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ACADEMIC DISCUSSION Open Access

Reply to discussions by Zavala (2019) and by Van Loon, Hüeneke, and Mulder (2019) on Shanmugam, G. (2018, *Journal of Palaeogeography*, 7 (3): 197–238): 'the hyperpycnite problem'

G. Shanmugam

Abstract

In this reply, I respond to 18 issues associated with comments made by Zavala (e.g., inverse- to normally-graded sequence, origin of massive sands, experimental sandy debris flows, tidal rhythmites, facies models, etc.), and 10 issues associated with comments made by Van Loon et al. (e.g., 16 types of hyperpycnal flows, anthropogenic hyperpycnal flow, etc.).

Keywords: Hyperpycnal flows, Hyperpycnites, Sandy debris flows, Turbidity currents

1 Introduction

Shanmugam (2018a) has identified inherent problems associated with hyperpycnites in deep-water environments. Such controversial papers are bound to generate debates, which is normal. Unmitigated academic debates are an integral and a necessary part of advancing science. I have chosen a total of 28 issues for discussion. Hopefully, this discussion and related questions will help students of this domain in future research.

2 Result and discussion: reply to Zavala (2019)

2.1 Paper title

Zavala has chosen an awkward title for his discussion, which is "The new knowledge is written on sedimentary rocks – a comment on Shanmugam's paper "The hyperpycnite problem". According to the Cambridge Dictionary, the term "knowledge" is defined as follows: "*Awareness, understanding, or information that has been obtained by experience or study, and that is either in a person's mind or possessed by people generally*". Cambridge Dictionary, URL: https://dictionary.cambridge.org/us/dictionary/english/knowledge, accessed March 10, 2019.

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In his book entitled "Use the Right Word", Hayakawa (1968) states that, "Knowledge is more than a store of facts in the mind; it also includes the contribution of the mind in understanding data, perceiving relations, elaborating concepts, formulating principles, and making evaluations."

Clearly, the word 'knowledge' refers to the acquired trait by the humankind, and one cannot write 'knowledge' on the rocks, as Zavala has falsely implied in his paper title.

2.2 What is a hyperpycnal flow?

Since the original description of hyperpycnal flows for deltaic settings (i.e., density of river water is greater than density of basin water) by Bates (1953), the basic definition of hyperpycnal flows is still elusive from a fluid dynamic point of view.

Zavala (2019) states that, "*Clearly, we don't equate turbidity currents (Newtonian turbulent flows) to hyperpycnal flows.*" This statement only informs the readership what hyperpycnal flows are not. This statement does not define as to what is a hyperpycnal flow in terms of fluid mechanical properties. Zavala notes that he is addressing various problems discussed in my paper in a forthcoming paper of his. In that paper, perhaps Zavala could easily solve the basic problems by answering the following questions for the benefit of readership:

1) What is the fluid rheology of hyperpycnal flows and how does it differ from that of turbidity currents?

2) What is the flow state of hyperpycnal flows and how does it differ from that of turbidity currents?

3) What is the sediment concentration of hyperpycnal flows by volume and how does it differ from that of turbidity currents?

Once Zavala establishes the above basic properties, then he could explain properties of 16 different types of hyperpycnal flows (see Section 3.1 below). In this regard, he could take one published example and provide the necessary details. As a starting point, he could consider tide-modulated hyperpycnal flows (Fig. 1) associated with the Yellow River in China (Wang et al. 2010) and could address the following issues.

1) Given that the Yellow River is a delta, how tide-modulated hyperpycnal flows differ from the concept of conventional hyperpycnal flows that was originally advocated by Bates (1953) for deltaic environments?
2) What are the fluid dynamical properties of tide-modulated hyperpycnal flows?
3) What are the sedimentary characteristics of deposits of tide-modulated hyperpycnal flows?
4) What are the sedimentary characteristics of deposits of baroclinic currents (Shanmugam 2014a, 2014b) that are closely associated with internal waves in the Yellow River (Wang et al. 2010)?

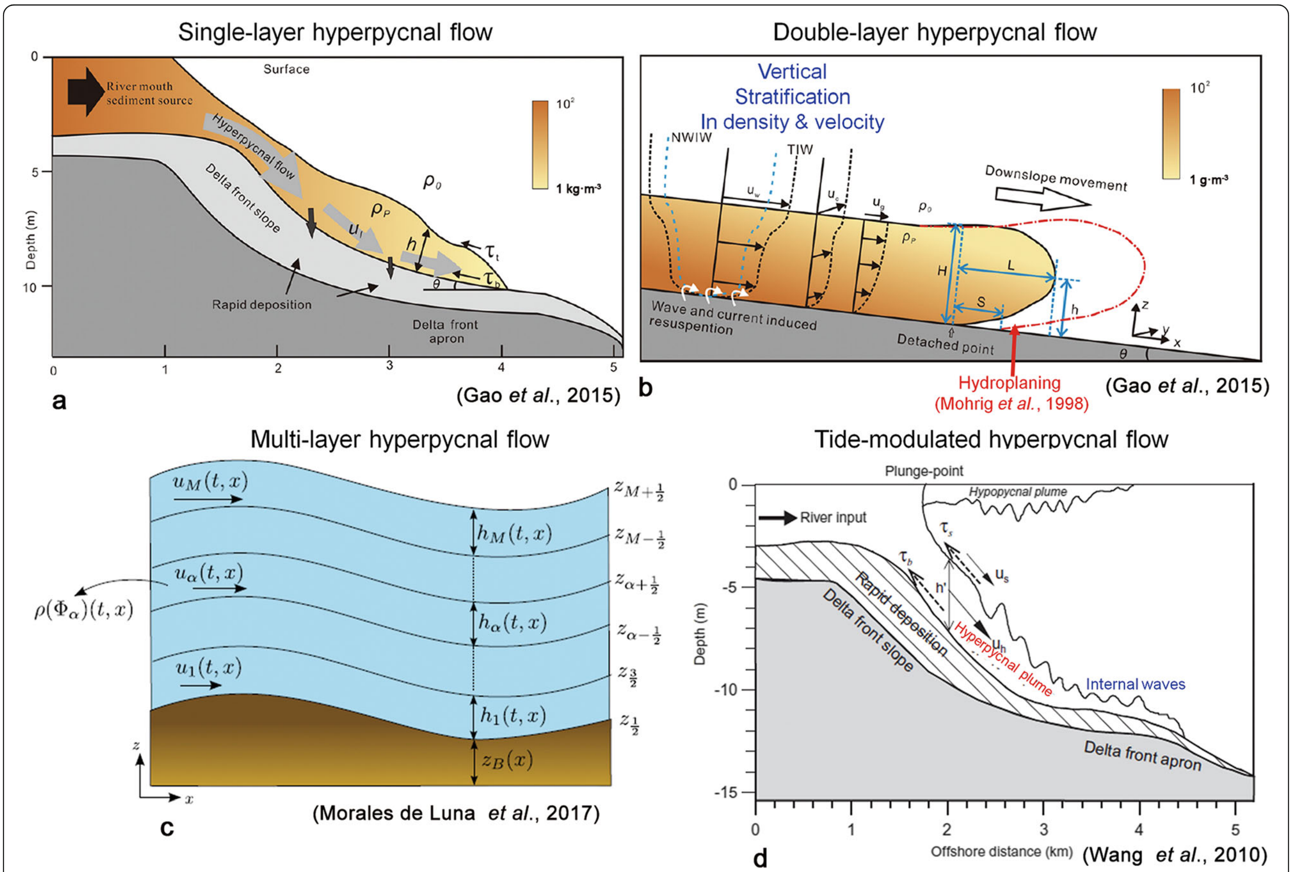

Fig. 1 Variable types of hyperpycnal flows. **a** Single-layer hyperpycnal flow, Yellow River, China. Color concentration = Suspended sediment concentration; h = Flow thickness; τt = Upper surface; τb = Bed shear stress. From Gao et al. (2015); **b** Double-layer hyperpycnal flow with density and velocity stratification (i.e., debris flow with hydroplaning, red arrow added in this article, see Mohrig et al. 1998), Yellow River, China. Uw = Wave orbital velocity; Uc = Along shelf current magnitude; Ug = Velocity of gravity current; NWIW = Normal wind-induced wave velocity; TIW = Typhoon-induced wave. The red line represents the downslope variation trend of the bottom-turbid layer. From Gao et al. (2015) with additional labels; **c** Multi-layer hyperpycnal flow in numerical modeling (Morales de Luna et al. 2017). Note that multi-layer numerical modeling was also applied to hypopycnal flows. h = Height of a fluid layer; u = Velocity; ϕ = Particle concentration; ρ = Density. See Morales de Luna et al. (2017) for details of various parameters and related equations; **d** Tide-modulated hyperpycnal flow, Yellow River (Wang et al. 2010; modified after Wright et al. 1988). Color labels by G. Shanmugam. Note internal waves. Internal waves occur only along pycnoclines (Shanmugam 2014a, 2014b), but there is no indication of pycnoclines in this diagram. From Shanmugam (2018a)

2.3 What is a turbidity current?

Zavala has confused the basic concept of sediment-gravity flows and related processes, such as turbidity currents. For example:

1) Zavala (2019) has adopted the flawed classification of sediment-gravity flows by Mutti et al. (1999) in which all sediment-gravity flows are classified as "turbidity currents" (Fig. 2) without regard for fluid mechanics.
2) According to Middleton and Hampton (1973), sediment-gravity flows are composed of four basic types, namely (a) turbidity currents, (b) debris flows, (c) grain flows, and (d) fluidized sediment flows (Fig. 2). Each flow type has a distinct set of fluid dynamical properties. Because Zavala has ignored the basic properties of sediment-gravity flows in his discussion, Zavala could classify all four types as turbidity currents. In other words, deposits of all four types would be called turbidites (Fig. 2), which is wrong. For example, deposits of debris flows should be classified as debrites, not turbidites.
3) I have adopted the Sanders' (1965) classification in which only deposits of turbidity currents are called turbidites (Fig. 2). Sanders' (1965) classification is consistent with principles adopted by eminent sedimentologists worldwide (e.g. Bagnold 1962; Dott Jr. 1963; Middleton and Hampton 1973; Allen 1985). Zavala (2019), however, is not among the list.
4) Zavala also classifies all turbidites as hyperpycnites (see Section 2.8).

2.4 Inversely- to normally-graded hyperpycnite sequence

In support of his false claim that inversely- to normally-graded sequence is the proof of hyperpycnite deposition, Zavala (2019) cites several published examples, all from the ancient sedimentary record. The issue is what kind of fluid mechanical properties that resulted in such a sequence? Zavala has never addressed this basic question. Previous explanations are flawed (Shanmugam 2018a). In fact, this was the issue that triggered the first debate on hyperpycnal flows with T. Mulder in 2002 (Shanmugam 2002b). I also debated this same issue in 2019 (Shanmugam 2019). There has been no solution to this problem during the past 17 years, although many papers have been published. For example contourite deposits also generate inversely- to normally-graded sequence (Shanmugam 2016), but Zavala has failed to address this basic issue.

2.5 Origin of massive sands and floating mudstone clasts

In defending the origin of massive sands by hyperpycnal flows, Zavala criticizes my paper (Shanmugam 1996) on sandy debris flows (also known as high-density turbidity currents) that was published 23 years ago. Renowned process sedimentologists did respond immediately to my publications on massive sands (e.g. Lowe 1997). Zavala had ample opportunities to debate these issues in 1996 or immediately thereafter, but he chose not to comment on these issues. In reality, these issues were raised by others and were responded to them in great detail by Shanmugam and Moiola (1997).

I respond to the origin of clasts in the following two sections on discussion of high-density turbidity currents

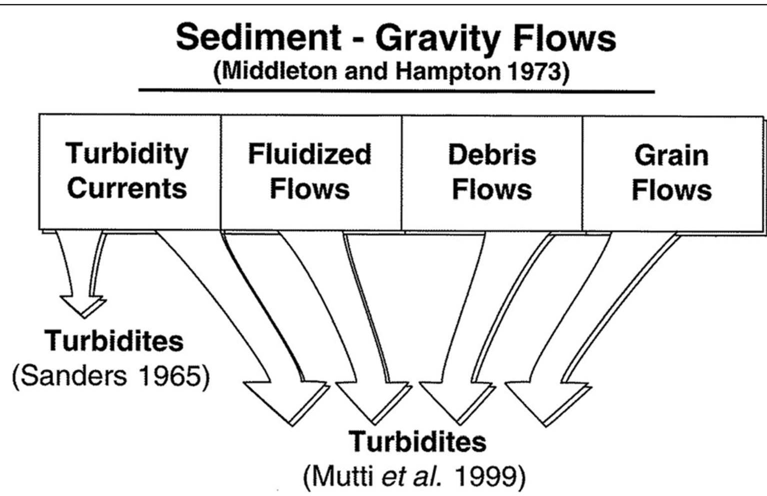

Fig. 2 Original classification of sediment-gravity flows by Middleton and Hampton (1973). Confusing application of the term 'turbidites' to deposits of all four types by Mutti et al. (1999) without regard for fluid mechanics, which Zavala (2019) has adopted in his comment. I have adopted Sanders' (1965) classification in which only deposits of turbidity currents are considered as turbidites. Figure from Shanmugam (2002a) with permission from Elsevier Earth-Science Reviews, Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 4614270994314. License Date: June 22, 2019

(Section 2.6) and experimental sandy debris flows (Section 2.7 below).

2.6 High-density turbidity currents (HDTC)

In explaining the origin of floating mudstone clasts, Zavala invokes high-density turbidity currents by citing the experimental study of Postma et al. (1988). The HDTC concept has been debunked in a critical article published in the *Journal of Sedimentary Research* (Shanmugam 1996). The term 'high-density turbidity current' is an euphemism for 'sandy debris flows' (Shanmugam 1996). Importantly, a) there is no agreement on what sediment concentration constitutes HDTC (Fig. 3a), and b) experiments by Postma et al. (1988) documented the emplacement of floating clasts at the rhelogical interface, which is the top of the basal sandy debris flow layer (Fig. 3b).

2.7 Experimental sandy debris flows

In criticizing my work on sandy debris flows, Zavala (2019) describes details of our laboratory flume work (Marr et al. 2001). It is worth noting that for the first time, to understand mechanics of sandy debris flows and their deposits, a Mobil-funded experimental flume study was carried out at St. Anthony Falls Laboratory (SAFL), University of Minnesota (1996–1998) under the direction of Professor G. Parker. Results were published in two major articles (Shanmugam 2000; Marr et al. 2001). The major advantage of experiments is that it allows researchers to measure fluid dynamical properties and observe sedimentary characteristics of deposits. Both Mutti et al. (1999) and Zavala (2019) have failed to appreciate the importance of fluid mechanics in defining turbidity currents. In our flume experiments, the distinction between debris flows and turbidity currents in terms of fluid rheology and flow state is inescapable (Fig. 4). Our experiments also illustrate the conceptual difference between two groups of researchers (Fig. 4). For example:

1) Group 1 of researchers would recognize the importance of bottom layer with different rheology and flow state (Bagnold 1956; Sanders 1965; Shanmugam 1996).
2) Group 2 would not (Kuenen 1951; Postma et al. 1988; Mutti et al. 1999; Zavala 2019). Postma et al. (1988) would combine both layers and classify them together as "High-density turbidity currents" (Fig. 3b).

2.8 What are coarse-grained hyperpycnites?

1) Zavala (2019) cited Zuffa et al. (2000) and their work on glacial lakes to document coarse-grained hyperpycnites.
2) But the original authors (Zuffa et al. 2000) called these deposits as "turbidites". In fact, the title of the paper by Zuffa et al. (2000) is "Turbidite megabeds in an oceanic rift valley recording Jokulhlaups of late Pleistocene glacial lakes of the western United States."
3) The reason that Zavala used this example because Zuffa et al. (2000) called the process "hyperpycnally derived turbidity currents". However, Zavala has failed to appreciate the basic tenet of process sedimentology, which is that deposits reflect physical conditions that existed at the final moment of deposition, which in this case are turbidity currents. This was the reason why that Zuffa et al. used the term turbidites, not hyperpycnites. A similar case on the Pacific Plate was described by Normark and Reid (2003).
4) On the one hand, Zavala (2019) states that, "*Clearly, we don't equate turbidity currents (Newtonian turbulent flows) to hyperpycnal flows.*" But on the other hand, he calls turbidites as coarse-grained hyperpycnites. This practice is inconsistent.
5) In some circles, hyperpycnal flows are considered analogous to turbidity currents (Mulder et al. 2003; Steel et al. 2016). This is why a clear definition of hyperpycnal flows is imperative (Section 2.2).

2.9 Tidal rhythmites

In defending his field example of lofting rhymites in Orinoco Fan, Zavala argues that tidal currents cannot operate in deep-water environments. Clearly, Zavala is unfamiliar with the classic work of Shepard and Dill (1966) and Shepard et al. (1979) on tidal currents in submarine canyons. In understanding tide-induced bottom currents, Shepard et al. (1979) measured current velocities in 25 submarine canyons worldwide at water depths ranging from 46 to 4200 m by suspended current meters, usually 3 m above the sea bottom. Maximum velocities of up- and down-canyon currents commonly ranged from 25 to 50 cm . s^{-1} (Shepard et al. 1979).

Klein (1975), based on studies of DSDP (Leg 30, Sites 288 and 289) cores, suggested that current ripples, micro-cross laminae, mud drapes, flaser bedding, lenticular bedding, and parallel laminae reflect alternate traction and suspension deposition from tidal bottom currents in basinal deep-marine environments. Deep-water tidal rhythmites have been documented from both modern and ancient examples worldwide (Shanmugam 2003), which include the Pliocene reservoir sands in upper-slope canyon environments, offshore Krishna-Godavari Basin, Bay of Bengal (Shanmugam et al. 2009).

2.10 Modern examples

Perhaps the best modern example of a sediment plume that has been dissipated by ocean currents is in the Rio de

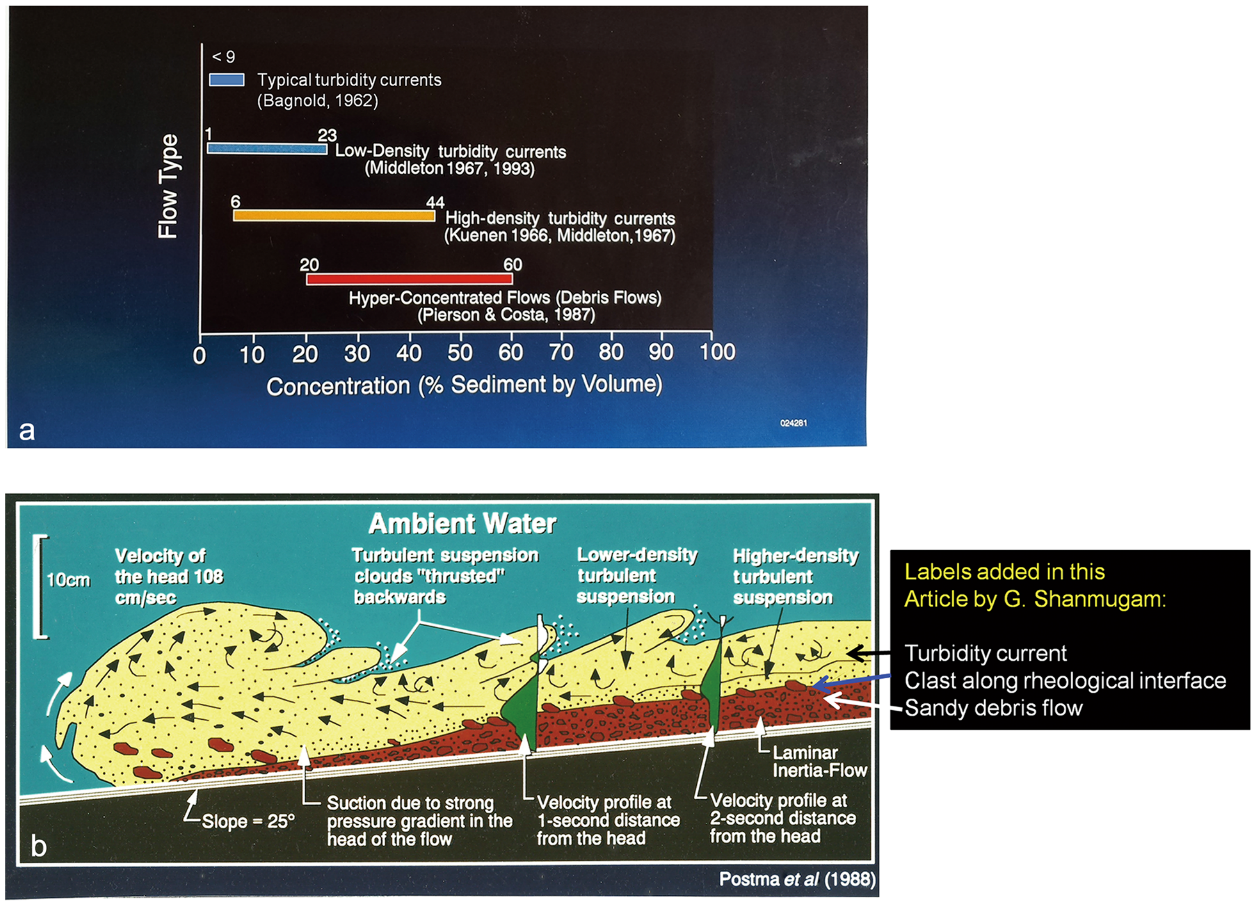

Fig. 3 **a** Plot of sediment concentration for different flow types. Note that a typical turbidity current can exist only in sediment concentration less than 9% by volume (Bagnold 1962). Note overlap in sediment concentration among low-density, turbidity currents, high-density turbidity currents, and hyper-concentrated flows. This confusion has never been resolved. Zavala does not address these basic issues. Modified after Shanmugam (1996). Reproduced with permission from SEPM; **b** Experimental stratified flows with a basal laminar-inertia flow and an upper (turbulent) turbidity current that have been termed as "high-density turbidity currents." Note clasts near the top of sandy debris flows along the rheological interface. Compare with Fig. 4. Figure from Postma et al. (1988) with permission from Elsevier Sedimentary Geology. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 4645450668368. License Date: August 10, 2019

Plata Estuary that is located between Argentina and Uruguay (Shanmugam 2018a, 2018b). I have documented this spectacular example in my paper. This modern plume is of significance in this debate for two reasons:

1) This modern example, which shows dissipation of plumes at estuary mouth (Fig. 5), directly contradicts Zavala's facies models that advocate transport of sediments into the deep sea by hyperpycnal flows.

2) Zavala has never acknowledged this obvious contradiction in any of his papers. Why?

2.11 Facies models of intrabasinal and extrabasinal turbidites

Zavala's skewed emphasis of hyperpycnites in the ancient sedimentary record tends to promote circular reasoning (see Section 3.8 below). This was the same approach that had led to the disaster of turbidite research that wasted away decades of valuable efforts (see review by Shanmugam 2006, 2012). We have learned a hard lesson from studying turbidites in the ancient rock record and of focusing on meritless genetic facies models (Bouma 1962; Walker 1978; Mutti 1992).

Specifically, in proposing his facies models of intrabasinal and extrabasinal turbidites, Zavala has failed to take into account the importance of submarine canyons in advocating submarine fan models (Shanmugam 2018a). Instead of providing empirical data for verification, he cites his own earlier publication as the proof that the facies models must be correct with the following statement (Zavala 2019): *"Intrabasinal and extrabasinal turbidites display diagnostic characteristics in their deposits that allow a clear differentiation between them (Zavala and Arcuri 2016)."* The issue here is the role of submarine canyons.

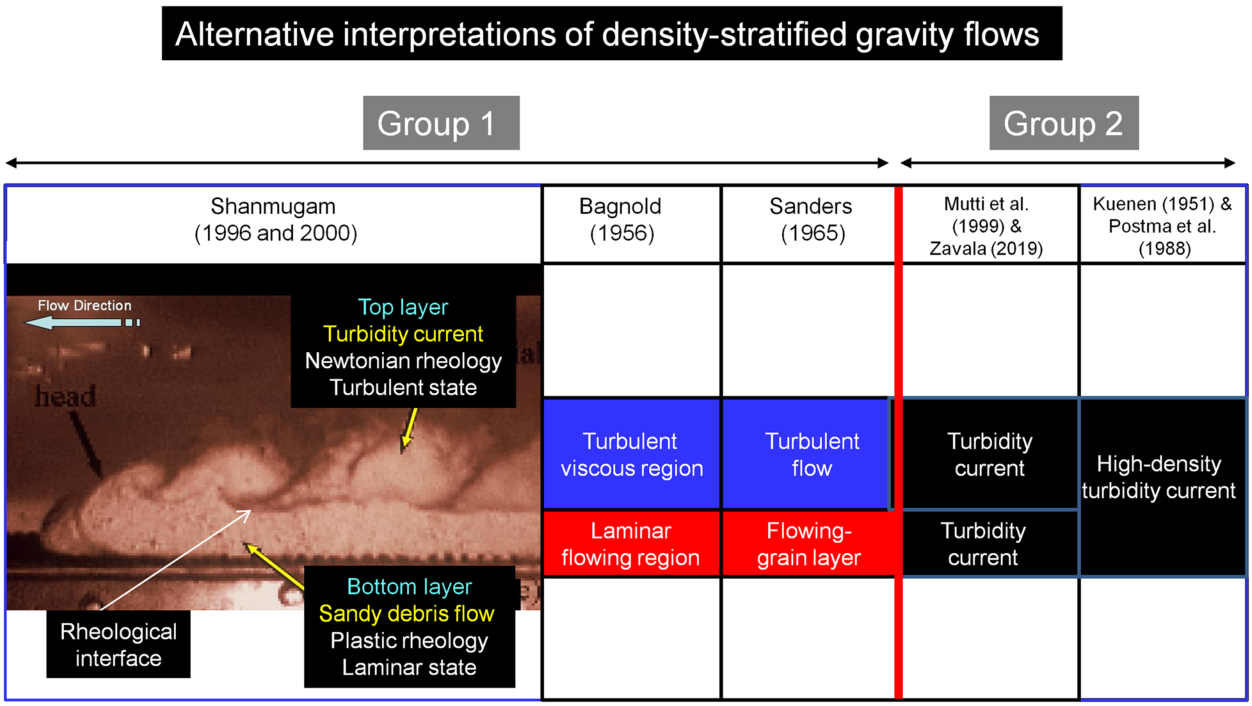

Fig. 4 Diagram illustrating the importance of distinguishing bottom layer based on fluid rheology and flow state in density-stratified gravity flows, which is based on a photograph of experimental density-stratified gravity flows showing the rheological difference between plastic debris flow (bottom layer) in massive sand and Newtonian turbidity current (top layer). Flow direction to left (arrow length = 10 cm). Note that only Group 1 of researchers would recognize the importance of bottom layer with different rheology and flow state. Note that Postma et al. (1988) would classify both layers together as 'high-density turbidity current' (see Fig. 3b). This Mobil-funded experimental flume study was carried out at St. Anthony Falls Laboratory (SAFL), University of Minnesota (1996–1998) under the direction of Professor G. Parker to evaluate the fluid dynamical properties of sandy debris flows. Results were published in two major articles (Shanmugam 2000; Marr et al. 2001;Kuenen 1951)

2.12 Representation of tsunami map as core photo of floating clasts

In disagreeing with my interpretation of a core photo with floating clasts as sandy debris flows, Zavala (2019) states that "Shanmugam (2015) *in his Fig. 15 (here reproduced in* Fig. 1*), provides an example of a core photograph of massive fine-grained sandstone showing a large floating mudstone clast with a planar clast fabric (*Fig. 1*), a typical bi-modal deposit*."

Let me summarize the problem with the above evidence:

1) In his References, the cited reference is listed as follows:
   "Shanmugam 2015. The landslide problem. *Journal of Palaeogeography* 4 (2): 109–166."
2) The Fig. 15 caption in Shanmugam (2015) reads as "*Map showing the site of Chicxulub meteorite impact at the K-T boundary in Yucatan, Mexico*,..." In other words, the tsunami map has nothing to do with floating clasts. In an academic debate, such a careless citation of references should be avoided.

2.13 Representation of mass-transport deposits (MTD) as hyperpycnites

In supporting his false notion that there are numerous cases of published examples of coarse-grained hyperpycnites, Zavala (2019) states that "*Shanmugam ignores one of the best known documentation of coarse grained hyperpycnal flows of different fan deltas in British Columbia, Canada (*Prior and Bornhold 1990;..."

In reality, Prior and Bornhold (1990, p. 75) state that "*The subaqueous morphology and geometry of developing Holocene fan deltas in fjords in British Columbia are used to interpret underwater sediment-dispersal processes. The fans are constructed by combinations of processes occurring with various frequencies and magnitudes, including subaqueous debris avalanching, inertia flows, turbidity flows, slope failure and settling of suspensions from buoyant plumes*." Clearly, the above study by Prior and Bornhold is about mass-transport deposits (MTD), not hyperpycnal flows.

2.14 Representation of turbidity currents as hyperpycnal flows

In documenting modern hyperpycnal flows in deep water, Zavala (2019) states that "Khripounoff et al.

Fig. 5 Rio de la Plata Estuary. **a** Location of the Rio de la Plata Estuary (white circle). Image credit: ETOPO1 Global Relief Model, C. Amante and B.W. Eakins, ETOPO1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis, NOAA Technical Memorandum NESDIS NGDC-24, March 2009. with additional labels by G. Shanmugam; **b** Satellite image showing the Rio de la Plata Estuary. This image is used as an index map to provide a regional perspective. Image courtesy Jacques Descloitres, MODIS Land Group, NASA GSFC. https://earthobservatory.nasa.gov/IOTD/view.php?id=651 Image acquired on April 24, 2000; **c** Satellite image showing the Rio de la Plata Estuary with hyperpycnal plumes that tend to move towards the Argentinian shelf to the south. Framiňan and Brown (1996) used the term "turbidity front" for this hyperpycnal plume. Note that the entire, 220-km wide, plume gets diluted and dissipated with an irregular front, which fails to advance into the South Atlantic. This dilution of plume is attributed to external controls, such as ocean currents operating on the shelf. The Paraná River, the second longest river in South America after the Amazon, supplies three-quarters of the fresh water that enters the estuary, with the remainder arriving from the Uruguay River. Image credit: NASA Earth Observatory, NASA image by Jeff Schmaltz, LANCE/EOSDIS MODIS Rapid Response. https://earthobservatory.nasa.gov/IOTD/view.php?id=77581 Image acquired on March 31, 2012. Fossati et al. 2014 and Fossati and Piedra-Cueva 2013

(2003) *documented on March 8, 2001, a sediment laden turbidity current in the Congo canyon travelling at 121 cm/sec at 4000 m depth, 150 m above the channel floor, transporting quartz rich well sorted fine grained sand (150–200 μm) and large plant debris (wood, leaves, roots). This single flow was sustained for10 days.*" In direct contradiction, Zavala (2019) also states that, "*Clearly, we don't equate turbidity currents (Newtonian turbulent flows) to hyperpycnal flows.*" On the one hand, Zavala considers turbidity currents as hyperpycnal flows, and on the other hand, he does not. His inconsistent philosophy can be confusing to the reader.

2.15 Representation of triggering mechanism as depositional process

In promoting the importance of hyperpycnal flows in the deep sea, Zavala (2019) used the Newport Canyon in Southern California (Covault et al. 2010). There are some basic factors that the readership should be aware of the Newport Canyon study:

1) The primary deep-water depositional process in this case was turbidity currents, not hyperpycnal flows. The reason is the presence of turbidites in U.S.G.S. cores (Normark et al. 2009).

2) Covault et al. (2010) attributed the initiation of sediment-gravity flows to three possible triggering mechanisms, namely (a) earthquakes associated with tectonic activities, (b) hyperpycnal fluvial effluents, and (c) deltaic buildup and related sediment failure.
3) Zavala selectively emphasized the hyperpycnal origin and ignored the other two. More importantly, Zavala confused the triggering mechanism with the depositional process.
4) According to Covault et al. 2010, p. 248), "*The contribution and timing of fluvial effluents relative to mass-wasting processes in the canyon and steep outer shelf to the initiation of sediment gravity flows in the Newport system are unknown.*" Clearly, Zavala has overlooked the critical factor that the importance of hypepycnal flows is unknown in this case study.
5) Turbidity currents, irrespective of their differences in triggering mechanisms, will invariably possess the same fluid mechanical properties. This is the reason why Zavala needs to define hyperpycnal flows in terms of fluid rheology, flow state, and sediment concentration.

In conclusion, even if a sediment-gravity flow is triggered solely by hyperpycnal discharge of a river, the resulting flow still has to be classified based on fluid mechanics at the point of deposition, not on triggering mechanisms at the point of initiation.

2.16 Original authors' conclusion

In documenting hyperpycnites, Zavala (2019) cited an example of deposits associated with the failure of the Malpasset Dam in the Mediterranean (Mulder et al. 2009). But the primary conclusion of Mulder et al. (2009) was stated as "*The deposits associated with the Malpasset Dam failure strongly differ from classical hyperpycnites...*". Mulder et al. (2009) also concluded that "*the process is closer to a slide-triggered, surge like flow forming a hyperconcentrated flow*," In other words, this case is not a hyperpycnite, as Zavala alleges.

2.17 Earthquake-triggered flows

In conflict with the original concept of hyperpycnal flows designed strictly for river-discharged sediment flows (Bates 1953), Zavala (2019) has confused the issue with an example from Taiwan in which normal river discharges are dominated by earthquake-triggered higher sediment concentrations (Dadson et al. 2005).

2.18 Recognition of hyperpycnal flows on seismic profiles

Zavala (2019) cites Sacchi et al. (2009) as an example of hyperpycnal flows in Italy. This study was based on interpretation of hyperpycnal flows on high-resolution seismic profiles. What are the seismic criteria that distinguish hyperpycnal flows from turbidity currents on seismic profiles in terms of fluid mechanics?

3 Result and discussion: reply to Van Loon, Hüeneke and Mulder (2019)

3.1 Definition of 16 types of hyperpycnal flows

There is a fundamental philosophical difference between myself and Van Loon et al. on hyperpycnal flows. For example, I am of the view that in order to effectively debate this issue, there must be a common agreement on the definition of hyperpycnal flows. But there is no such common ground. The problem is that there are 16 types of hyperpycnal flows (Shanmugam 2018a). Unlike me, Van Loon et al. consider that 16 types of hyperpycnal flows are not a problem. In this context, they state that "*it remains unclear why the existence of different type would pose a problem regarding the fact that they are all sediment-gravity flows and that they can form deposits with their own sedimentary characteristics (as far as the flow types and/or conditions differ!).*"

The problem is that Van Loon et al. do not provide answers to the following questions given the fact that there are single-, double-, and multi-layer (Fig. 1) hyperpycnal flows (Shanmugam 2018a):

1) What is difference in sedimentary characteristics between deposits of single-layer and double-layer flows?
2) What is difference in sedimentary characteristics between deposits of single-layer and multi-layer flows?
3) What is difference in sedimentary characteristics between deposits of double-layer and multi-layer flows?
4) What is difference in sedimentary characteristics between deposits of double-layer and tide-modulated hyperpycnal flows?
5) What are the sedimentary characteristics of deposits of internal waves associated with tide-modulated hyperpycnal flows (Wang et al. 2010)?, to mention a few issues.

Baroclinic currents associated with internal waves and tides (Wang et al. 2010) are one of the most controversial topics that resulted in lively scientific debates (Shanmugam 2014a, 2014b). Van Loon et al. have avoided discussing these natural complexities.

Historically, the less the knowledge about a particular process that we possess, the more the number of flow types that we propose. Analogous to 16 types of hyperpycnal flows, there are 78 types of mass-transport deposits (MTD), which include over 34 types of high-density turbidity currents (see Section 2.6 above), in the published literature (Shanmugam 2012, his Table 2.2). Unless Van Loon et al. can define the fluid mechanics of each flow type and explain corresponding deposits in terms of sedimentary structures, this debate is futile.

3.2 A review article

Van Loon et al. (2019) assert that my paper is not a review article. They are correct in that my paper is not strictly a 100% review in the conventional sense. However, I published it as a review article in the *Journal of Palaeogeography* (JOPG) with the approval of journal editors and reviewers. The reason is that JOPG has only four categories of manuscript submission, namely 1) original article, 2) review, 3) brief report, and 4) academic discussion. My paper is a hybrid type, comprised of original contribution, review, and discussion. However, my paper can be better classified as a review category than as the other types.

3.3 Anthropogenic “hyperpycnal flows”

The main focus of the discussion by Van loon et al. (2019, their Fig. 1) is on a modern example of anthropogenic hyperpycnal flows. This example is totally out-of-place in this debate because I did not consider anthropogenic flows in my original paper (Shanmugam 2018a), where I only discussed natural flows. However, I am compelled to discuss anthropogenic flows in this reply.

Their photograph shows a dam of the Xiaoliangdi Reservoir and related flows with a bottom brown-color layer and an upper white-color layer. Van Loon et al., without any field measurements of flow properties, concluded that this example is the positive proof of modern hyperpycnal flows. In a serious scientific discussion, one expects meaningful nomenclature and verifiable empirical data in documenting a specific process. Let’s rigorously evaluate their claim of a modern “hyperpycnal flow” based on an article by Yang et al. (2018).

1) Yang et al. (2018) claimed that hyperpycnal flows were associated with a dam built by human activity (i.e., anthropogenic). However, the concept of hyperpycnal is meant for natural river-mouth processes (Bates 1953), not for artificial flows associated with an anthropogenic dam.
2) In their Fig. 1 caption, Van Loon et al. claim that their Fig. 1 is from an article by Yang et al. (2018) published in Marine and Petroleum Geology (MPG) and from a website “www.quanjing.com“. But this figure is absent in the MPG article by Yang et al. (2018). Quanjing is a Chinese language website that also does not display their Fig. 1. So, what is the source of their Fig. 1?
3) The color difference between upper and lower layers could be due to any number of factors (e.g., differences in composition, grain size, sediment concentration, etc.). Hyperpycnal flows are defined on the basis of flow density (Bates 1953), not color.
4) Their frequent use of terms “hyperpycnites” and “hyperpycnal flows” in the comment by Van Loon et al. (2019) is problematic because the term “hyperpycnal flows” has never been defined (see Section 2.2 above). The reason is that there are at least 16 types of hyperpycnal flows (e.g., density flow, underflow, high-density hyperpycnal plume, high-turbid mass flow, tide-modulated hyperpycnal flow (Wang et al. 2010), cyclone-induced hyperpycnal turbidity current, multi-layer hyperpycnal flows, etc., see Shanmugam 2018a, 2018b), without an underpinning principle of fluid mechanics. Which one of the 16 types best represents the flow types shown in their Fig. 1? Why?
5) Their Fig. 1 with two layers of different colors could be due to differences in density. In fact, Gao et al. (2015) proposed density-stratified hyperpycnal flows. Did Van Loon et al. measure the density difference between upper and lower layers? Density-stratified flows are a source of major controversy in debating the origin of high-density turbidity currents (Shanmugam and Moiola 1997; Shanmugam et al. 1997).
6) What is the difference in fluid rheology (Newtonian vs. Bingham plastic) between two layers that is critical in distinguishing turbidity currents from debris flows? (Dott Jr. 1963; Middleton 1993)?
7) What is the difference in flow state (turbulent vs. laminar) between two layers that is critical in distinguishing turbidity currents from debris flows? (Middleton and Hampton 1973; Middleton 1993; Middleton and Wilcock 1994)?
8) What is the difference in sediment concentration by volume between two layers that is critical in defining turbidity currents?

In summary, all designations of flow types must be based on principles of physics and empirical data.

3.4 Anthropogenic Elwha sediment plume, Strait of Juan de Fuca

In discussing a modern anthropogenic example of “hyperpycnal flows” associated with a dam in China (their Fig. 1), Van Loon et al. would be interested in the most spectacular example of an anthropogenic Elwha sediment plume in the Strait of Juan de Fuca (Fig. 6). This classic plume was triggered by the demolition of Elwha Dam in the Olympic Peninsula, State of Washington (Fig. 6a). This anthropogenic sediment plume (Fig. 6c) was the result of sediment released from the world’s largest dam demolition (Ritchie et al. 2018). The University of Washington (Seattle, WA) first reported this phenomenal event and its oceanographic and sedimentologic implications in the UW News (Hickey 2013). According to USGS (2018), this demolition event flushed out 20 million tons of sediment into the Strait of Juan de Fuca. Following the flawed logic of Van Loon et al., one could classify these Elwha sediment plumes (Fig. 6c) as modern hyperpycnal flows based on visual observation alone. However, without measurements of fluid theology, flow state, and flow density, any classification of these Elwha plumes either as hyperpycnal flows, or as turbidity currents, or as sandy debris flows, is a sedimentological fallacy.

Distinguishing hyperpycnites from turbidites or contourites is still a major challenge. Serious scientific discussions on hyperpycnal flows must be based on measured physical properties of natural flows, not on color difference between two layers in artificial conditions.

Despite the uncertain nature of flow types, an important lesson learned from the Elwha sediment plume is

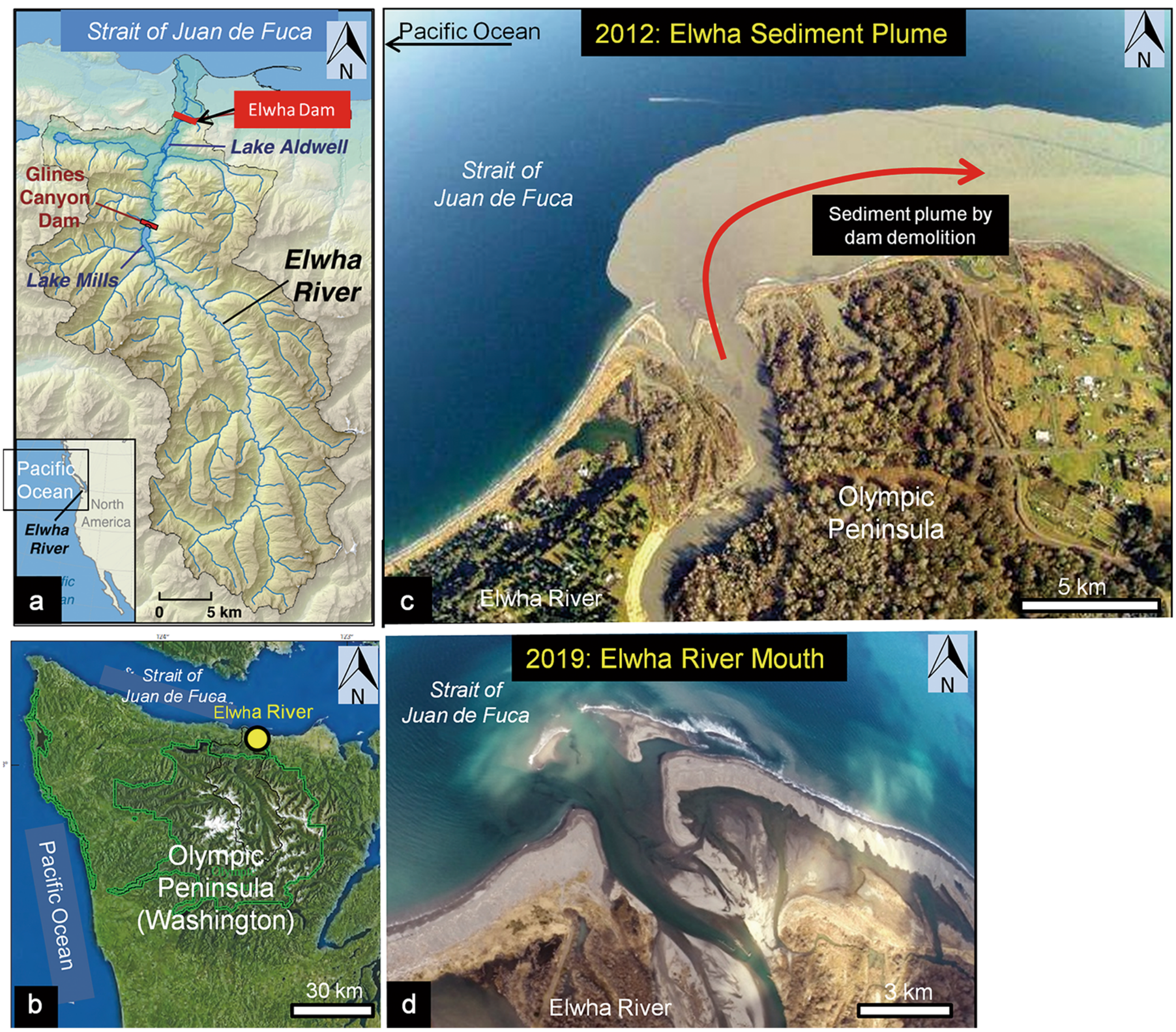

Fig. 6 Sediment plume triggered by Elwha Dam demolition in the State of Washington (USA). **a**. *index* map showing Elwha Dam (arrow). The 108-ft dam, built in 1910 and demolished in 2012, is located approximately 7.9 km upstream from the river mouth. Credit: U.S. Geological Survey Public Domain map; **b** Aerial photograph of the Olympic Peninsula and the Strait of Juan de Fuca. Note the Elwha River mouth is shown by a filled yellow circle. From Duda et al. (2011) with additional labels by G. Shanmugam; **c** Elwha sediment plume triggered by the demolition of Elwha Dam in 2012. Red arrow shows easterly deflecting plume, away from the Pacific Ocean. This deflection could be attributed to tidal currents in this estuarine environment. Also, the Strait of Juan de Fuca is subjected to easterly upwelling winds. Photo credit: Tom Roorda. Aerial photo was taken on March 30, 2012. From Hickey (2013), UW News, March 7, 2013, University of Washington, Seattle, WA; **d** Aerial photo of Elwha River mouth showing absence of sediment plume in 2019 (compare with **c**). Photo courtesy of Tom Roorda, Roorda Aerial, Port Angeles, WA. Aerial photo was taken on February 28, 2019

that external factors are critical in redirecting sediment transport. The deflection of Elwha plume to the east (Fig. 6c) could be attributed to tidal currents in this estuarine environment (Cannon 1978; Thomson et al. 2007; Warrick et al. 2011). Also, summer upwelling winds move easterly into the Strait of Juan de Fuca. Such summer winds could also explain deflecting sediment plume to the east of the Elwha River mouth. The reason is that winds reach a maximum speed of $8\ \mathrm{m\,s^{-1}}$ off Vancouver Island with increasing magnitudes eastward in the Strait of Juan de Fuca (Foreman et al. 2008).

3.5 Tidal shear fronts and internal waves

Van Loon et al. (2019) defend the occurrence of hyperpycnal flows amid the presence of tidal shear fronts in the Yellow River in China. The reality is that tidal shear fronts do indeed serve as natural barriers for sediment transport by hyperpycnal flows. According to Wang et al. (2010), tide-modulated hyperpycnal flows are associated with internal waves (Wang et al. 2010). As mentioned earlier, baroclinic currents associated with internal waves and tides are one of the most controversial topics that resulted in spirited scientific debates (Shanmugam 2014a, 2014b). Van Loon et al. have avoided discussing these natural complexities.

3.6 Turbidite facies models

Van Loon et al. strongly believe in the origin of complete Bouma Sequence by turbidity currents, which is their prerogative. However, no one has ever generated the ubiquitous Bouma Sequence with five divisions by turbidity currents in a laboratory flume during the past 82 years, since the first experiment on density flows by Kuenen (1937). Nor has any one documented the complete Bouma Sequence from modern deep-sea sediments. And yet, according to Van Loon et al., there are thousands of examples of ancient turbidites in the published literature. Why? The answer is simple. The application of the turbidite facies model (i.e., the Bouma Sequence) to ancient sedimentary record guarantees a model-driven turbidite interpretation with a 100% success. For example, if one describes a deep-water sand as Ta, there is only one possible interpretation, which is that the Ta interval represents the basal part of a turbidite bed. In other words, one begins rock description with a turbidite facies model and ends up with interpreting the bed as a turbidite. This kind of logic is called 'circular reasoning'.

3.7 Scientific documentation

Van Loon et al. (2019) state that "Having studied – and still studying hyperpycnites in the field...". Van Loon coauthored an article by Yang et al. (2017). The problem with that paper published in the AAPG Bulletin exhibits problems, such as grain-size analysis of hyperpycnites. Shanmugam (2019a) pointed out the following flaws:

1) They (Yang et al. 2017; their Fig. 8) used "dark shale" as a grain-size term. However, neither dark color nor shale is a grain-size term.
2) Conventionally, the term shale has been used for indurated lithofacies with fissility (Folk 1968, p. 31). Fissility is not a grain-size term.
3) Importantly, the term shale can represent different grain sizes, such as "clay-shale," "silt-shale," and "sandy-silt-shale" (see Table 2 in Folk 1968).
4) Yang et al. (2017) also used "tuff" as a grain-size term. However, tuff is a genetic term reserved for volcanic ash, not for grain size.

3.8 Copyright clearance

Van Loon et al. note that I used a figure from an article by Yang et al. (2017) without obtaining permission from the authors. The figure in question was published in the AAPG Bulletin. According to AAPG Bulletin Permission guidelines to authors, "*If you want to use a single figure, a brief paragraph, or a single table from an AAPG publication in a paper in another publication, AAPG considers this to be fair usage, and you need no formal permission.*" 'Fair usage' policy has been adopted by many international journals. For all other figures, I did obtain formal permissions from Copyright Clearance Center's RightsLink (see figure captions for license numbers and dates in my article, Shanmugam 2018a).

3.9 Importance of satellite images

Van Loon et al. (2019) also criticize my article for using satellite images, which was a major objective of my paper (Shanmugam 2018a). I used satellite images as a proxy to fill the knowledge gap on sediment transport in marine and lacutrine environments (Shanmugam 2018a, 2018b). Ironically, Mulder et al. 2003, their Fig. 1) used an aerial photograph of hyperpycnal discharge in Lake Tanganyika (Tanzania) as the very first figure in their article on hyperpycnal flows. Such comments are hypocritical.

3.10 Flawed recognition criteria

Finally, in their conclusions, Van Loon et al. are disappointed that I used only one photograph of hyperpycnites in my 42-page long paper (Shanmugam 2018a). I admit that I could have used more examples. The reason that I used only one figure (Shanmugam 2018a, his Fig. 14b) was to illustrate the absurdity of interpreting a sediment as hyperpycnites without a reliable criterion. In that example, the authors (Yang et al. 2017) used an "erosional surface" within a depositional unit. The presence of an erosional surface within a single hyperpycnite depositional unit is antithetical to the basic principles of stratigraphy and sedimentation (Krumbein and Sloss 1963). It is sedimentologically meaningless to relate layers above and below an erosional surface, with a break in deposition in the middle, to the same process. My point was that there are no reliable criteria for recognizing hyperpycnites. Without criteria, one cannot recognize hyperpycnites. Without hyperpycnites, there cannot be photographs of hyperpycnites. Therefore, whether I used one or a thousand photographs is irrelevant!

4 Conclusions

Despite a deluge of incoming literature on hyperpycnal flows, our understanding of these flows is still muddled.

5 Methods/experimental study

A Mobil-funded experimental flume study was carried out at St. Anthony Falls Laboratory (SAFL), University of Minnesota (1996–1998) under the direction of Professor G. Parker to evaluate the fluid dynamical properties of sandy debris flows. Results were published in two major articles (Shanmugam 2000; Marr et al. 2001).

Abbreviations

AAPG: American Association of Petroleum Geologists; HDTC: High-density turbidity currents; JOPG: Journal of Palaeogeography; JSR: *Journal of Sedimentary Research*; Km: Kilometer; m: Meter; MIT: Massachusetts Institute of Technology; MPG: Marine and Petroleum Geology; MTD: Mass-transport deposits; N: Neap tide; NASA: National Aeronautics and Space Administration; NNW: North-northwest; S: Spring tide; SAFL: St. Anthony Falls Laboratory; SSE: South-southeast; USA: United States of America; USGS: United States Geological Survey; μm: Micrometer

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Author's contributions

The author read and approved the final manuscript.

Competing interests

The author declares that he has no competing interests.

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