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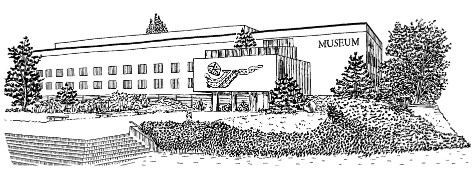

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The importance of plant remains as diagnostic criteria for the recognition of ancient hyperpycnites

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Abstract

According to its original conception, turbidites have been related to slope instability of previously accumulated shallow water deposits. These are intrabasinal (I) turbidites, since the parent flow derived from a subaqueous sediment failure originated within the basin, and are characterized by an interstitial fluid having a similar density compared to that of the ambient water. In recent years, growing evidences support that turbidites can also be originated by direct discharges of rivers in flood. These fluvial discharges (via hyperpycnal flows) accumulate extrabasinal (E) turbidites, since the parent flow is originated on land, and is composed of interstitial freshwater. This paper provides for the first time a sedimentological criterion to differentiate between intrabasinal and extrabasinal turbidites (here called I and E turbidites respectively). Intrabasinal turbidites, related to slope instability, are affected by several hydraulic jumps and flow transformations during their travel basinward. They are characterized by a fast moving head and high flow entrainment. On the contrary, pure extrabasinal turbidites are fully turbulent flows, characterized by a slow moving head and limited flow entrainment. The last result in the common occurrence of extrabasinal light components (as plant debris and charcoal) in the deposit, which are derived from the fluvial parent flow. The occurrence of plant remains is here considered a diagnostic criterion for the recognition of extrabasinal (hyperpycnal) turbidites. Main plant bearing hyperpycnal facies are medium to fine grained sandstone beds showing low angle asymptotic cross stratification, massive and laminated bedding, climbing ripples and lofting rhythmites.

Keywords

Hyperpycnites, intrabasinal turbidites, extrabasinal turbidites, plant remains.

INTRODUCTION

One of the greatest advances in sedimentology during the twentieth century was the recognition of turbidites by CARLO MIGLIORINI (1949). In its original conception, turbidites were related to remobilization of coastal deposits into deep marine settings by slope instability and intrabasinal sediment gravity flows. More recently, an alternative origin of turbidites as related to direct discharges of rivers in flood was proposed (NORMARK & PIPER, 1991; STOW *et al*., 1998). This mechanism was proved to be able of transferring huge volumes of sediments and freshwater into related lacustrine or marine basins by flood generated hyperpycnal flows. Since these turbidity flows are originated on land (extrabasinal), the interstitial fluid is freshwater, with important consequences for accumulation of fine-grained materials in marine settings. Although growing evidences highlight the importance of the direct transfer of sediments from rivers in flood, there are currently no diagnostic criteria to discriminate between the deposits of these two different types of turbidity flows. Based on more than 15 years of study on turbidity deposition, this paper provides a series of diagnostic criteria to clearly differentiate intrabasinal (classical) turbidites from extrabasinal (hyperpycnal) turbidites. The examples shown in this paper belong to different basins of Argentina and Trinidad (Table 1). The particular stratigraphy and tectonic setting of these basins will be not discussed here, and the reader is referred to the listed papers.

INTRABASINAL TURBIDITES (I TURBIDITES)

After the excellent contributions of MIGLIORINI (1949), KUENEN & MIGLIORINI (1950) and NATLAND & KUENEN (1951), turbidite deposits were originally conceived as the result of resedimentation of shallow water sediments into deep marine settings. According to this concept, coarse grained materials originally accumulated in coastal-shelfal areas would be periodically transferred into deeper basin areas through slope destabilization. Since these turbidites are originated within the basin, they are here termed **intrabasinal (I) turbidites**. Theoretical and conceptual models of **I** turbidites, mainly derived from the analysis of fossil deposits (BOUMA, 1962; MUTTI & RICCI LUCCHI, 1972; MUTTI, 1992), were complemented with flume experiments (SIMPSON, 1987) and studies of

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Table 1: Main units and sedimentary basins considered in this study.

Unit	Age	Basin	Tectonic Setting	Country	References
Los Molles Fm	Early Jurassic	Neuquén	Back Arc Basin	Argentina	Zavala & Gonzalez, 2001
Cabo Ladrillero Beds	Lower Miocene	Austral	Foreland Basin	Argentina	Ponce *et al.,* 2008
Mayaro Fm	Pliocene	Columbus	Pull Apart Basin	Trinidad & Tobago	Zavala *et al.,* 2008
Pliocene Sandstones	Pliocene	Columbus	Pull Apart Basin	Trinidad & Tobago	Gamero *et al.,* 2008

recent turbidites (Nice 1979, Grand Bank 1929), achieving a detailed understanding of this phenomenon. Since **I** turbidites originate from destabilization within the marine setting, the interstitial water of this turbulent flow is seawater, having a similar density respect to the ambient water.

One of the main mechanisms for the initiation of **I** turbidites is the **collapse of unstable materials in slope areas** (Hampton, 1972). Currently, these flows initiate as a cohesive debris-flow which progressively transform (by hydraulic jumps and flow transformations) into a granular and finally a turbulent flow (Piper *et al.*, 1999). These flow transformations are the consequence of acceleration and entrainment of ambient water in slope areas. Once the transition between plastic and Newtonian flow occurs, the **I** turbidite flow rapidly evolves into a bipartite flow (Sanders, 1965; Mutti *et al.*, 1999, 2003), consisting of an inertial head moving at high velocity (supercritical granular flow) followed by a subcritical slow moving turbulent flow (Fig 1).

Granular flows necessarily require steep gradients to move, so they often develop in slope areas. Once these granular flows reach the basin floor, the decrease in slope forces granular flow to stop by frictional freezing, so turbulent flow passes over it (Fig. 2) forming a low-density **I** turbidite.

From a mechanical standpoint, a low-density **I** turbidite has a finite length, and consists of three basic elements (Middleton, 1966): **head, body and tail** (Fig. 3).

The head of an **I** turbidite flow is one of the most important elements, since it is the main "engine" that manages the energy of the turbidite. The head is where mainly erosion, deposition and incorporation of ambient water (entrainment) occurs, so it is capable of converting potential energy into kinetic energy and vice versa. Thus, if the volume of sediment (mass) eroded from the bottom, converted into kinetic energy, is greater than the energy loss by friction, the **I** turbidite will increase its volume and velocity in a process known as flow ignition (Parker, 1982). On the other hand, if the eroded volume (and the resulting energy) is similar to the energy loss through friction (energy balance), **I** turbidites can travel great distances without significant changes through a process known as autosuspension (Bagnold, 1962). Finally, if the **I** turbidite is unable to erode the sea bottom and incorporate energy, the **I** turbidite flow will die according to the negative energy balance induced by friction.

In the analysis of fossil **I** turbidite deposits, sea bed erosion can be recognized by the existence of sole marks (tool marks and flute casts). Consequently, the absence of sole marks indicates that the **I** turbidite is within an area of final deposition. As a conclusion, the health of an **I** turbidite will necessarily depend on the existence of a regional slope, because it needs to get its energy from materials eroded at the sea bottom. If the seabed is horizontal, then the energy balance will be always negative and the **I** turbidite will be forced to accumulate.

In **I** turbidites, the largest flow velocity is achieved at the head, and progressively decreases towards the body and tail (Kneller & Buckee, 2000). When advancing on static seawater, the **I** turbidite flow should necessarily displace backward the ambient water. This results in a flow divergence at the head, and the generation of a return current that should maintain in suspension all materials transported by the advancing turbulent flow (Fig. 4) This permanent resuspension at the head area derives in an overall excellent grain sorting due to a continuous "washing" of the sandy turbulent suspension. The coarsest sandy fraction is then reincorporated into the advancing flow (c in Fig. 3), while finest and lighter materials remain in suspension and are derived to the tail of the flow. Thus, **I** turbidites have an overall tendency to lose lighter materials, and must necessarily incorporate them from the substrate. Consequently, **I** turbidites cannot transport land-derived light materials as charcoal (density 0.208 g/cm^3) or plant debris (0.09-0.55 g/cm^3) for long distances, since they would be quickly washed out and excluded from the main turbidite flow.

EXTRABASINAL (HYPERPYCNAL) TURBIDITES (E TURBIDITES)

Extrabasinal (hyperpycnal) turbidities (hereafter termed **E** turbidites) and their deposits (hyperpycnites, Mulder *et al.*, 2003) appeared more recently in the geological literature. Basically an **E** turbidite occurs when a subaerial (fluvial) system discharges a mixture of water and sediment having a bulk density which is greater than water in the reservoir. In the case of the marine environment, a concentration of 35-45 kg/m^3 of suspended sediment is

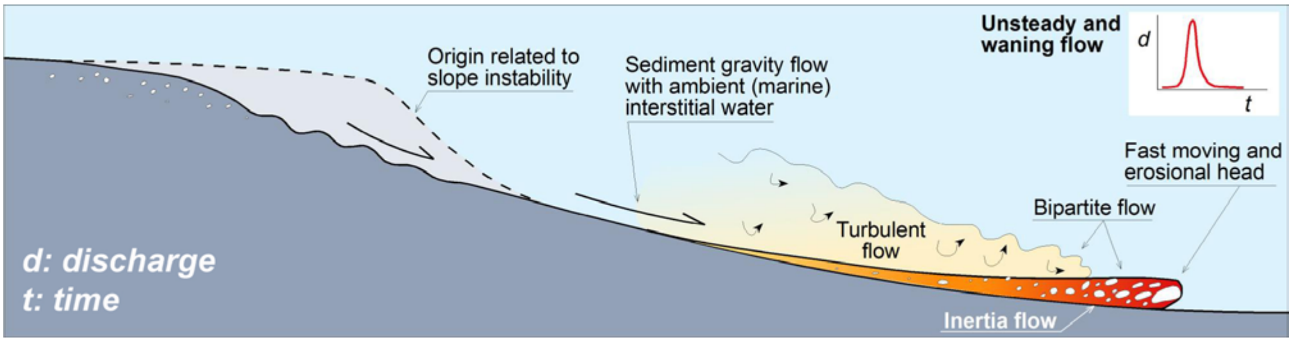

Fig. 1: Main components of an **I** turbidite, originated from slope destabilization. After ZAVALA *et al.,* 2011.

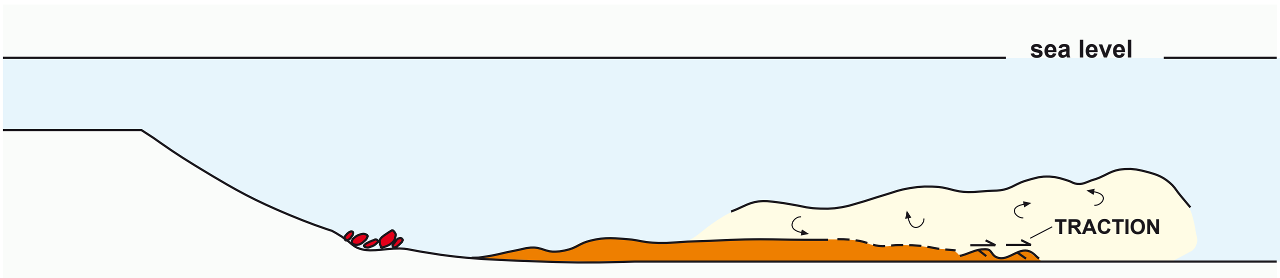

Fig. 2: Diagram showing the transformation between a granular flow and a low-density **I** turbidite. Note that the passage of the low-density turbulent flow partially reworks previous deposits accumulated by the granular flow. After MUTTI *et al.,* 1999.

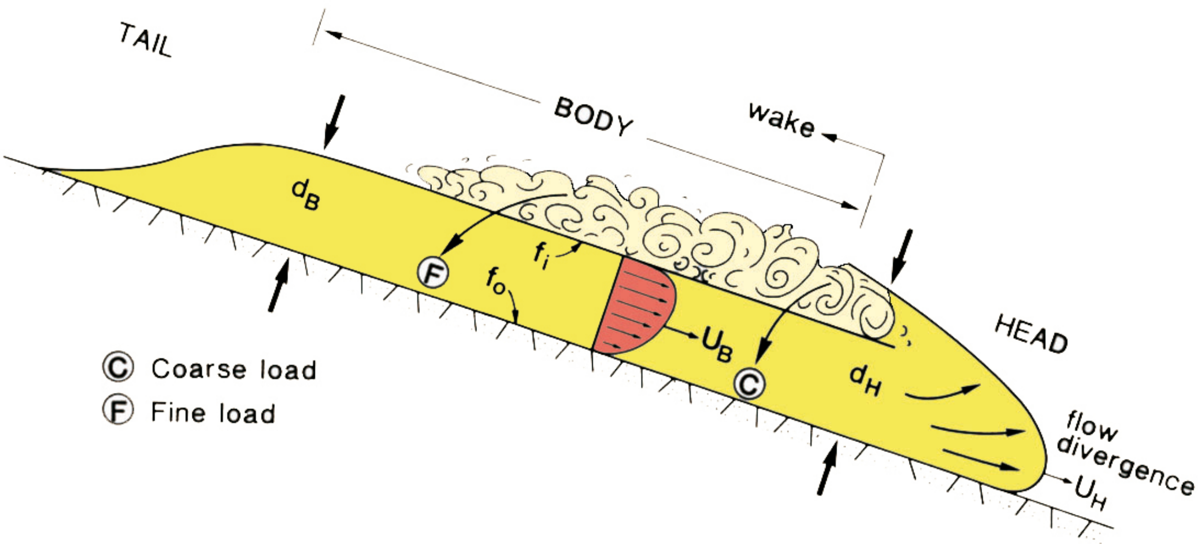

Fig. 3: Longitudinal profile of an **I** turbidite showing its main components (head, body and tail). $d_{B:}$ body thickness, $d_{H:}$ head thickness, $f_{0:}$ dimensionless *Darcy-Weisbach friction coefficient for bed friction,* $f_{i:}$ dimensionless friction coefficient for interfacial friction at the top of the body, $U_{B;}$ velocity of the body, and $U_{H:}$ velocity of the head. After PICKERING *et al.,* 1989.

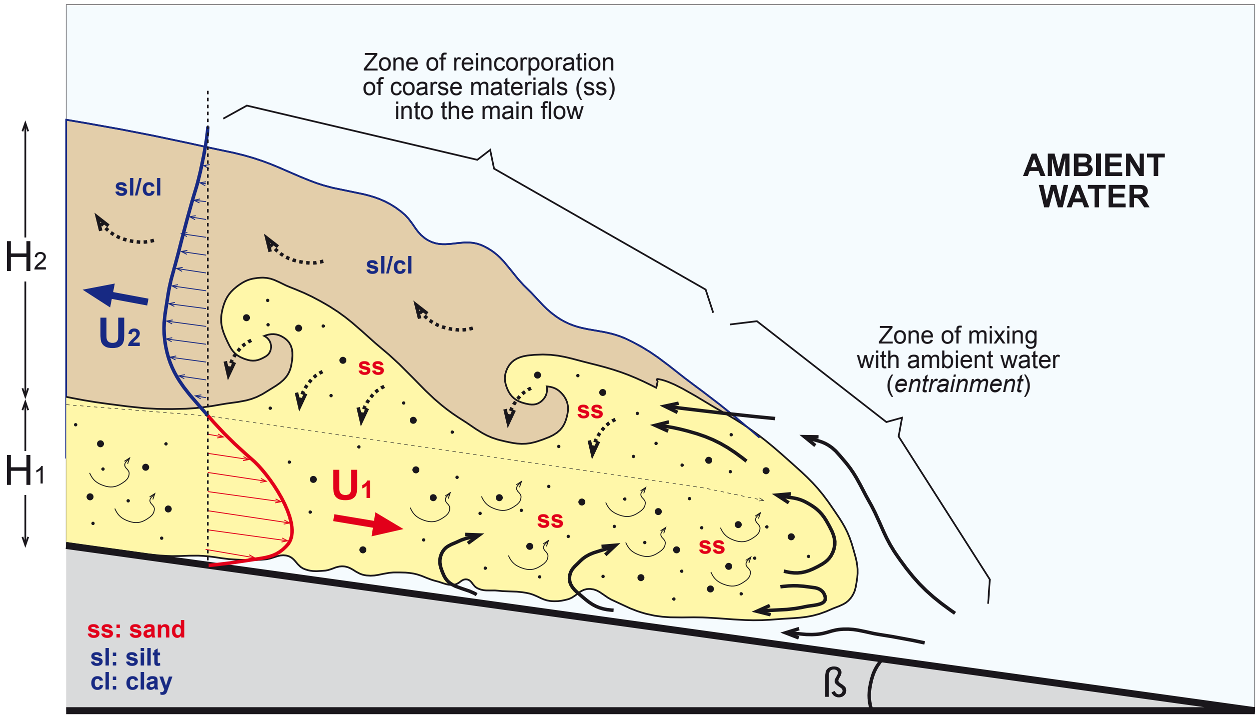

Fig. 4: Detail of the head of an **I** turbidite, which shows the zone of mixing with the ambient water, and the area of reincorporation of sandy materials into the main turbulent flow (U_1). Note that fine-grained and lighter materials are not reincorporated into the main flow and will remain in suspension, being derived to the flow tail by the return current (U_2). Modified from SIMPSON, 1987.

required in the fluvial discharge to overcome the density contrast with sea water (MULDER & SYVITSKI, 1995). When this situation occurs, the incoming flow sinks below the sea water forming a hyperpycnal flow (BATES, 1953) which can travel considerable distances carrying large volumes of sediment directly supplied from a river in flood. It is remarkable that 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 was originated on land. The last excluded from the definition of "hyperpycnal flow" to all kinds of underflows generated within the basin, as the case of mass-transport complexes, **I** turbidites, tempestites, cascadites, and turbulent flows derived from convective instability (PARSONS *et al.*, 2001). Since a hyperpycnal flow directly derives from a river discharge, it is characterized by a turbulent suspension with interstitial freshwater within. When the more dense fluvial discharge plunges in coastal areas, the resulting downward flow (hyperpycnal flow) induces a downwelling in surface reservoir waters, progressively avoiding the generation of buoyant (hypopycnal) plumes (Fig. 5). Buoyant plumes in hypopycnal (littoral) deltas are composed of freshwater and finest and lighter materials, like silt, mud and (if are present in the fluvial discharge) plant remains. Consequently, during a hyperpycnal discharge, freshwater and lighter materials originally transported by the fluvial discharge, like plant debris, leaves, trunks and charcoal, are forced to sink and to travel basinward within the hyperpycnal discharge.

Depending on the nature of the subaerial discharge, a hyperpycnal flow can be episodic or sustained (long lived). An episodic hyperpycnal flow usually last few hours, and commonly develops in fan-delta settings with steep gradients and small catchment areas. Since these hyperpycnal discharges are relatively highly concentrated and short lived, these deposits have a limited distribution in the associated basin, and in high gradient delta slopes they can also trigger **I** turbidites. Their deposits could be very variable depending on the density of the incoming flow (cohesive debris flow, hyperconcentrated flow, turbulent flow) and their possible evolution into **I** turbidites, and will not be discussed in this paper.

Sustained (long lived) E turbidites

Sustained (long lived) hyperpycnal flows, on the other hand, are associated to medium to large-sized rivers, with discharges that can last for weeks or even months depending on the size of the drainage area. These last characteristics result in a turbulent flow which is very different compared to that associated to **I** turbidites. Figure 6 summarizes the main characteristics of sustained **E** turbidites. These characteristics include 1) an origin related to a direct fluvial discharge, which is often characterized by long lived flows with fluctuating discharges; 2) common occurrence of bedload processes

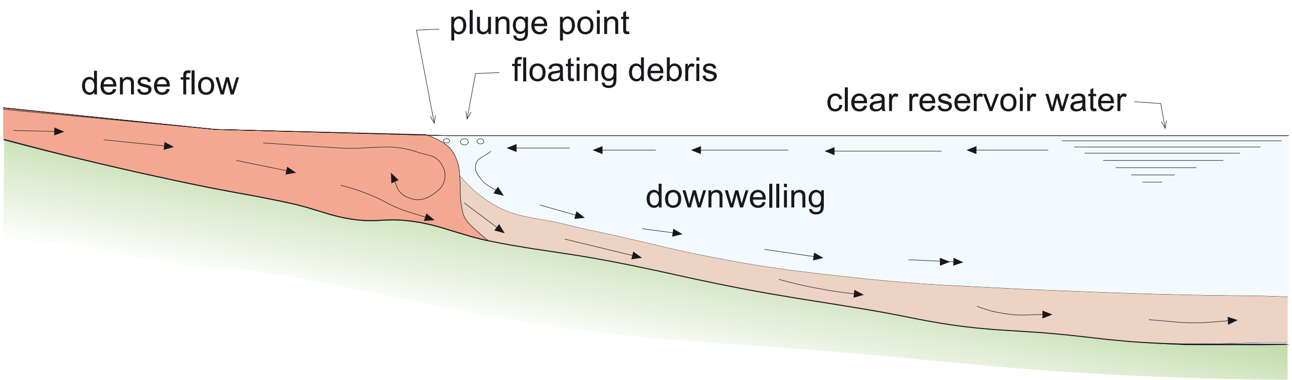

Fig. 5: Diagram showing the sinking of a hyperpycnal flow. Note that when the more dense flow plunges, an associated downwelling flow occurs, avoiding the generation of a buoyant plume. Consequently, freshwater and lighter materials like plant remains are forced to sink together with the hyperpycnal flow. Redrawn after KNAPP, 1943.

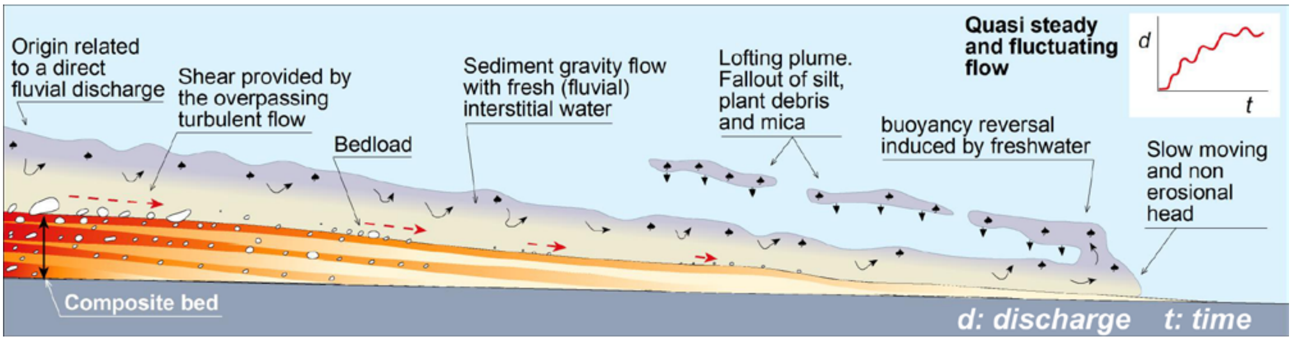

Fig. 6: Main characteristics of long-lived hyperpycnal flows and their typical deposits (From ZAVALA *et al.*, 2011). The complexity of these flows results in the accumulation of composite beds (ZAVALA *et al.*, 2007).

(carrying both terrestrial and basinal components) with shear provided by the passing-by hyperpycnal flow; 3) a turbulent flow having a light interstitial fluid (freshwater) and other light components in suspension, like plant remains.

Sustained **E** turbidites consist of three distinct parts: the plunge region, the main body, and the leading head (KASSEM & IMRAN, 2001). In contrary to **I** turbidites, sustained **E** turbidites have a slow moving and non-erosional leading head (ZAVALA *et al.*, 2006a) and main erosion and deposition occurs in the flow body instead of at the flow head (DE ROOIJ & DALZIEL, 2001; PEAKALL *et al.*, 2001; ZAVALA *et al.*, 2006a). The last results in a limited mixing of sustained **E** turbidites with ambient waters at the flow head (Fig. 7), and in their ability of transporting freshwater and plant debris (if any) for long distances basinward as long as the river discharge continued (PRIOR *et al.*, 1987; ZAVALA *et al.*, 2011).

Field observations indicate that most hyperpycnites are composed of an inversely graded (waxing) basal unit, followed in transition by a normally graded (waning) unit (MULDER & ALEXANDER, 2001; MULDER *et al.*, 2003; ZAVALA *et al.*, 2006a). The inversely graded interval is accumulated in the flow head, and commonly starts with climbing ripples (ZAVALA *et al.*, 2006a) suggesting a flow speed smaller than 0.2 m/sec. for the advancing leading head. NAKAJIMA (2006) described hyperpycnites in the central Japan Sea 700 km away from the Toyama Bay. This author estimates a flow speed of 0.3 m/s and a hyperpycnal discharge lasting for about 3 or 4 weeks to achieve the indicated distance.

Main key points to understand why freshwaters and plant debris can achieve such long distances probably reside in a) the slow moving head, compared with the velocity along the main body, which prevent the development of strong turbulence vortices and a substantial mixing with marine waters; b) lofting processes at flow head and flow laterals, which avoid the reincorporation of the lifted-up water and sediments; and c) the continuous supply and pumping provided by the continuous fluvial discharge, which provide the energy to maintain turbulence and flow velocity for long distances (Fig. 7).

Although several theoretical models predict that freshwater, introduced by hyperpycnal discharges, will completely disappear by entrainment and mixing with seawaters in a short distance from the rivermouth, an

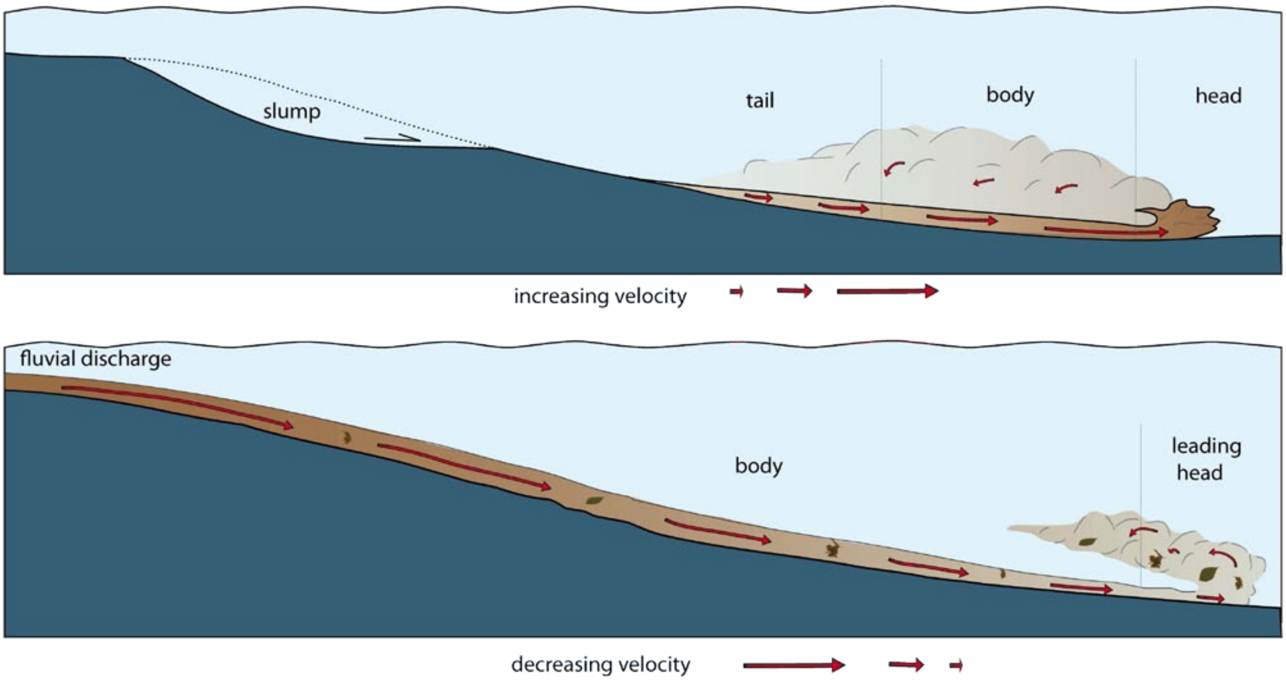

Fig. 7: Comparison between the flow behavior of **I** turbidites (above) and sustained **E** turbidites (below). Note that the velocity profile is the opposite in the two situations, favoring the limited mixing of sustained H turbidites with ambient waters.

increasing number of direct measurements revealed that the original freshwater supplied by a sustained river discharge and associated terrestrial light materials can travel long distances without substantial mixing with ambient waters. As an example, Johnson *et al.* (2001; see also Farnsworth, 2000) reported over 12 yr, the direct association between extreme turbidity activity in the Monterrey Submarine Canyon and largest flood events in the nearby Salinas River (California). These **E** turbidites were studied at different research stations, located between 5.2 and 22 km far from the river mouth, and water depths ranging between 230 and 1170 m. The studied hyperpycnal flows are characterized by fresher and warmer waters that extended to depths below 1000 m, carrying substantial amount of terrestrial organic carbon (Baudin *et al.*, 2010). A large turbidity current in the Zaire submarine valley at 4000 m and 330 km seaward of the Congo River mouth was registered by Khripounoff *et al.* (2003), composed of warm and turbulent flows with velocities exceeding the 121.4 cm/s^{-1}. This discharge lasted for about 10 days, and transported basinward large amounts of fine (0.15 to 0.2 mm) quartz sand and large plants debris (wood, leaves, and roots). These **E** turbidites are probably related to flooding episodes in the Congo River (Savoye *et al.*, 2009) since they correlate with submarine cable breaks across the canyon (Heezen *et al.*, 1964). More recently Kao *et al.* (2010) observed at 180 km off southwestern Taiwan an anomalously warm and low salinity turbid water current at 3000-3700 m depths immediately after Typhoon Morakot in 2009, thus proven the ability of freshwater to travel long distances during **E** turbidites. The direct input of freshwaters (meteoric-waters) into deep-water deposits via hyperpycnal flows has also being proposed by Mansurbeg *et al.* (2006) for the formation of kaolinite owing to the dissolution of detrital silicates in the Shetland–Faroes Basin on the British continental shelf.

PLANT REMAINS IN HYPERPYCNITES: A DIAGNOSTIC FEATURE

Plant debris, pieces of wood, coal fragments, charcoal and entire leaves are very common in turbidites (Fig. 8), and also were considered an important source of oil and gas (Saller *et al.*, 2006; Nakajima *et al.*, 2009; Baudin *et al.*, 2010). In the past, one of the most enigmatic components in fine-grained sandstones related to sediment gravity flows in shelfal and deep waters was the occurrence of plant debris, charcoal and occasionally entire leaves. These materials are very light, and their occurrence in this setting was difficult to be explained since they cannot accumulate by free fallout from the water surface according to their lower density. Additionally, these plant remains commonly occur within fine-grained sandstone deposits, thus indicating a common origin in their accumulation with that of the associated sediment gravity flow.

The existence of plant remains, leaves, charcoal or other very light land-derived materials in sediment gravity flow deposits at shelfal to deep water settings could be considered as a direct evidence of a hyperpycnal origin of the parent flow. These light materials are transported within the main flow together with the original freshwater due to the excess of density provided by the sand – clay materials transported in turbulent suspension. Fig. 9 (from Zavala *et al.*, 2011) depicts the main characteristics of a hyperpycnal flow, which is composed of buoyant and load components.

Sustained **E** turbidites provide a rational explanation for the occurrence of plant debris since they can be transported in turbulence together with freshwater and other suspended (load component) materials. Plant remains are often trapped within the hyperpycnal deposit, mainly in facies categories associated with high rate of fallout from the parent flow. Although all hyperpycnal deposits are usually characterized by plant remains, the most common plant-bearing sandstone facies in sustained **E** turbidites are: 1) low angle asymptotic cross stratification deposits, 2) massive and laminated bedding, 3) climbing rippled deposits, and 4) lofting rhythmites.

Low angle asymptotic cross stratification deposits

One of the most characteristic features of confined hyperpycnal flows in proximal setting is low angle asymptotic cross bedding deposits, which correspond to facies B2 of Zavala *et al.* (2006b; 2011) genetic facies tract for hyperpycnal deposits. This sedimentary structure develops as a consequence of migrating straight or sinuous dunes at the base of a long lived turbulent flow. The amount of suspended materials in the flow and the high rates of fallout in the lower foreset results in low angle grainfall dunes dominated by flow expansion

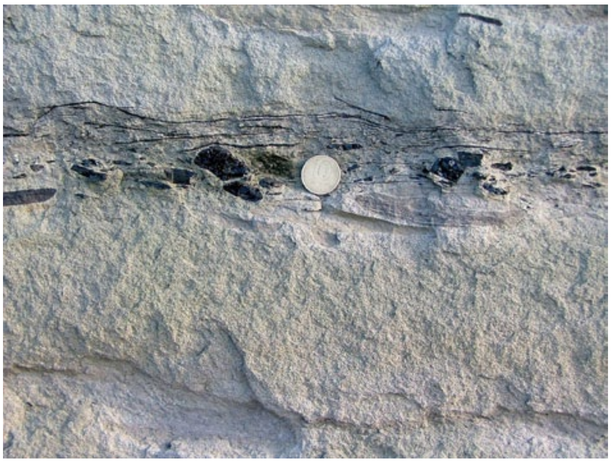

Fig. 8: Example of plant debris and charcoal fragments in Lower Miocene deep-water massive fine grained sandstones outcropping at the Cabo Ladrillero locality, Austral Basin, Argentina.

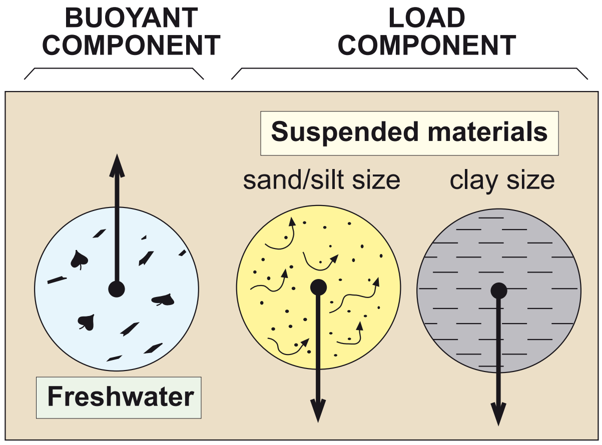

Fig. 9: Buoyant and load components as the basic constituents of a turbulent hyperpycnal flow. After Zavala *et al.*, 2011.

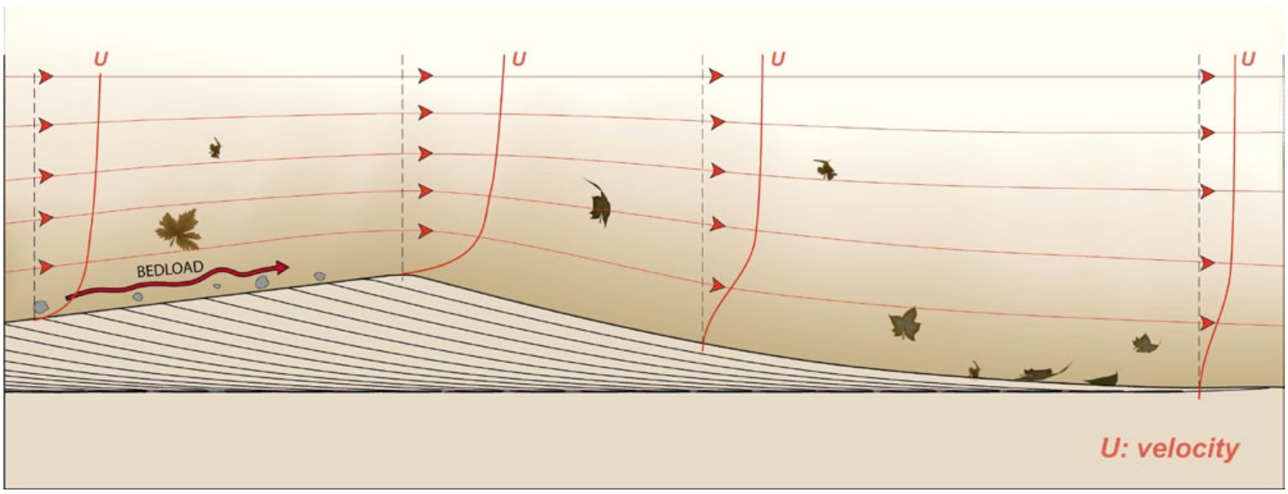

Fig. 10: Low angle asymptotic cross bedding generated by flow expansion at the base of long lived and confined turbulent flow. Main characteristics include a) low angle (<25°) foreset, b) normal grading in internal laminas, and c) inverse grading in laminaset. This structure is common in subaqueous channels associated with long lived turbulent flows.

(Fig. 10). In these dunes, the progressive decrease in velocity towards the toe of the foreset (related to flow expansion) induces a high rate of fallout which often traps the finest and lightest particles in suspension inside the hyperpycnal flow. Consequently the toe of the dune foreset is often characterized by massive deposits with diffuse lamination, with interval surfaces draped with abundant mica and plant debris.

Massive and laminated bedding

Massive and laminated fine grained sandstones in **E** turbidites are very common, and usually form a continuum depending on the rate of fallout. These deposits correspond to S1 (massive sandstones) and S2 (laminated sandstones) facies in the genetic facies tract for hyperpycnal deposits introduced by ZAVALA *et al.* (2011). The origin of this facies would be related to the progressive aggradation from the bottom by long lived turbulent flows having high suspended load (SANDERS, 1965; KNELLER & BRANNEY, 1995; CAMACHO *et al.*, 2002). Experimental studies (ARNOTT & HAND, 1989; SUMNER *et al.*, 2008) indicate that this facies originates from a turbulent flow with fallout rates greater than 0.44 mm/s. For smaller fallout rates at similar flow velocities, the result will be laminated sandstones. Fig. 11 depicts the accumulation of massive to laminated deposit as related to different fallout rates. On high rates of fallout (a) the absence of a rheological surface results on massive sandstones. If the rate of fallout decreases, sandstone deposits start to show a faint lamination, often draped with plant remains. This progressive aggradation has been proposed as a mechanism that partially inhibits the formation of primary sedimentary structures. Massive deposits could therefore be related to the absence of a sharp boundary between the moving flow and the deposit, resulting in a zone of aggrading transition characterized by a high sediment concentration associated with water escape. Since sand-size materials are carried and segregated from a turbulent suspension, the resulting deposit will be relatively well sorted.

In the Pliocene of Trinidad, massive sandstones are usually very well sorted (Fig. 12) and are composed of fine to very fine grained sandstones, usually showing abundant plant debris.

The high rates of fallout of sand-size materials results in the trapping of plant debris and other light components (leaves) in the resulting deposit (Figs. 13a, b).

Climbing ripples

Climbing ripples have been recognized as a diagnostic sedimentary structure indicating traction plus fallout processes from waning turbulent flows with high suspended load (JOPLING & WALKER, 1968; MULDER & ALEXANDER, 2001; SUMNER *et al.*, 2008). In hyperpycnal deposits, fine grained sandstones with climbing ripples were termed as facies S3 by ZAVALA *et al.* (2011). The high rate of fallout in the ripple foreset results in the common occurrence of small plant debris forming

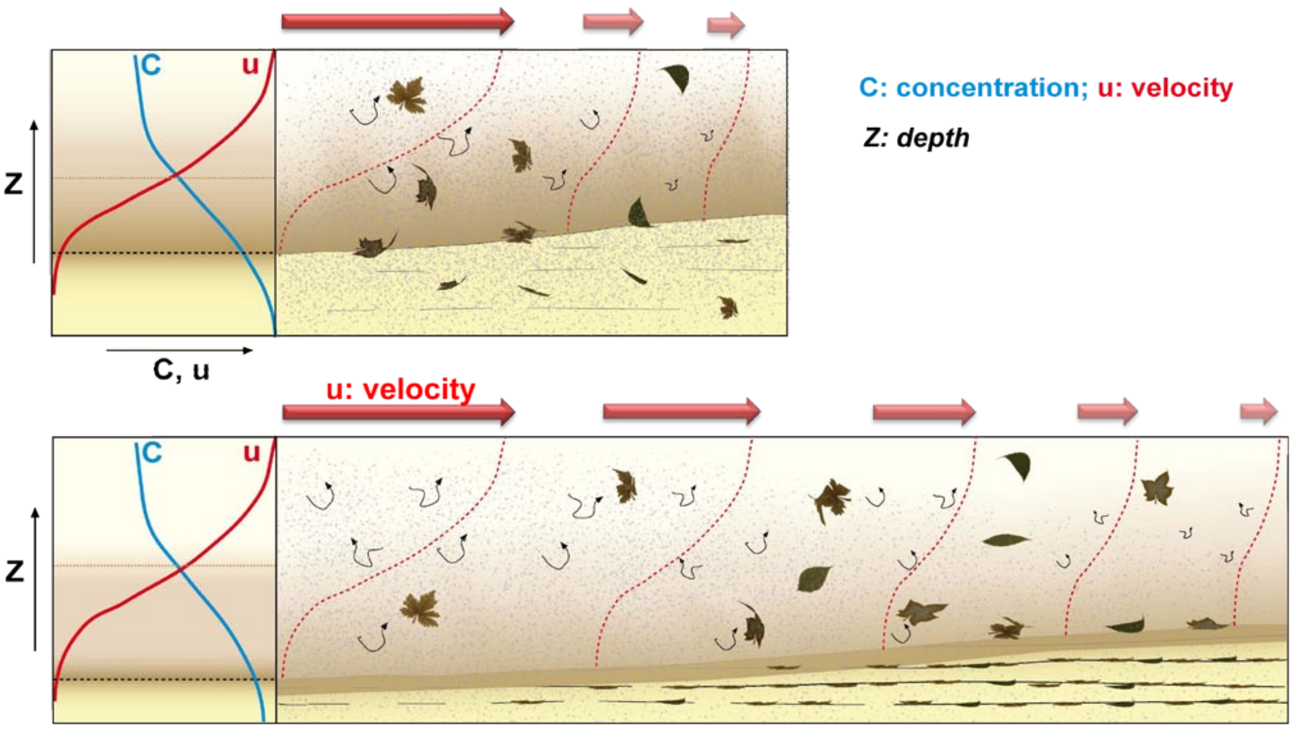

Fig. 11: Diagram showing the accumulation of massive (above) and laminated (below) sandstone deposits with plant debris at the base of a long lived and waning turbulent flow.

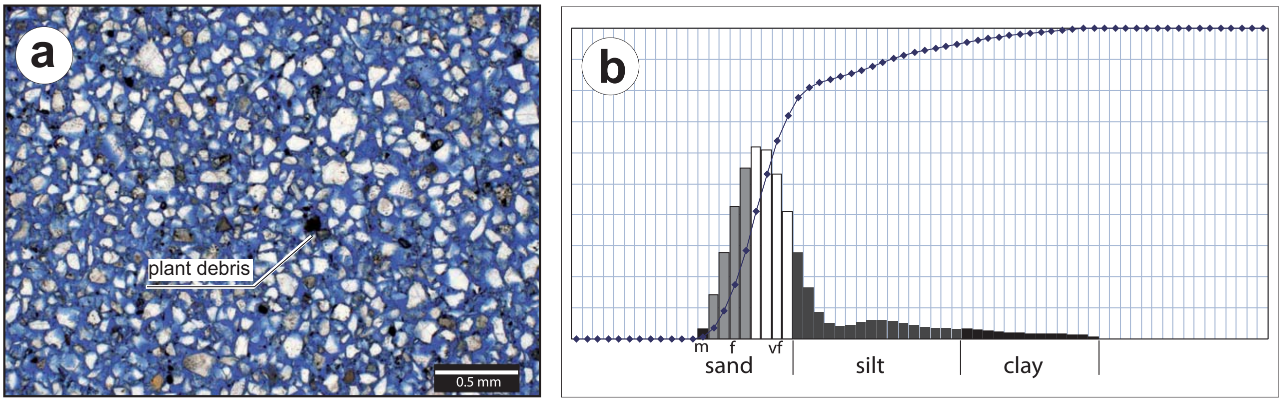

Fig. 12: Microphotography (a) and laser grain size analysis (b) of massive sandstones of Pliocene E turbidites in the offshore of Trinidad & Tobago. In "a", black components are plant debris. This deposit is mainly composed of poorly consolidated fine to very fine grained sands.

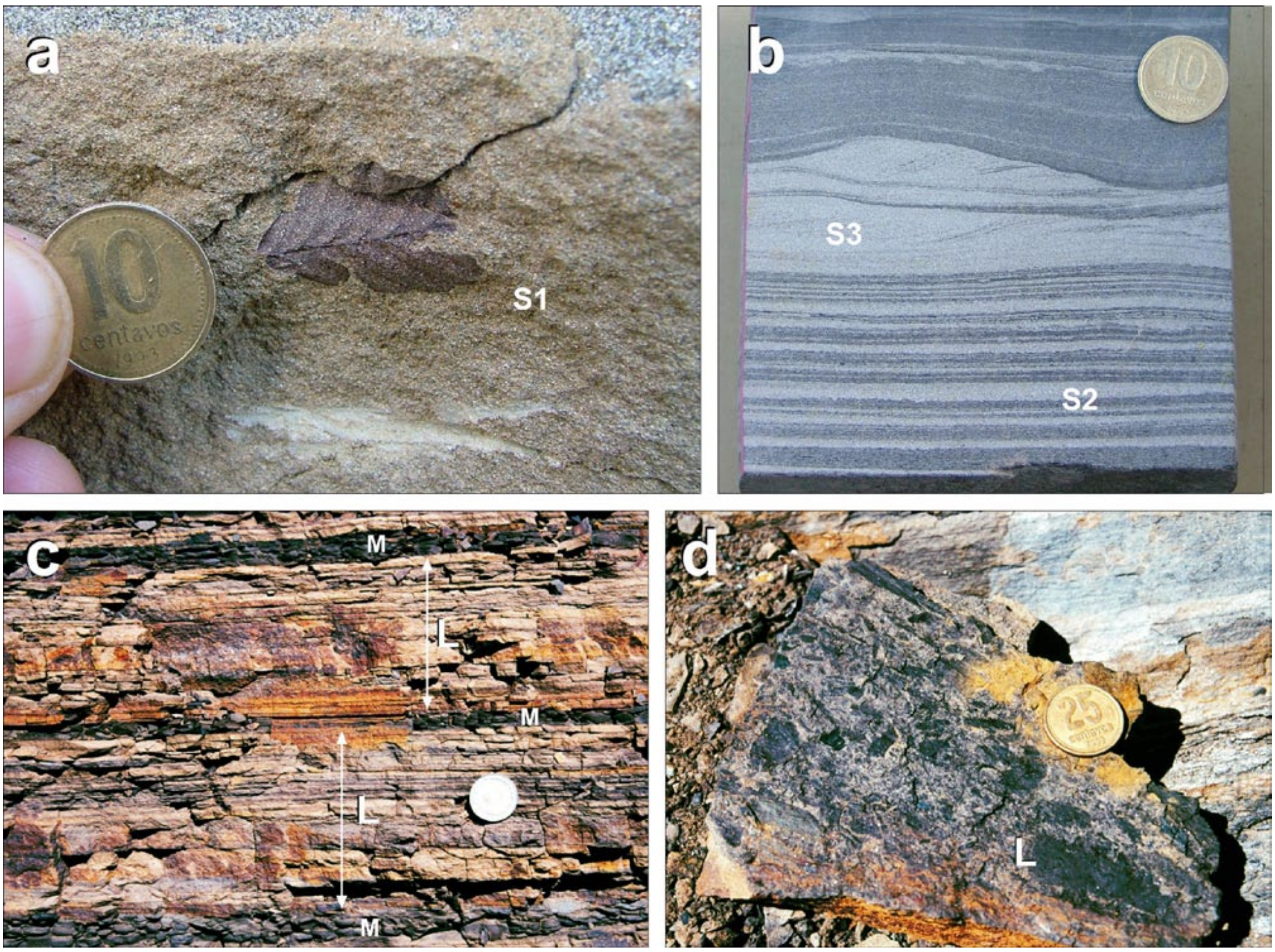

Fig. 13: a) Massive fine grained sandstones (facies S1) with entire leaves of *Nothofagus* in Lower Miocene deep-water deposits of the Austral Basin, Argentina. b) Laminated (facies S2) and rippled (facies S3) fine grained sandstones with abundant plant debris in outer shelf deposits of the Lower Jurassic Los Molles Formation, Neuquen Basin, Argentina. c) Lofting rhythmites (facies L). Each laminaset is composed of several rhythmites accumulated during a single and pulsating long lived hyperpycnal discharge, bounded by mudstones (M) accumulated by normal settling during non discharging periods. Outer shelf deposits of the Lower Jurassic Los Molles Formation, Neuquen Basin, Argentina. d) Detail of an internal surface of lofting rhythmites shown in "c". Note the abundance of plant remains.

discontinuous concave upward lenses (Fig. 13b). Climbing ripples often grade horizontally and vertically into laminated sandstones (SANDERS, 1965; ZAVALA *et al.*, 2006a), thus evidencing a common origin for both facies, controlled by fluctuations in the velocity of the overpassing turbulent flow.

Lofting rhythmites

Lofting rhythmites (ZAVALA *et al.*, 2006c; 2008) are composed of thin rhythmic sand-silts couplets with abundant plant material (Figs. 13c, d). Individual levels are often up to 2 mm thick and show great lateral continuity. Silt/sandstone couplets and their intercalations integrate laminated and decimeter thick packages (laminasets). These laminated packages lack or show rare and poorly diverse ichnofaunas. Lofting rhythmites appear isolated between mudstone successions or located in between or towards the top of massive to laminated tabular sandstone beds. Lofting rhythmites accumulate from a lofting plume, which is a typical feature of hyperpycnal inflows in marine environments (ZAVALA *et al.,* 2006c). In this situation, the hyperpycnal discharge contains a fluid (freshwater) that is less dense than ambient sea water. Consequently, when the flow progressively loses part of its suspended load by deposition, the current will lift from the substrate through buoyancy reversal (SPARKS *et al.*, 1993; KNELLER & BUCKEE, 2000), forming lofting plumes charged with fine-grained sediments, plant debris and micas. Lofting rhythmites mostly accumulate at flow margins (ZAVALA *et al.*, 2011) and show a more extended distribution compared with that of the main hyperpycnal flow. The recognition of lofting facies in marine environments is therefore extremely important, because it allows the diagnosis of a direct fluvial connection and a hyperpycnal origin for associated deposits. Analysis of thin sections (Fig. 14) of lofting rhythmites provides clear evidences about the origin of this feature apart of giving some diagnostic criteria for its recognition (ZAVALA *et al.*, 2008). According to its accumulation from normal settling, the deposition of fine-grained materials from lofting plumes is very selective. The free fallout of fine grained clastic materials from suspension clouds is governed by the Stokes' law. The genetic analysis of the thin section of Fig. 14 allows to tract the origin of lofting rhythmites.

Fig. 15 shows a step-by-step accumulation of lofting rhythmites, according to the interpretation of the Fig. 14. In (A) a heterogeneous lofting cloud is introduced by a hyperpycnal wave, in a lateral position respect to the main flow. In (B) the free fallout of different grain-sized clastic materials results in a normally graded interval with silt and oriented micas on top. According to their low density, leaves and plant materials remain in suspension. In (C), a new suspension cloud is introduced by a new wave during the same hyperpycnal discharge. The free fallout of the largest sand grains forces the deposition of leaves and plant fragments. As a consequence, a thin level of carbonaceous materials develops in between massive sand-silt levels.

DISCUSSION AND CONCLUSIONS

From a conventional point of view, plant remains were considered in the geological literature as typical of fluvial-delta plain-delta front-prodelta deposits. Although plant debris are in fact very common in these environments, their occurrence associated to shelfal to deep water sediment gravity flow deposits was poorly understood. In this contribution we provide an explanation for the transfer of freshwater and plant remains for long distances also in marine settings. Consequently, the existence of plant remains in sediment gravity flow deposits in shelfal to deep waters could be considered as a diagnostic criterion of a hyperpycnal origin for their associated deposits. Plant remains can be easily recognized through analysis

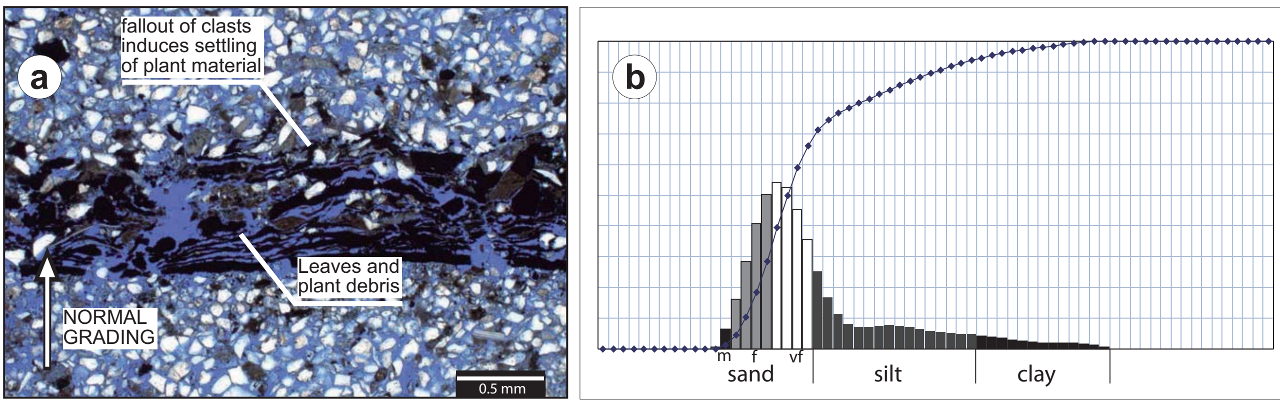

Fig. 14: Thin section (a) and grain-size analysis (b) of lofting deposits in the Pliocene of Trinidad & Tobago. Fallout of sand-silt materials from suspension clouds are normally graded, and are bounded by thin levels of plant debris, trapped by the next wave of sand fallout. Modified after ZAVALA *et al.*, 2008.

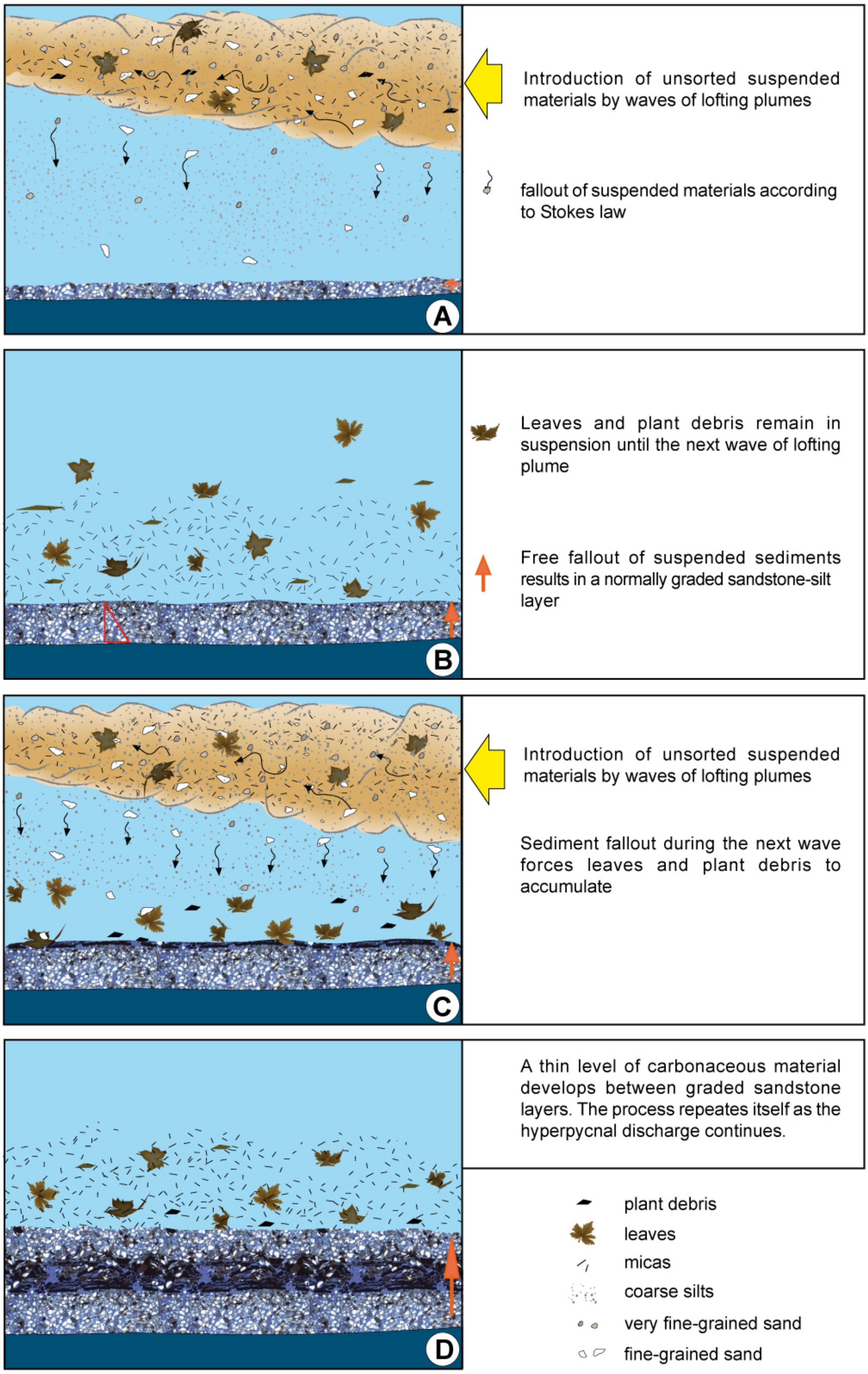

Fig. 15: Lofting rhythmites are the result of the repeated aggradation of fine grained materials from suspension clouds related to the buoyant inversion of hyperpycnal flows at flow margin areas. Explanations in the figure. Modified from ZAVALA *et al.*, 2008.

of thin sections from outcrops, cores and also cutting. Although plant debris are very common in marine and lacustrine sandstone hyperpycnites, lofting rhythmites are exclusive of marine or saline environments. Lofting rhythmites are a diagnostic and useful feature for the recognition of hyperpycnal deposits in marine settings, since they provide a direct evidence of the buoyant inversion of a less dense fluid (in the case freshwater) in a saline environment. Additionally, lofting rhythmites provide a non-biological indication of marine and saline waters. Since lofting rhythmites are directionally oriented, thin sections of core and outcrops can provide also additional criteria to determine base and top in problematic intervals.

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REFERENCES

Arnott, R.W.C. & B.M. Hand (1989) - Bedforms, primary structures and grain fabric in the presence of suspended sediment rain. *Journal of Sedimentary Petrology,* 69: 1062-1069.

Bagnold, R.A. (1962) - Auto-suspension of transported sediments: turbidity currents. *Proceedings Royal Society of London,* A265: 315-319.

Bates, C. (1953) - Rational theory of delta formation. *AAPG Bulletin*, 37: 2119-2162.

Baudin, F., J.-R. Disnar, P. Martinez & B. Dennielou (2010) - Distribution of the organic matter in the channel-levees systems of the Congo mud-rich deep-sea fan (West Africa). Implication for deep offshore petroleum source rocks and global carbon cycle. *Marine and Petroleum Geology,* 27: 995-1010.

Bouma, A.H. (1962) - *Sedimentology of some flysch deposits, a graphic approach to facies interpretation*. Elsevier Co., Amsterdam, 168 p.

Camacho, H., C.J. Busby & B. Kneller (2002) - A new depositional model for the classical turbidite locality at San Clemente State Beach, California. *AAPG Bulletin*, 86: 1543-1560.

De Rooij, F. & S.B. Dalziel (2001) - Time and space resolved measurements of deposition under turbidity currents. *In:* McCaffrey, B., B. Kneller & J. Peakall (eds.), *Particulate Gravity Currents*. International Association of Sedimentologists, Special Publication 31: 207-215.

Farnsworth, K.L. (2000) - Monterey Canyon as a Conduit for Sediment to the Deep Ocean. *Moss Landing: MBARI.* 25 p.

Hampton, M.A. (1972) - The role of subaqueous debris flow in generating turbidity currents. *Journal of Sedimentary Petrology*, 42: 775-793.

Heezen, B.C., R.J. Menzies, E.D. Schneider, W.M. Ewing & N.C.L. Granelli (1964) - Congo submarine Canyon. *AAPG Bulletin,* 48: 1126-1149.

Johnson, K.S., C.K. Paull, J.P. Barry & F.P. Chavez (2001) - A decadal record of underflows from a coastal river into the deep sea. *Geology,* 29: 1019-1022.

Jopling, A.V. & R.G. Walker (1968) - Morphology and origin of ripple-drift cross lamination, with examples of Pleistocene of Massachusetts. *Journal of Sedimentary Petrology*, 38: 971-984.

Kao, S.J., M. Dai, K. Selvaraj, W.P. Zhai, S.N. Cai, J. Chen, Y.T. Yang, J.T. Liu, C.C. Liu & J.P.M. Syvitski (2010) - Cyclone-driven deep sea injection of freshwater and heat by hyperpycnal flow in the subtropics. *Geophysical Research Letters,* 37, L21702.

Kassem, A. & J. Imran (2001) - Simulation of turbid underflows generated by the plunging of a river: *Geology*, 29: 655-658.

Khripounoff, A., A. Vangriesheim, N. Babonneau, P. Crassous, B. Dennielou & B. Savoye (2003) - Direct observation of intense turbidity current activity in the Zaire submarine valley at 4000 m water depth. *Marine Geology,* 194: 151-158.

Kneller, B. & M. Branney (1995) - Sustained high-density turbidity currents and the deposition of thick massive sands. *Sedimentology*, 42: 607-616.

Kneller, B. & C. Buckee (2000) - The structure and fluid mechanics of turbidity currents: a review of some recent studies and their geological implications. *Sedimentology*, 47: 62-94.

Kuenen, P.H. & C.I. Migliorini (1950) - Turbidity currents as a cause of graded bedding. *The Journal of Geology*, 58: 91-127.

Mansurbeg, H., M.A.K. El-ghali, S. Morad & P. Plink-Björklund (2006) - The impact of meteoric water on the diagenetic alterations in deep-water, marine siliciclastic turbidites. *Journal of Geochemical Exploration,* 89: 254-258.

Middleton, G.V. (1966) - Experiments on density and turbidity currents. I Motion of the head. *Canadian Journal of Earth Sciences,* 3: 523-546.

Migliorini, C.I. (1949) - Sedimentazione delle brecciole calcaree e del macigno. *Atti Societá Toscana di Scienze Naturale, Memorie A*, 56: 2141.

Mulder, T. & J. Alexander (2001) - The physical character of subaqueous sedimentary density flows and their deposits. *Sedimentology*, 48: 269-299.

Mulder, T. & J.P.M. Syvitski (1995) - Turbidity current generated at river mouths during exceptional discharges to the world oceans. *Journal of Geology*, 103: 285-299.

Mulder, T., J.P.M. Syvitski, S. Migeon, J.C. Faugéres & B. Savoye (2003) - Marine hyperpycnal flows: initiation, behavior and related deposits. A review. *Marine and Petroleum Geology*, 20: 861-882.

Mutti, E. (1992) - Turbidite sandstones. *AGIP - Istituto di Geologia Università di Parma,* San Donato Milanese, 275 p.

Mutti, E. & F. Ricci Lucchi (1972) - Le torbiditi dell'Appennino Settentrionale: introduzione all'analisi di facies. *Memorie della Società Geologica Italiana,* Roma, 11: 161-199.

Mutti, E., N. Mavilla, S. Angella & LL. Fava (1999) - An introduction to the analysis of ancient turbidite basins from an outcrop perspective. *AAPG Continuing Education Course Note*, Tulsa, 39: 1-98.

MUTTI, E., R. TINTERRI, G. BENEVELLI, D. DI BIASE & G. CAVANNA (2003) - Deltaic, mixed and turbidite sedimentation of ancient foreland basins. *Marine and Petroleum Geology*, 20: 733-755.

NAKAJIMA, T. (2006) - Hyperpycnites deposited 700 km away from river mouths in the Central Japan Sea. *Journal of Sedimentary Research*, 76: 59-72.

NAKAJIMA, T., H. KATAYAMA & T. ITAKI (2009) - Climatic control on turbidite deposition during the last 70 Kyr along the Toyama deep-sea channel, central Japan Sea. External Controls on Deep-Water Depositional Systems. *SEPM Special Publication*, 92: 159-177.

NATLAND M.L. & P.H. KUENEN (1951) - Sedimentary history of the Ventura Basin, California and the action of turbidity currents. *In:* HOUGH, J.L. (ed.), Turbidity currents and the transportation of coarse sediments to deep water. *Society of Economic Paleontologists and Mineralogists, Special Publication,* 2: 76-107.

NORMARK W.R. & D.J. PIPER (1991) - Initiation processes and flow evolution of turbidity currents: implications for the depositional record. *SEPM Special Publication,* 46: 207-230, Tulsa.

PARKER, G. (1982) - Conditions for the ignition of catastrophically erosive turbidity currents. *Marine Geology*, 46: 307-327.

PARSONS, J.D., J. BUSH & J.P.M. SYVITSKI (2001) - Hyperpycnal flow formation with small sediment concentrations. *Sedimentology,* 48: 465-478.

PEAKALL, J., M. FELIX, B. MCCAFFREY & B. KNELLER (2001) - Particulate gravity currents: Perspectives. *In:* MCCAFFREY, B., B. KNELLER & J. PEAKALL (eds.), *Particulate Gravity Currents*, International Association of Sedimentologists, Special Publication 31: 1-8.

PICKERING, K.T., R.N. HISCOTT & F.J. HEIN (1989) - *Deep marine environments: clastic sedimentation and tectonics*. Unwin Hyman Ltd. 416 p.

PIPER, D.J.W., R.N. HISCOTT & W.R. NORMARK (1999) - Outcrop-scale acoustic facies analysis and latest Quaternary development of Hueneme and Dume submarine fans, offshore California. *Sedimentology,* 46: 47-78.

PONCE, J.J., E. OLIVERO & D.R. MARTINIONI (2008) - Upper Oligocene-Miocene clinoforms of the foreland Austral Basin of Tierra del Fuego, Argentina: Stratigraphy, depositional sequences and architecture of the foredeep deposits. *Journal of South American Earth Sciences*, 26: 36-54.

PRIOR, D.B., B.D. BORNHOLD, W.J. WISEMAN & D.R. LOWE (1987) - Turbidity current activity in a British Columbia fjord. *Science,* 237: 1330-1333.

SALLER, A., R. LIN, & J. DUNHAM (2006) - Leaves in turbidite sands: the main source of oil and gas in the deep-water Kutei Basin, Indonesia. *AAPG Bulletin*, 90/10: 1585-1608.

SANDERS, J. E. (1965) - Primary sedimentary structures formed by turbidity currents and related sedimentation mechanisms. *In:* MIDDLETON, G.V. (ed.), *Primary sedimentary structures and their hydrodinamic interpretation*. SEPM Special Publication 12: 192-219.

SAVOYE, B., N. BABONNEAU, B. DENNIELOU & M. BEZ (2009) - Geological overview of the Angola-Congo Margin, the Congo deep-sea fan and its submarine valleys. *Deep Sea Research, Part II: Topical Studies in Oceanography*, 56: 2169-2182.

SIMPSON, J. E. (1987) - *Gravity currents: In the environment and the laboratory*. John Wiley & Sons, New York, Chichester, Brisbane, and Toronto, 244 p.

SPARKS, R.S.J., R.T. BONNECAZE, H.E. HUPPERT, J.R. LISTER, M.A. HALLWORTH, J. PHILLIPS & H. MADER (1993) - Sediment-laden gravity currents with reversing buoyancy. *Earth & Planetary Sciences Letters,* 114: 243-257.

STOW, D.A.V., J.C. FAUGÈRES, A. VIANA & E. GONTHIER (1998) - Fossil contourites: a critical review. *Sedimentary Geology,* 115: 3-31.

SUMNER, E.J., L.A. AMY & P.J. TALLING (2008) - Deposit structure and processes of sand deposition from decelerating sediment suspensions. *Journal of Sedimentary Research*, 78: 529-547.

ZAVALA, C. & R. GONZALEZ (2001) - Estratigrafía del Grupo Cuyo (Jurásico inferior-medio) en la Sierra de la Vaca Muerta, Cuenca Neuquina. *Boletín de Informaciones Petroleras*, Buenos Aires, 65: 52-64.

ZAVALA, C., J. PONCE, D. DRITTANTI, M. ARCURI, H. FREIJE & M. ASENSIO (2006a) - Ancient lacustrine hyperpycnites: a depositional model from a case study in the Rayoso Formation (Cretaceous) of west-central Argentina. *Journal of Sedimentary Research*, 76: 41-59.

ZAVALA, C., M. ARCURI & H. GAMERO (2006b) - Towards a genetic model for the analysis of hyperpycnal systems. 2006 GSA Annual Meeting, 22-25 October, Philadelphia, PA., USA. Topical session T136: River Generated Hyperpycnal Events and Resulted Deposits in Modern and Ancient Environments.

ZAVALA, C., H. GAMERO & M. ARCURI (2006c) - Lofting rhythmites: A diagnostic feature for the recognition of hyperpycnal deposits. 2006 GSA Annual Meeting, 22-25 October, Philadelphia, PA., USA, Topical session T136: River Generated Hyperpycnal Events and Resulted Deposits in Modern and Ancient Environments.

ZAVALA, C., M. ARCURI, H. GAMERO DÍAZ & C. CONTRERAS (2007) - The Composite Bed: A New Distinctive Feature of Hyperpycnal Deposition. 2007 AAPG Annual Convention and Exhibition (April 1 - 4, 2007), Long Beach, California.

ZAVALA, C., L. BLANCO VALIENTE & Y. VALLEZ (2008) - The origin of lofting rhythmites. Lessons from thin sections. AAPG Hedberg Conference "Sediment Transfer from Shelf to Deepwater – Revisiting the Delivery Mechanisms", March 3-7, 2008 – Ushuaia-Patagonia, Argentina.

ZAVALA, C., M. ARCURI, H. GAMERO, C. CONTRERAS & M. DI MEGLIO (2011) - A genetic facies tract for the analysis of sustained hyperpycnal flow deposits. *In:* R. M. SLATT & C. ZAVALA (eds.), Sediment transfer from shelf to deep water—Revisiting the delivery system. *AAPG Studies in Geology,* 61: 31-51.

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