtonian flow rheology. Note that as bedding plane has not developed between these two layers, the entire bed is called a densite (hybrid of debrite and turbidite; compare with Figs. 5E-F). (C) Turbidite in Miocene base-of-slope deposits of the Bengal Basin, Bangladesh (modified from Gani and Alam, 1999). The entire bed shows distribution grading with the development of Bouma T_{abc} divisions and without any floating clasts in T_a division. These indicate differential grain settling from a Newtonian fluid. Compare with Fig. 5G.

rents' are densites (Figs. 5D-F). However, the top part of these deposits should show normal grading (e.g., Baas, 2004), otherwise they are debrites. The only real-world example of quasi-steady turbidity currents are the hyperpycnal flows produced during river floods. These hyperpycnites show reverse-then-normal grading analogous to a waxing-then-waning flood hydrograph (Mulder et al., 2003; Fig. 5H). Hyperpycnal flows are regarded as low-concentration (0.2-3% by volume) and medium-grained turbidity currents (Fig. 3). Therefore, their deposits (Fig. 5H) should not be confused with deposits of dense flows (Figs. 5D-F). However, more study is needed for successful identification of ancient hyperpycnites. Future research is also necessary in order to identify deposits of fluid muds commonly developed on modern continental shelves (Traykovski et al., 2000) from ancient records. Because sediment concentration of fluid muds is very low (<<1% by volume), it is debatable whether these should be regarded as fluid gravity flows or sediment gravity flows. Nonetheless, if these mudrock beds show normal grading they are best identified as turbidites. Alternatively, if these beds are ungraded they are debrite, in which case the sediment concentration of fluid muds should exceed 2% (cf. Baas and Best, 2002).

CONCLUSIONS

The overuse and misuse of the term 'turbidite' for many types of sediment gravity flow deposits has resulted in what I refer to here as the turbidite controversy. This controversy is rooted in the classification scheme of sediment gravity flows, which is poorly constrained and somewhat contradictory. I suggest a simple but well-constrained classification of sediment gravity flows based on flow rheology. Turbidity currents are Newtonian fluids, whereas debris flows are not. Debris flows can be of two types: a cohesive debris flow (a non-Newtonian Bingham plastic) or a non-cohesive debris flow (non-Newtonian dilatant fluid). Some sediment gravity flows may be rheologically stratified (or bipartite) in nature, so that commonly a lower layer of non-Newtonian rheology is overlain by a layer of Newtonian rheology. These types of flows are called dense flows and their deposits are named densites. Identification of flow rheology from ancient deposits may not be an easy task. Nonetheless, there are some diagnostic depositional features of debrites, turbidites, and densites that relate to the physics of corresponding flows. In order to avoid confusion, if it is not possible to determine the category of a sediment gravity flow deposit, we should simply call the deposit a gravite.

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