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ACADEMIC DISCUSSION

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The new knowledge is written on sedimentary rocks – a comment on Shanmugam's paper "the hyperpycnite problem"

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Abstract

In a recent contribution G. Shanmugam (2018) discusses and neglects the importance of hyperpycnal flows and hyperpycnites for the understanding of some sediment gravity flow deposits. For him, the hyperpycnal flow paradigm is strictly based on experimental and theoretical concepts, without the supporting empirical data from modern depositional systems. In this discussion I will demonstrate that G. Shanmugam overlooks growing evidences that support the importance of hyperpycnal flows in the accumulation of a huge volume of fossil clastic sediments. Sustained hyperpycnal flows also provide a rational explanation for the origin of well sorted fine-grained massive sandstones with floating clasts, a deposit often wrongly related to sandy debris flows.

Keywords: Hyperpycnites, Turbidites, Sediment gravity flows

1 Introduction

In a recent paper G. Shanmugam (2018) relativized the importance of hyperpycnal flows as an important sediment transfer mechanism to associated lacustrine and marine basins. Controversially, hyperpycnal flows were the first documented land derived sediment gravity flows in lakes (Forel 1885) and in deep marine settings (Heezen et al. 1964). At present, our understanding of hyperpycnal flows and their related deposits (hyperpycnites) has been deeply improved due to a join effort on the study of ancient and recent deposits, complemented with detailed oceanographic observations, flume experiments and mathematical modeling.

Full discussion with Shanmugam (2018) will be the scope of a forthcoming full paper. The objective of this short reply is to discuss some points observed by G. Shanmugam (2018) concerning my recent paper (Zavala and Arcuri 2016) focused on the recognition and interpretation of ancient hyperpycnites.

2 Comments on Shanmugam (2018) paper "The hyperpycnite problem"

2.1 Sand transport to deep waters by hyperpycnal flows

Shanmugam (2018), page 199 right line: "*There is not a single documented case of hyperpycnal flow, which is transporting sand across the continental shelf, and supplying sand beyond the modern shelf break*".

There is growing evidences provided by the study of the discharges of Taiwan rivers (Dadson et al. 2005) especially SW Taiwan rivers into the Gaoping Canyon (Liu et al. 2006, 2012, 2016; Chiang and Yu 2008; Zhang et al. 2018), the case of the Cap Timiris Canyon (Antobreh and Krastel 2006), the Rhone fan (Mear 1984; Droz et al. 2001; Tombo et al. 2015), the Var deep sea fan (Mulder et al. 2001; Khripounoff et al. 2009, 2012), the Hueneme canyon in the Santa Monica Basin (Romans et al. 2009), the very thick deep water hyperpycnites related to the Missoula flood (Griggs et al. 1970; Brunner et al. 1999; Normark and Reid 2003; Reid and Normark 2003), the Newport canyon in Southern California (Covault et al. 2010), the Geremeas river in the Sardinian southern margin (Meleddu et al. 2016), the Alsek Sea Valley in Alaska (Milliman et al. 1996), the failure of the Malpasset Dam in the Mediterranean (Mulder et al. 2009), the Eel

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submarine fan in the offshore of northern California (Paull et al. 2014), the Al Batha hyperpycnal system in Oman (Bourget et al. 2010), the Santa Barbara Channel in California (Warrick and Milliman 2003), and the Zaire (Congo) canyon (Heezen et al. 1964; Khripounoff et al. 2003; Savoye et al. 2009; Azpiroz-Zabala et al. 2017) among others. Khripounoff et al. (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 for ten days. More recently Azpiroz-Zabala et al. (2017) recognized in the same turbidity system flows lasting an average of 6.7 days with peak velocities between 80 and 100 cm/sec. Additionally in their review of recent sinuous deep-water channels, Wynn et al. (2007) claimed that "*Deep-water sinuous channels are dominantly fed by high-frequency or semi-continuous, low-density turbidity currents, some of which may be hyperpycnal at times of peak fluvial discharge*". More recently Zhang et al. (2018) showed the results of monitoring the turbidity currents in the Gaoping submarine canyon during 3.5 years. The mooring system was located at a water depth of 2104 m, 146 km far from the canyon head. They recorded 20 turbidity currents directly attributed to peak river discharges during flood periods. The duration of each individual flow ranged from a week up to a month. The associated interstitial water had high temperature and less salinity respect to the ambient water, thus demonstrating that these turbidites were originated directly from hyperpycnal flow discharges. Zhang et al. (2018) concluded that "*These observations strongly suggest that hyperpycnal flow conditions associated with the river floods during the typhoon season are the dominant drivers of sediment redistribution in tectonically active and climatically disturbed areas such as Taiwan and its connected submarine canyons, and support the link between upstream hyperpycnal flows and sustained turbidity currents in the deep sea*".

2.2 The origin of hyperpycnal flows

Shanmugam (2018), page 199 right line: "*Thus far, the emphasis has been solely on river mouth hyperpycnal flows (Mulder et al. 2003), thus ignoring density plumes in other environments, such as open marine settings, far away from the shoreline*".

Of course, the hyperpycnal condition can only be achieved at the coast. According to Bates (1953) a hyperpycnal flow occurs when a subaerial (fluvial) system discharges a mixture of water and sediment with a bulk density higher than that of the water in the reservoir. When this situation occurs, the incoming flow sinks below basin waters forming a hyperpycnal flow which can travel considerable distances carrying large volumes of sediment directly supplied from a river in flood. An underflow can only be considered as hyperpycnal (from the Greek ὑπέρ (hyper) meaning "over", pycnal = density, from Greek: πυκνός (puknos) meaning "dense") if it's originated on land. The last excluded from the definition of "hyperpycnal flow" to all kinds of underflows generated inside the basin, as the case of mass-transport complexes, intrabasinal turbidites, tempestites, cascadites, and turbulent flows derived from convective instability (Parsons et al. 2007) or density stratification. Consequently hyperpycnal flows can only be formed at river mouths.

2.3 Turbidity currents from plunging rivers

Shanmugam (2018), page 205 right line: "*No one has documented the transformation of river currents into turbidity currents at a shallow plunge point in modern marine environments*".

There is a lot of documentation about the hyperpycnal origin of turbidites, both in shallow and deep waters (see comments on chapter 2.1 with references there). Additionally, a very nice documentation of the 1954 Bonea River flood in Italy and its related hyperpycnal flow deposits is also available (Budillon et al. 2005; Violante 2009; Sacchi et al. 2009). Recently Katz et al. (2015) published a detailed observation of an actual hyperpycnal discharge in the Gulf of Aqaba (Red Sea). They shared a very interesting video available online https://www.youtube.com/watch?v=4r9ndJ80_1Y

2.4 Hyperpycnal flow deposits and turbidites

Shanmugam (2018), page 205 right line: "*Hyperpycnal flows are defined solely on the basis of fluid density. Therefore, it is misleading to equate turbidity currents with hyperpycnal flows*".

In our paper (Zavala and Arcuri 2016) we follow the approach of Mutti and Ricci Lucchi (1972), Mutti (1992) and Mutti et al. (1999), considering as turbidites all those sediments deposited by sediment gravity flows and not strictly turbidity currents. According to this definition, turbidites (intrabasinal or extrabasinal) include a broad spectrum of deposits ranging from matrix–or clast—supported conglomerates to graded mudstone beds. We absolutely agree with Mutti's point of view, and we are convinced that this broad definition substantially simplifies the discussion in a field in which sedimentary processes, flow rheology, flow states are in most cases inferred from the careful analysis of sedimentary rock bodies. In our paper (Zavala and Arcuri 2016) we have clarified this topic in page 37 "*Note that in this approach, the criterion of Mutti et al. (1999) is followed, considering as turbidites the deposits of all types of* *subaqueous sediment gravity flows independently if they are related or not to purely turbulent flows. Consequently, in this work, the deposits of both Newtonian (fluid) and non-Newtonian (plastic) flows are included in this category*". Clearly, we don't equate turbidity currents (Newtonian turbulent flows) to hyperpycnal flows. Hyperpycnal flows can originate from different high density flows, ranging from cohesive debris flows up to low density turbidity currents (Zavala 2018).

2.5 Coarse-grained deltas and hyperpycnal flows

Shanmugam (2018), page 206 right line "*At present, coarse-grained deltas are totally ignored in studying hyperpycnal flows. As a consequence, all published examples of hyperpycnal flows are from fine-grained deltas, such as the Yellow River delta in China*".

Not true. Probably G. 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; Bornhold and Prior, 1990). Additionally, several additional examples of recent bedload dominated hyperpycnal flows and their deposits are available in Mulder and Chapron (2011).

2.6 Hyperpycnal flows and the inverse to normally-graded sequence

Shanmugam (2018), page 217 left line "*Importantly, no one has reproduced the entire inverse to normally-graded sequence with internal erosional surface (i.e., the hyperpycnite facies model) in laboratory flume experiments; nor has anyone documented this sequence from modern settings. The conceptual hyperpycnite model exists only in theory in publications, not in the real-world sedimentary record*".

This is not true. Violante (2009), in his Fig. 10, provided a nice example- of an inverse to normally-graded interval in recent hyperpycnal flow deposit generated by the Bonea flood in 1954. Similar inverse to normally-graded intervals have been documented in recent hyperpycnal deposits from the Al Batha lobes by Bourget et al. (2010), his Fig. 12. Hyperpycnites characterized by couples of inverse-normal grading were well documented in the Triassic Yanchang Formation (Ordos Basin, central China). Hyperpycnites developed not only in sandstones (Yang et al., 2017a), but also in fine-grained sediments (Yang et al., 2017b).

2.7 Hyperpycnal flows and the origin of fine-grained massive sandstones

Shanmugam (2018), page 217 left line "*Massive sandstones, considered to be a recognition criteria for hyperpycnites (Steel et al. 2016; Zavala and Arcuri 2016), are not unique to deposits of hyperpycnal flows. There are alternative processes that can equally explain the origin of massive sands". "The Ta division has also been attributed to deposition from sandy debris flows (Shanmugam 1997)*".

In my paper (Zavala and Arcuri 2016) I don't consider the occurrence of massive sandstones as a diagnostic criteria for the recognition of hyperpycnites. Although fine-grained massive sandstones are a very common product of hyperpycnal flow deposits, only the presence of entire leaves within fine-grained massive sandstones is considered a diagnostic feature that allows the recognition of hyperpycnal flow deposits (Zavala and Arcuri 2016, pp. 46). This is because the existence of entire leaves proves that extrabasinal materials were transported together with sand grains within a turbulent suspension, and were then trapped during the progressive collapse of the suspension cloud.

Of course, the accumulation of massive sandstones has been for long in the past related to an "en masse" accumulation but this origin was largely speculative, since most arguments were supported in the lack of sedimentary structures and the observation of floating clasts which were considered as supported by an internal flow cohesion.

In his discussion about the validity of the high density turbidity current paradigm, G. Shanmugam (1996) introduces the concept of sandy debris flows for cohesive to cohesionless debris flows supported by matrix strength, dispersive pressure and buoyant lift. G. Shanmugam also pointed out that these sandy debris flows are common in fine-grained sands with low to moderate mud content. According to G. Shanmugam's point of view: (I) almost all kinds of massive or inversely graded clastic deposits should be interpreted as accumulated by sandy debris flows; (2) deposits containing floating outsized clasts can be produced only by debris flows; and (3) a traction carpet developed beneath a turbulent flow should be regarded as a debris flow (Sohn 1997).

G. Shanmugam (2015) proposed a sandy debris flow origin for fine-grained massive sandstones based on flume experiments carried out by Marr et al. (2001). These experiments were conducted in a 10 m long glass flume with a slope ranging from 4.6° to 0°. Experimental sediment gravity flows were primarily composed of clay, well sorted fine-grained silica sand (110 μm), tap water, and a siliceous material produced as a residue from burning coal. These experiments show that, for these considered slopes, the generation of coherent gravity flows with water contents ranging from 25 to 40 wt% require the addition of some clay. The experiments were carried out with bentonite (0.7 to 5 wt%) and kaolinite (7 to 25 wt%). No experiments were performed to analyze the requirement of other common clays in lacustrine and marine settings, like chlorite, illite and smectite. Of course the final deposit was well sorted because they use well sorted sand in the experiment. Nevertheless, flows having a matrix strength can transport different grain size materials which are deposited “en masse” by cohesive freezing, giving the typical poorly sorted characteristic of debris flow deposits.

G. 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. According to him these “evidences” suggest a deposition from a laminar sandy debris flow. The occurrence of mudstone clasts of different sizes and the sharp and irregular upper bedding contact are interpreted as indicative of flow strength and deposition from cohesive freezing in a laminar plastic flow. According to me, this interpretation is absolutely wrong.

Sohn (1997, p. 507) strongly criticizes the point of view of G. Shanmugam about the deposition of fine-grained massive sandstones and floating clay clasts: “.. *large floating clasts cannot be foolproof evidence of debris flows because they can be produced under turbulent flow conditions as long as the deposition of large clasts lags behind in a traction carpet.*”

Main evidences that are against the interpretation of a sandy debris flow origin for the example shown in Fig. 1 include:

1) The deposit is clearly bimodal, suggesting the join occurrence of two different depositional processes, A) gradual collapse of suspended load (massive well sorted fine-grained sands and silt) transported within a diluted sustained turbulent flow as a consequence of a progressive loss of flow capacity and B) bedload (large and occasionally rounded clay clasts) of large clast dragged by shear forces provided by the overpassing long lived turbulent flow over the rising deposit-flow interface.
2) Texture, sorting and sedimentary structures don’t support a debris flow origin for this interval. The deposit is mainly composed of well sorted fine-grained sandstones, which suggest a highly selective

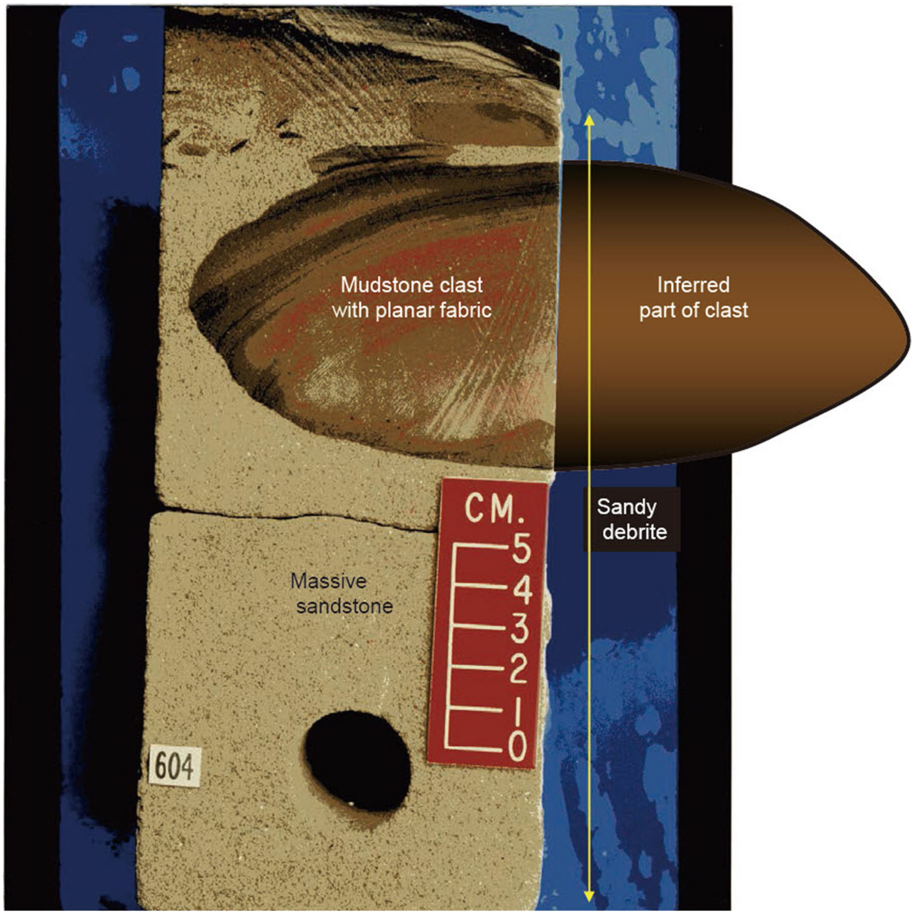

Fig. 1 Core photograph showing a typical example of a sandy debris flow deposit according to G. Shanmugam. Note the imbrication in the small clay clasts located close to the top. From Shanmugam (2015)

transportation mechanism like suspension of sand grains in a long lasting low density turbulent flow. Dispersive pressure in very fine grained sands is not an efficient support mechanism because of the negligible inertia of very small sand grains. Additionally there is no evidence of escaping pore fluid.

3) The evident low clay matrix of the deposit is also against the interpretation of a debris flow origin.
4) The imbrication of the small clay clasts at the top indicates a flow moving from left to right. Imbrication is very important since it suggest that clasts were transported as bedload at the base of a sustained turbulent flow. Once again, not a debris flow.

The above evidences suggest for these fine-grained massive sandstones a gradual accumulation (Sanders 1965) from sustained low density turbidity currents with associated bedload.

Shanmugam (2012, 2015), p 138 considered that "*Debris flows are capable of transporting gravel and coarse-grained sand because of their inherent strength. In contrast, turbidity currents cannot transport coarse sand and gravel in turbulent suspension*". The assumption that turbidity current cannot transport clasts can result in dangerous oversimplifications.

Floating clasts in turbidites are not only possible but very common, because they are transported as bedload (mostly creep and rolling) above a progressively raising depositional surface (Postma et al. 1988; Kneller and Branney 1995; Sohn 1997; Branney and Kokelaar 2002; Manville and White 2003). Flume experiments performed by Banerjee (1977), Arnott and Hand (1989) and Sumner et al. (2008) demonstrated that the accumulation of massive sandstones occur by the collapse of suspended load from waning dilute turbulent suspensions (1–2 vol% of particles) at bed aggradation rates in excess of 0.44 mm/s.

As a conclusion, the interpretation of fine-grained massive sandstones as accumulated by sandy debris flows creates more problems than it solves, because:

1) Almost all thick fine-grained massive sandstones are relatively well sorted and have very little or no clay content (Zavala and Pan 2018, their Fig. 12).
2) Slopes in inner shelf and in lakes usually are less than 0.5°, which will not favor the movement of cohesive or poorly cohesive debris flows characterized by matrix strength.
3) An accumulation from sandy debris flows cannot adequately explain the facies recurrence between massive and laminated sandstones commonly observed in the field (Zavala and Pan 2018, their Fig. 15), and also the common association of massive sandstones with low angle cross bedding.
4) Massive fine-grained sandstones are commonly associated with levels of similar composition and grain size, showing planar lamination and climbing ripples. The last suggests a common origin to these deposits related to traction plus fallout of fine-grained sand sediments from a turbulent suspension, under different velocity and rates of sediment fallout (Zavala and Pan 2018, their Fig. 15).
5) Sandy debris flows cannot explain clast imbrication within massive sandstones, since this structure suggests that clasts were free to roll as bedload at the base of a progressively aggrading depositional surface (Zavala and Pan 2018, their Fig. 5)

2.8 Lofting rhythmites

Shanmugam (2018), page 217 right line: "*Zavala and Arcuri (*2016*, their Fig. 18), in justifying their criteria for recognizing hyperpycnites, presented a core photograph showing rhythmites, which they called "lofting rhythmites". The core photograph is from the modern Orinoco Fan, off Orinoco Delta in Eastern Venezuela (their Fig. 15). Such rhythmites are common in deep-water tidal deposits (Cowan* et al. 1998*; Shanmugam* 2003*)*".

The "deep water" tidal rhythmites studied by Cowan et al. (1998) are from the Muir Inlet, a macrotidal fjord in Alaska. These rhythmites are not equivalent to those described in our case studies, since they were described in a core recovered from a water depth of 241 m, located less than 1 km far from the coast (Cowan et al. 1998, their Fig. 1). These rhythmites are composed of silt-clay couplets accumulated by a tide modulated suspension settling from turbid plumes originating from meltwater discharges, where black intervals are plankton (no plant remains were recognized). The example from the Orinoco Fan is located at a water depth of 1994 m, more than 300 km far from the Orinoco littoral delta. In all case studies shown in our paper, lofting rhythmites are never associated with sedimentary structures indicative of tidal action like sigmoidal cross bedding, and are always associated with massive and cross-bedded sandstones suggesting an origin associated with sediment gravity flows. The analysis of thin sections allows to tract step by step the origin of this structure (Zavala et al. 2008, 2012), and conveniently explains the occurrence of plant remains and mica at the surface lamina.

2.9 Intrabasinal and extrabasinal turbidites

Shanmugam (2018), page 220 left line: "*Intrabasinal turbidites are those with sediments derived locally from adjacent shelf and got transported into the basin by "classic" turbidity currents. In contrast, extrabasinal turbidites are those with sediments derived from distant land and delta and got transported into the basin by "flood-triggered" turbidity currents or hyperpycnal flows*

(Fig. 16). In other words, large river-delta fed submarine fans on passive continental margins, such as the Mississippi Fan and the Amazon Fan, would be classified as extrabasinal turbidite".

This is not true. The distinction between intrabasinal and extrabasinal turbidites applies for single flows and should not be generalized for entire systems. A deep sea fan can be internally composed of both intrabasinal and extrabasinal turbidites. Intrabasinal and extrabasinal turbidites display diagnostic characteristics that allow a clear differentiation between them (Zavala and Arcuri 2016).

2.10 Sand and gravel transport by hyperpycnal flows

Shanmugam (2018), page 221 left line: "*However, hyperpycnal flows cannot be responsible for transporting gravel and sand from the land, carrying them 10–100 km/s− 1 across the shelf, and delivering them to the deep sea. For example, no one has ever documented by direct measurements or observations of transport of gravel and sand by hyperpycnal flows in suspension from the shoreline to the deep sea in modern settings.*"

This is not true. The existence of deep water gravel and pebbly sandstone deposits related to hyperpycnal discharges of the Columbia river has been clearly documented in the Cascadia Channel (Zuffa et al. 2000) in cores located 200 km far from the coast and at a water depth of 3820 m (Griggs et al. 1970; Normark and Reid 2003). Individual pebbles are rounded to subrounded with diameters up to 4 cm. These gravel deposits contain a mixture of intrabasinal and extrabasinal components like molluscan shells, wood fragments, and different water depth foraminifera.

3 Concluding remarks

The discovery of hyperpycnal flows and their related deposits (both in coarse and fine-grained successions) constitutes one of the most important and genuine recent advances in clastic sedimentology. Current understanding in this field was possible from the decadal joint effort of a multi-disciplinary global community of recognized geoscientists. Of course too much work will be necessary in the future to achieve a more comprehensive understanding of these flows and their related deposits. G. Shanmugam's claims that this research branch is a "hype specially designed for the petroleum industry" sounds, at least, offensive.

In his paper G. Shanmugam (2018) tries to minimize the importance of hyperpycnal flows claiming that the recognition of these flows and their related deposits is based strictly on experimental or theoretical basis, without the supporting empirical data from modern depositional systems. Although this is not absolutely true, when G. Shanmugam (2018) generalizes the case of the Yellow River, he over enhanced the role of present depositional processes both in their characteristics and magnitudes to try to explain the sedimentary rock record.

The fact is that the application of a strict "uniformitarianism" to the understanding of fossil sedimentary successions can lead to serious mistakes, since it constrains past geologic rates and conditions to those of the present. For a stratigrapher, it's important to understand if certain geological phenomena were possible in the geological record, and not only if these conditions are achieved nowadays. The key point resides in carefully describing, reading, and interpreting sedimentary rocks in the field, since only the stratigraphic record contains both present and future knowledge. "*Somewhere, something incredible is waiting to be known*" Carl Sagan (1934–1996).

Abbreviations

cm: centimeter; cm/sec: centimeters for second; et al.: et alii; Fig: Figure; Km: kilometer; m: meter; mm/s: millimeters for second; vol%: volume percent; wt%: weight percent; μm: micrometer

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Authors contributions

The author read and approved the final manuscript.

Competing interests

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