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Thin-bedded plumites: an overlooked deep-water deposit

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ABSTRACT - Field observations suggest that hypopycnal plumes can generate thin-bedded sand/mud couplets, here termed plumites, that are virtually ubiquitous in turbidite systems. This close association is the best and most direct evidence of the relationship between turbidite and fluvial sedimentation. Plumes propagate in seawater as dilute surface flows and, depending upon their original volume, sediment concentration and basin size, may mantle the basin floor with their fine-grained deposits from shelfal to deep basin plain regions. They may trigger major hyperpycnal flows and deposit thick sand beds in basinal regions, but most commonly form thin beds displaying a spectrum of highly diagnostic facies. Much care must be taken not to mistake these facies for the distal or overbank sediments of turbidity currents. Most of the fine details of plumites are certainly better observed in cores; most cores should be therefore re-analyzed in the light of these new data.

Keywords: Hypopycnal flows; thin-bedded sand/mud couplets; plumites. turbidite systems.

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1. INTRODUCTION

Thin-bedded and fine-grained turbidites are certainly a poorly described and understood deposit in both modern and ancient deep-water basin fills. Nonetheless, they comprise a volumetrically important component of turbidite successions, enclosing and interfingering with both channelized and unchannelized sandstone bodies. In most systems they appear to be the result of background sedimentation interrupted by the more episodic deposition of thicker bedded and coarser grained facies. Unfortunately, their study is hampered in many cases by the poor quality of the exposures because of vegetation or other kinds of cover. Wherever possible, these sediments should be studied in cores, where their fine details are completely preserved.

Despite early attempts to understand their complexity (Mutti, 1977), these sediments still form an elusive family within the broad spectrum of turbidite facies, being generally interpreted as the product of overbank or distal deposition of turbidity currents. Thin-bedded turbidites are even described as a heterolithic facies, a meaningless term with which to mask our ignorance about the real nature of the deposit. The purpose of this short and preliminary note is to show that a considerable proportion of these sediments can be interpreted as the product of processes primarily related to the proximity of delta systems. In relatively small and tectonically-active basins, flood-dominated deltas may generate buoyant plumes that can deposit thin-bedded sand and mudstone in a variety of environments, from shelfal to basin-plain regions. These beds are here termed plumites. An attempt is made here to define some of their main facies types.

2. NEW DATA FROM FLUME EXPERIMENTS AND MONITORING OF MODERN DELTAS

Based on flume experiments, Parson et al. (2001) and Mulder et al. (2003) have developed some very important concepts about depositional processes of hyperpycnal flows. Basically, hyperpycnal flows are not only produced by sediment-laden river outflows through plunging plumes, but also by more dilute hypopycnal plumes through diffusive convection processes. These give way to layers with sufficient sediment concentration to sink and generate a hyperpycnal flow.

Based on detailed time-lapse monitoring of the modern Squamish Delta in British Columbia, Canada, Hizzett et al. (2018) have subsequently expanded on these concepts and shown that hyperpycnal flows generated by dilute surface river plumes can dominate the triggering of turbidity currents, rather than submarine slope failures or dense plunging plumes. If the dense bottom-riding layer can increase its density by bed erosion, the flow undergoes acceleration and a turbidity current, or a "plume-triggered event" as termed by the authors, is ignited. Obviously, the process is limited to fine-grained sediment (< medium sand), which is that originally transported as suspended load by plunging hyperpycnal plumes and dilute hypopycnal plumes.

The above conclusions and data are strongly substantiated by field observations from many ancient turbidite systems and the associated flood-dominated fluvio-deltaic systems of tectonically-active basins, allowing for the first time a better appreciation of the meaning of most thin-bedded and fine-grained turbidites. In particular, the turbidites of the Eocene Hecho Group basin of the south-central Pyrenees offer an excellent example of this kind of setting. In this basin fill, turbidite systems can be physically and confidently traced from their proximal to distal elements and, most importantly, into their feeder and flood-dominated fluvio-deltaic deposits. In the delta-slope elements separating basinal turbidites from their fluvio-deltaic equivalents on the shelf, sedimentation is dominated by hypopycnal plumes and low-concentration hyperpycnal flows (Mutti et al., 2003, pp. 739-741). Distinguishing this new group of deep-water sediments from the distal or overbank deposits of turbidity currents generated by denser bipartite underflows raises a series of problems that will require extensive field research in the future.

3. TYPES OF OCCURRENCE OF THIN-BEDDED TURBIDITES IN ANCIENT BASIN FILLS

One of the most puzzling features of exposed turbidite successions is certainly the close association of thick and relatively coarse-grained sandstone beds (TKBs) with thin-bedded and finer-grained sandstone beds (TNBs). The latter consist of sandstone/mudstone couplets rarely exceeding individual thickness of 20cm; most commonly the sandstone or coarse siltstone divisions are less than 3cm thick and, at first glance, could be simply described as Tc-e and Td-e Bouma sequences. The association occurs at different scales and has, since the pioneering work of Parea (1965) and Walker (1967), been interpreted as a typical expression of proximal (TKBs) and distal (TNBs) turbidite deposition

For convenience, the scales considered are those of the hierarchical classification of turbidite sediments suggested by Mutti and Normark (1987). The three kinds of occurrence described below were also noted in previous work by Mutti et al. (1994) and interpreted as related to forestepping-backstepping cycles of different physical and temporal scale primarily produced by changes in the volume of individual gravity flows and mainly triggered by retrogressive sediment failures.

At the largest scale (tens to hundreds of meters), stratigraphic units of dominantly TKBs (turbidite systems) are overlain by similarly thick units of TNBs developed in dominantly muddy successions (Figs.1 and 2). As clearly observed in many basins, the muddier units are the shelf-slope equivalents of marginal deltas on the shelf (e.g., Mutti et al., 2003; Petter and Steel, 2006).

At an intermediate scale, m-thick packets of TKB alternate with similarly thick packets of TNBs with variable amounts of interbedded mudstone. These alternations are virtually ubiquitous in the channel, channel-lobe transition, and lobe elements of turbidite systems (Fig. 3), comprising the sub-stages of Mutti and Normark (1987). These cyclic alternations have given rise to many controversial opinions about their possible origin and their sequential organization that are beyond the purpose of this note (see Pickering and Hiscott, 2016, for an updated review). Based on the writer's experience, the basic facies sequence observed at this scale is overall thinning and fining upward. It consists of a lower TKB facies (either channelized or unchannelized; see figure 3) overlain, either abruptly or transitionally, by a TNB facies (Figs. 4 and 5). Transitional contacts are typically expressed as an alternation of progressively thinner turbidite beds with TNBs. The figure 6 shows a clear example of how the basic thinning-upward sequence can be inverted into a thickening-upward one over short distance at an onlap termination of a sandstone lobe.

At the bed scale (small scale), say within a sandstone-rich sub-stage, the observations lead to similar conclusions. Thick to medium and relatively coarse-grained beds can stack without thinner-bedded partings, or be separated from each other by a limited number (<10-15) of TNBs (Fig. 7).

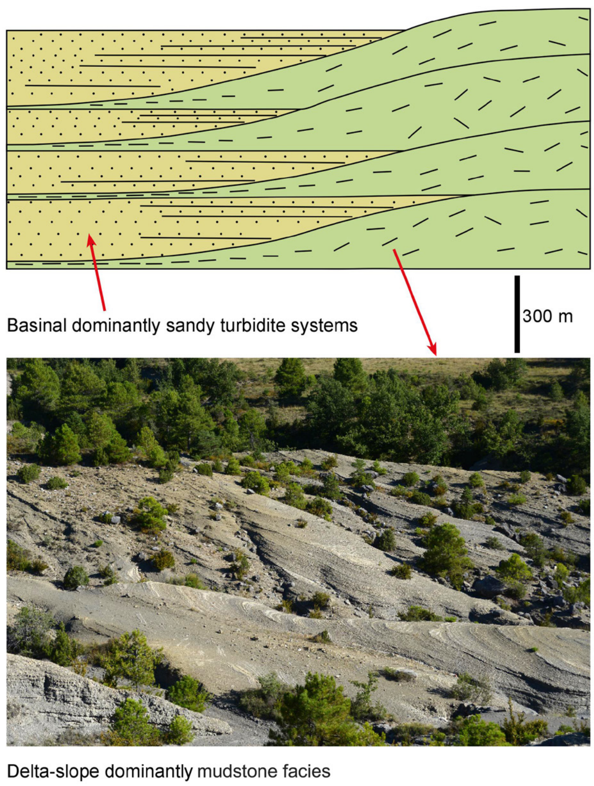

Fig. 1 - Large-scale stratigraphic relationships between basinal turbidite systems and delta-slope thin-bedded and mudstone-dominated facies.

Fig. 2 - Thin-bedded and fine-grained sandstone beds (TNBs) successions typical of delta-slope elements. In some cases event bed frequency can result in almost 100 beds/m. Eocene Castissent Group, south-central Pyrenees. Lens cap for scale.

4. PLUMITES: FACIES DESCRIPTION AND INTERPRETATION

Regardless of the scale at which they occur and the position they occupy in the basin fill, sandstone/mudstone couplets produced by both hypopycnal plumes or relatively dilute, hyperpycnal and subcritical flows are well characterized in terms of grain size and internal depositional structures. The main facies types are summarized below.

4.1. DESCRIPTION

Type 1 (Fig. 8 A,B,C) - Very thin (mm-scale) beds with a lower division made of coarse siltstone forming mm-thick and laterally persistent parallel laminae or laminasets. These beds alternate with rarer and slightly thicker beds with a basal division made of small starved ripples, commonly with variable length and separated by intervening parallel laminae. Both kinds of bed show a sharp contact between the coarse-siltstone division and the overlying mudstone. Very rarely, thin climbing ripples can be observed.

Type 2 (Figs. 9, 10, 11, 12) - This facies includes several types of beds here thought to be genetically interrelated (see below). These sandstone/mudstone couplets have individual thickness ranging between a few cm and 15-20 cm and their sandstone divisions display a variety of internal structures. These structures include soft-deformation features (Type 2a, Fig. 9), structureless muddy sandstone with pseudonodules of ripple-laminated sandstone, mudstone clasts and plant fragments (Type 2b, Fig. 10), and structureless clean

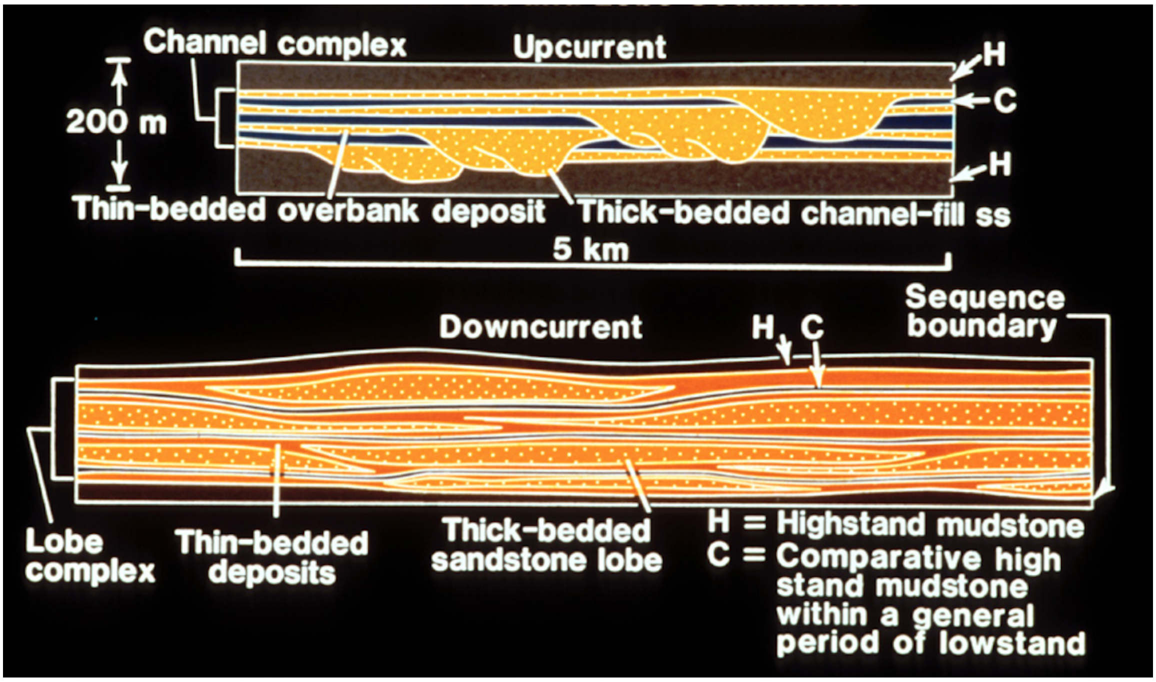

Fig. 3 - Typical occurrence of thin-bedded sandstones associated with coarser-grained turbidite deposits in channelized (A) and non-channelized (B) elements. Modified from Mutti (1992).

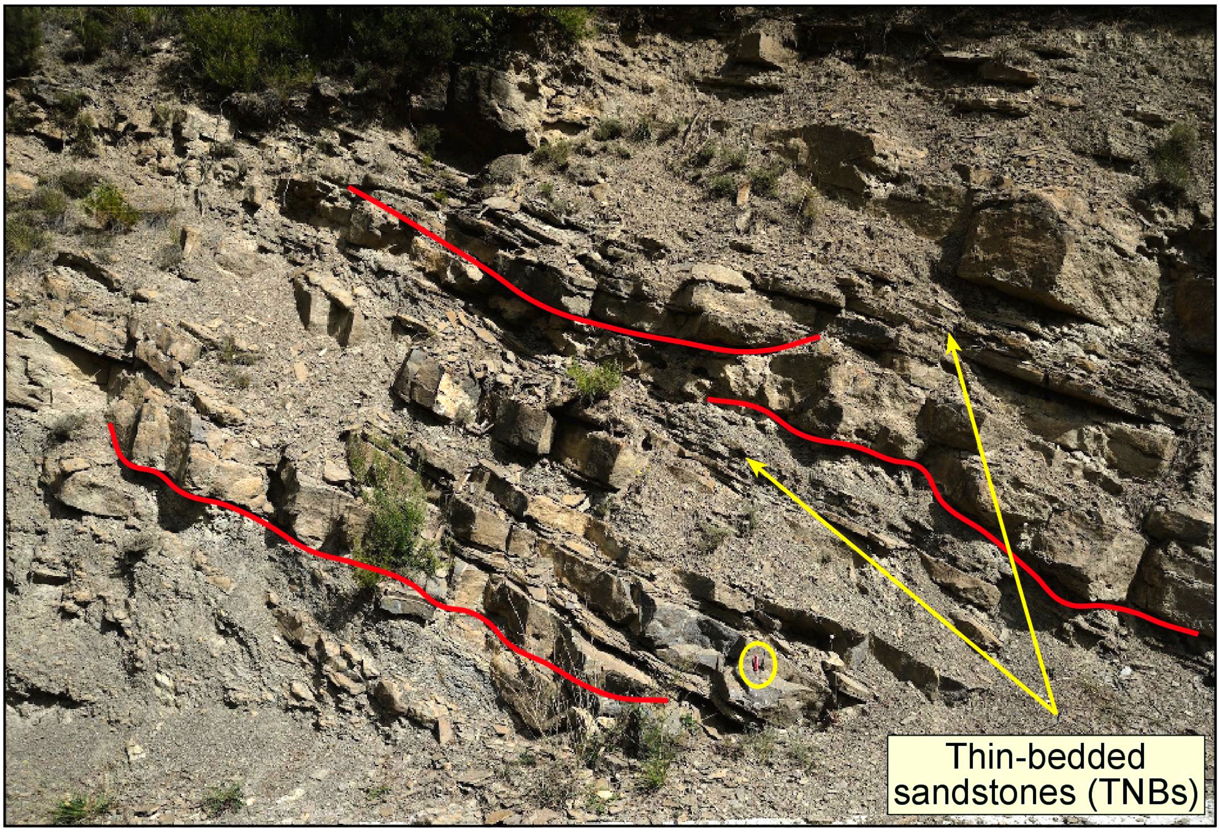

Fig. 4 - Thin packets of thin-bedded sandstones (TNBs) at the top of small channelized and coarse-grained turbidites. Red lines show erosional contacts. Eocene Broto system, south-central Pyrenees. Swiss Army knife for scale (yellow ellipse).

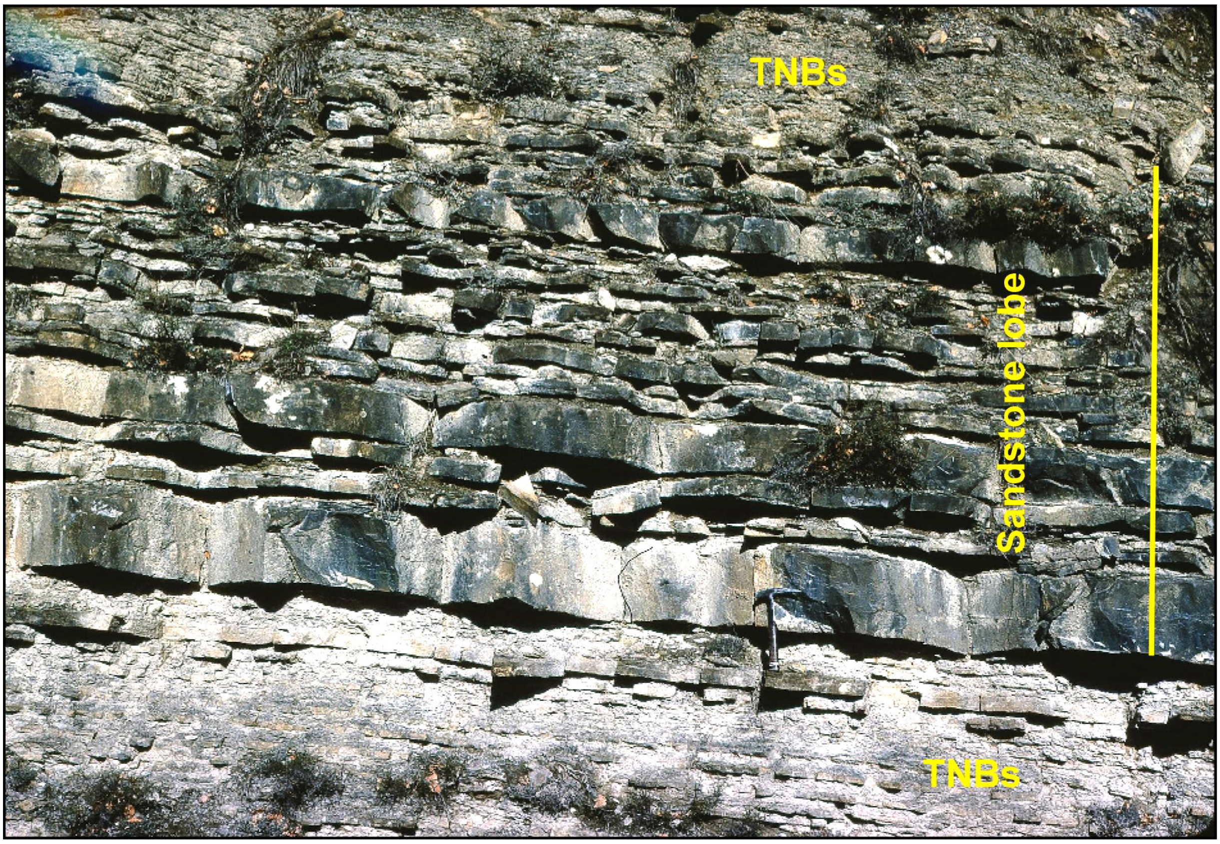

Fig. 5 - Sandstone lobe, with an overall thinning-upward trend, resting above and overlain by thin-bedded sandstones (TNBs). Eocene Broto turbidite system, south-central Pyrenees.

Fig. 6 - Onlap termination of a turbidite sandstone lobe against a bounding slope. Note how, approaching the slope, an original thinning-upward facies sequence is inverted into thickening-upward one. Similarly abrupt changes can be produced by compensation of depositional relief. Cengio system, Tertiary Piedmont Basin. Photograph courtesy of Franco Fonnesu.

Fig. 7 - Packets of closely spaced, thin-bedded sandstones separating medium-bedded turbidite sandstones. Eocene turbidite Broto system, south-central Pyrenees.

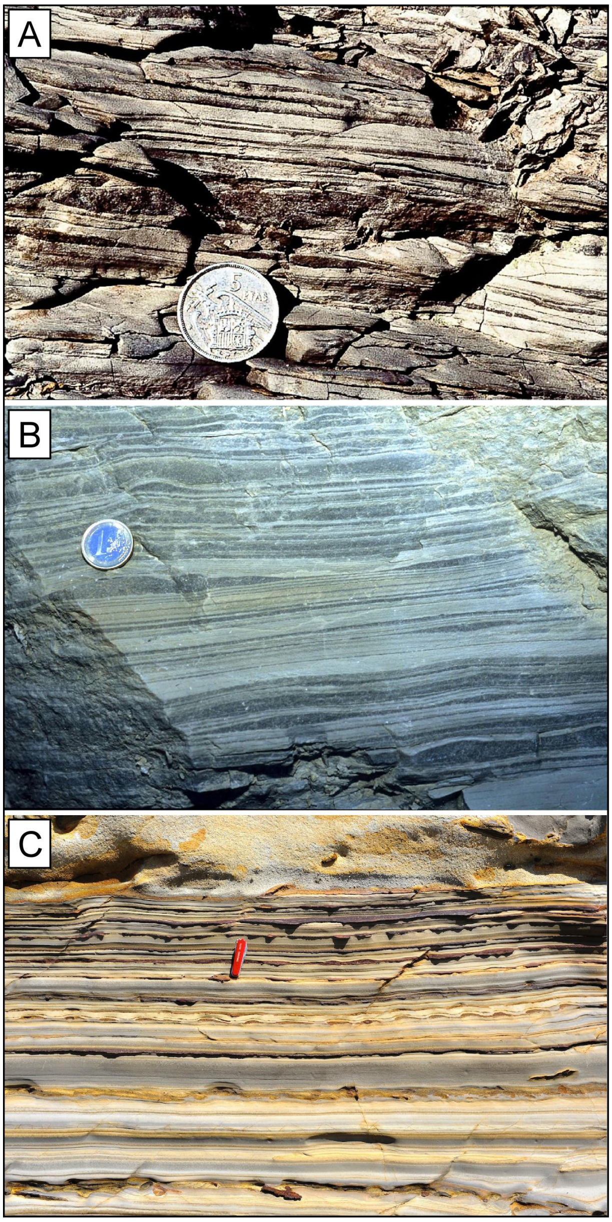

Fig. 8 - *Type-1* plumites. A, B) Very thin bedded siltstone/mudstone couplets. Siltstone forms mm-thick parallel laminae or slightly thicker starved ripples. Eocene Castigaleu Group, south-central Pyrenees; C) Plumites showing good examples of starved ripples with varying length. Cretaceous Maceiò Formation, Brazil.

sandstone (Type 2c, Fig. 11 A,B). Through a break in grain size, all these divisions are capped by one or few sets of current ripples that grade into overlying mudstone divisions. Ripples may be locally deformed by water escape and/or downcurrent flowage of the entire sandy division. This facies can be locally characterized by an extremely variable geometry of individual beds and their tendency to pinchout downcurrent over short distance (Fig. 12).

Type 3 (Fig. 13 A,B) - Thin beds (cm-scale) with a lower subtly graded division of very fine, clean sandstone containing current-ripple laminae transitionally overlain by thinner, sinusoidal or parallel laminae. Typically, ripples show a final backstepping stage indicating waning flow conditions and transition to the overlying mudstone divisions.

4.2. INTERPRETATION

Type 1 and its parallel laminae (Fig. 8) suggest direct deposition onto the bed from hypopycnal plumes with low sediment concentration and through differential settling imposed by the Stokes settling velocity. As suggested by the experiments of Parson et al. (2001), these plumes allow for discrete particle settling without being affected by convection processes. The starved ripples indicate some traction on the bottom probably produced by weak and turbulent flows in the absence of sufficient coarse silt fallout.

Type 2 beds are here interpreted as a typical deposit of "plume-triggered events" (Hizzett et al., 2018) which could not fully ignite to transform into hyperpycnal flows (hyperpycnal turbidity current) and were thus forced to rapid deposition from a thin near-bed layer with high-sediment concentration.

The figure 9A shows an example of these dense layers just sunk into a soft substratum and still preserving some of the original "fingers" (Type 2a). Further sinking produces complex "cloudy" features and transition to structureless liquefied layers (Fig. 9 A,B). The figure 10A shows parallel-sided muddy sandstone divisions containing pendolous load casts and detached pseudonodules of rippled and "cloudy" sandstone, mudstone clasts and plant fragments. The sandy division are plume-triggered layers which underwent limited motion (flowage) during and immediately after deposition. These divisions can be capped by either plastically deformed or flat-lying current ripples (Type 2b). Basically, these beds are almost identical to some "slurry" beds of classical turbidites (e.g., Tinterri et al., 2016) except for the lack of a basal clean sand division. Most importantly, turbidite "slurry" divisions are the final deposit of cohesive flows within a clear turbidite event, whilst in our case these cohesive flows apparently represent the initial stage of a flow that would tend to originate a turbidity current. After a phase of limited bed erosion and mud clast incorporation, these flows move as cohesive debris flows concomitantly with the deposition of current ripples from an overlying turbulent flow on their top. The first ripples move in a "piggy-back" fashion, becoming incorporated into the basal flow forming pseudonodules (Fig. 10B). Through progressive loss of excess pore pressure and elutriation, the basal flow may transform into a basal layer of clean sand. Such division is here interpreted as the product of plume settling which failed to transform into hyperpycnal turbidity currents and underwent local freezing and limited reworking by a trailing turbulent flow. These beds either die out over short distance, being reworked into ripples by an overlying and waning turbulent flow (Fig. 12), or keep moving as a structureless layer impelled by an overlying, weak turbulent flow (Type 2c, Fig. 11 A,B).

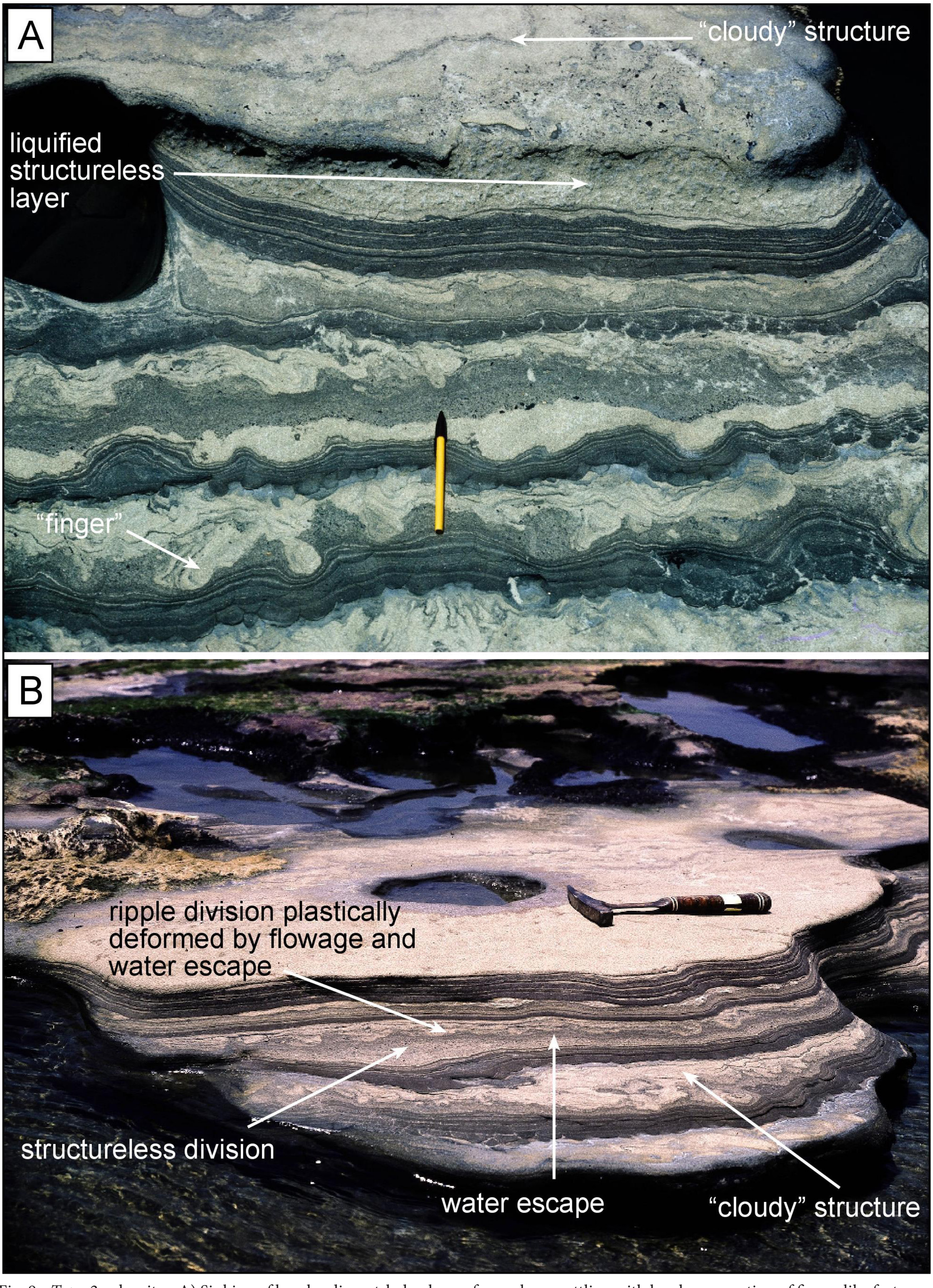

Fig. 9 - *Type-2a* plumites. A) Sinking of basal sediment-laden layers from plume settling with local preservation of finger-like features, commonly obliterated into a "cloudy" structure. Note how a "cloudy" structure evolves into a basal liquefied and structureless layer. Cretaceous, unrecorded stratigraphic unit, Cameroun. B) Other example of "cloudy structure and ripple division deformed by flowage and water escape.

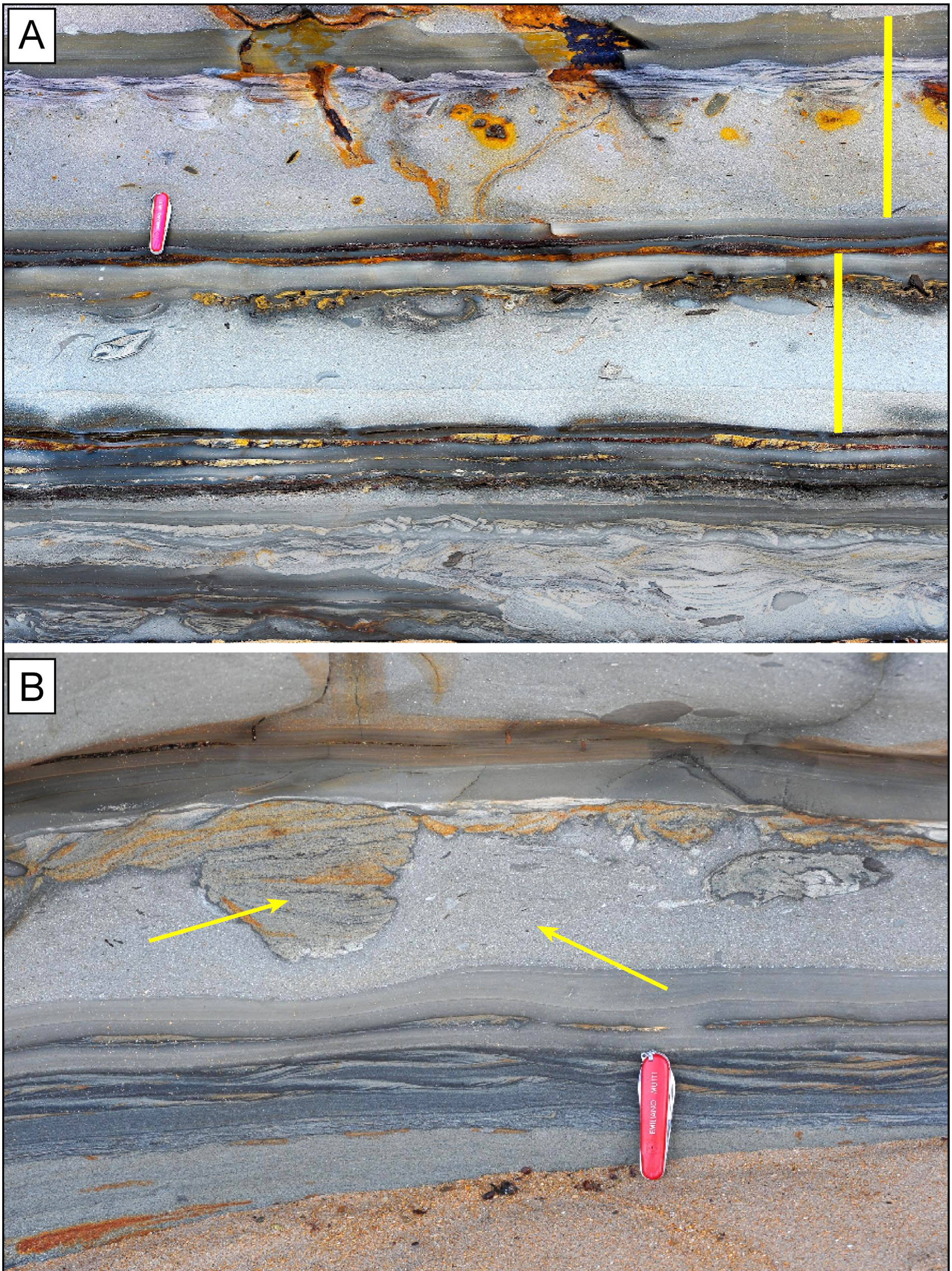

Fig. 10 - *Type-2b* plumites. A) Beds (yellow lines) showing a basal sandy structureless division with pseudonodules, plant fragments and mudstone clasts sharply overlain by climbing ripples. B) Structureless fine sandstone with floating pseudonodules of rippled and "cloudy siltstone. Cretaceous Maceiò Formation, Brazil.

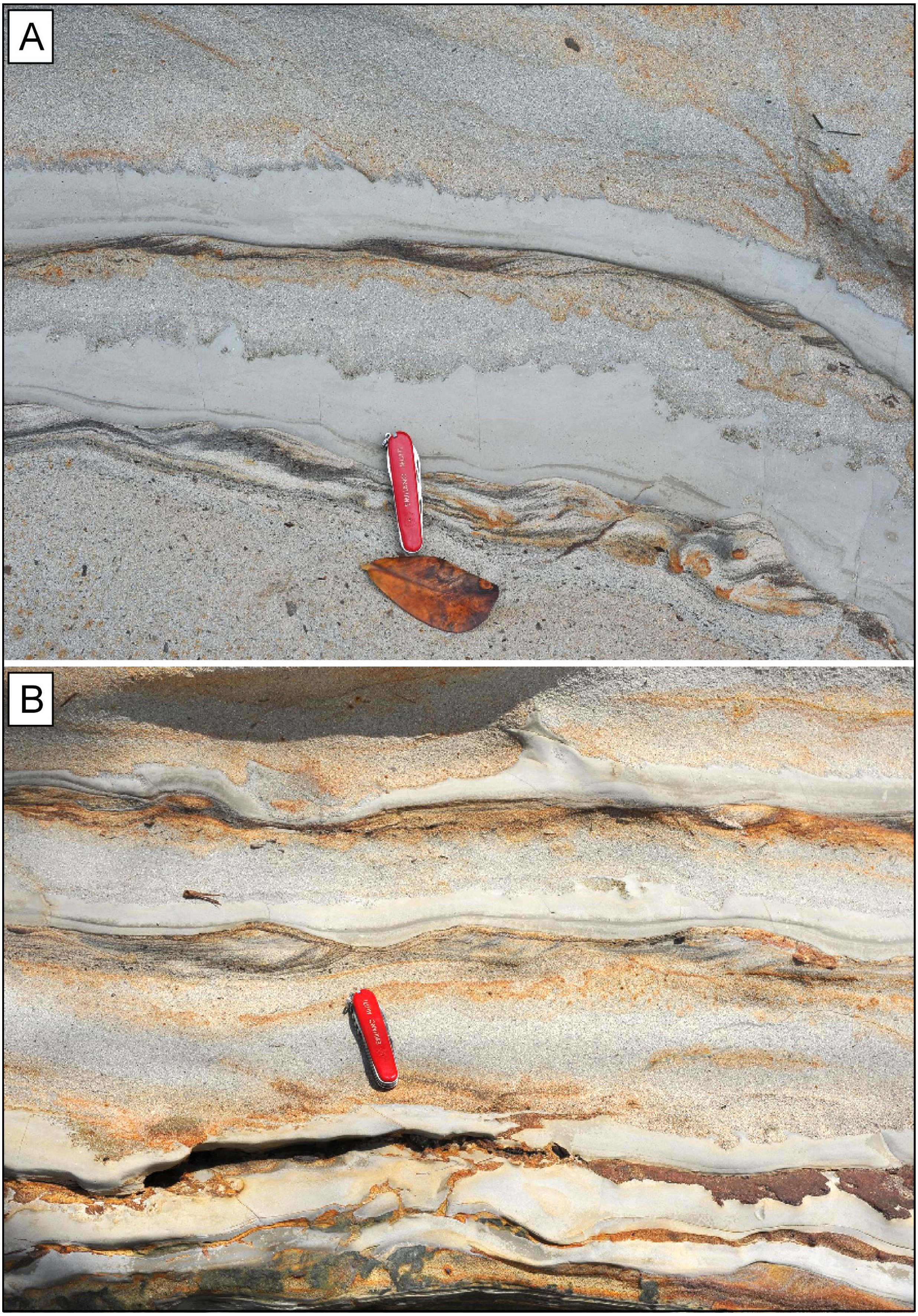

Fig. 11 - *Type-2c* plumites. A, B) Beds showing a basal, graded and virtually structureless sandstone division, with load structures at the base, which is sharply overlain by one or two sets of small ripples. Cretaceous Maceiò Formation, Brazil.

Fig. 12 - *Type-2c* plumites. Three beds (indicated by arrows) of structureless sandstone capped by thin ripple divisions, The sandstone divisions have sharp tops, highly irregular geometry, and pinch out in a downcurrent direction (left).

At this point the flow has become a bipartite and poorly-efficient "plume-triggered" turbidity current. Type 2c beds are essentially the F9b facies of Mutti (1992). An example of such beds in a weathered exposure is shown in figure 14.

Type 3 beds are clearly the product of traction-plus-fallout processes related to dilute, turbulent and subcritical hyperpycnal flows either generated as the distal product of denser flows in the shelf, or most likely by feeding from overlying plumes. The general lack of basal plane-bed laminae strongly suggests that the velocity of these flows never exceeded that of the ripple bedforms. Type 2c and Type 3 facies (and their intergradational members) dominate plumite sedimentation in most lobe regions probably because of the size of the original surface plumes (Fig. 15 A,B).

Summing up Type 1 deposits suggest deposition from very dilute plumes recording periods of relatively low fluvial discharge. Types 2 and 3 indicate deposition from larger volume plumes with abundant suspended load and thus indicative of increased fluvial discharge. The alternation of the two types of facies and the occurrence of essentially sand-free mudstone units provide good evidence of the varying fluvial regime in the alluvial environment. These sediments can be really considered as the ideal final depositional zone of fluvial systems as intended by Schumm (1981).

5. PLUMITES AND ASSOCIATED TURBIDITE ELEMENTS

At largest scale, the thick wedges of TNB facies and the mudstones that enclose them are characterized by thin sandstone beds that may occur in isolation within predominantly mudstone successions, or more commonly as m-thick packets of closely alternating cm-to mm-thick sandstone/ mudstone couplets. Sediments of this type may form successions up to several hundreds of meters thick in front of relatively large delta systems with abundant suspended load. Stratigraphic relations leave little doubt that these sediments were deposited by hypopycnal plumes and dilute hyperpycnal flows (Mutti et al., 2003). Though commonly bioturbated and generally more lenticular, the same sediments in fact also alternate with shelfal sandstone lobes. In delta-slope elements with high-sedimentation rates, these deposits are characteristically associated with chaotic units produced by sediment creeping and slumping. Most of these sediments can be safely interpreted as plumites.

At intermediate scale, TNBs have been generally interpreted as internal or external levee or channel-margin deposits where associated with channelized TKB packets. The interpretation is clearly supported by the stratigraphic relationship of these TNBs to channel-fill deposits. However, TNB packets also occur within

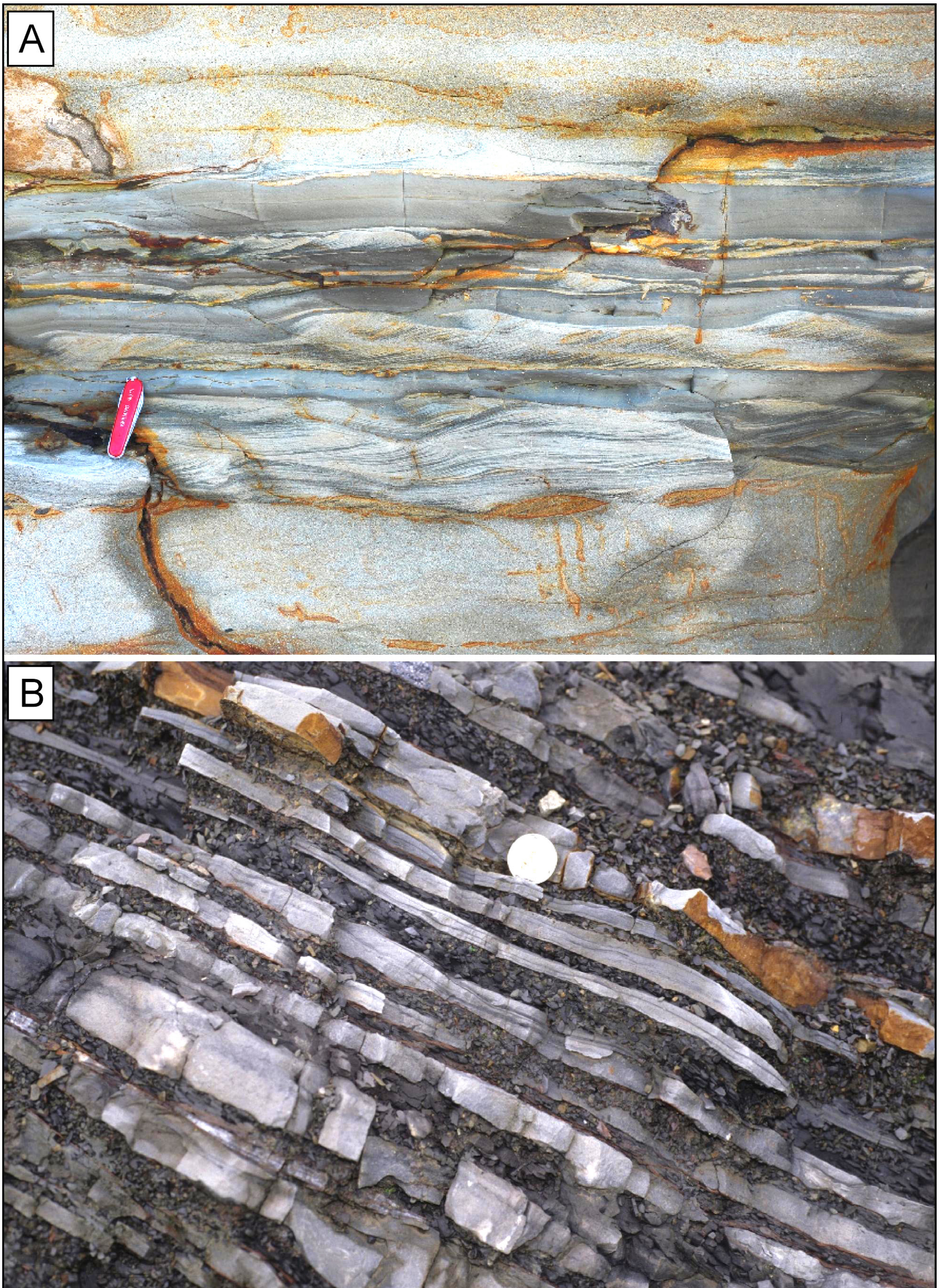

Fig. 13 - *Type-3* plumites. A) Beds of very-fine sandstone and ripple laminae deposited by waning turbulent suspensions (dilute hyperpycnal flows). Note the backstepping of ripple-lamina sets. Cretaceous Maceiò Formation, Brazil; B)Thin-bedded plumites showing ripple lamination. Paleocene-Eocene Chicontepec Formation, Sierra Madre, Mexico.

Fig. 14 - *Type-2c* plumites. Weathered exposure of Type-2c plumites. Bed geometry is still observable, but internal structures are almost entirely obliterated. Eocene-Oligocene Ranzano Sandstone, northern Apennines.

channel-free mudstone units vertically separating channel and channel complex deposits. In the absence of laterally associated channels, these units can only be interpreted as downsystem extensions of plumites in the prodeltaic or delta-slope region (see above).

More problems arise when considering the TKB/TNB alternation in lobe and lobe-fringe elements. The alternation, producing in some cases a spectacular cyclicity, occurs in the main sandy depositional zone of turbidite systems, where turbidity currents exit their channels and spread out as unconfined flows across the lobe region and its fringe, forming the well-known un-channelized sandstone lobes. The best cyclicity is developed at some distance from channel exits and beyond the channel-lobe transition zone (CLTZ), since in these zones extensive scouring, amalgamation and compensation cycles largely prevent or modify the preservation of the entire succession. However, compensation cycles, which may partly or entirely reverse the original thinning-upward trend, occur also in more distal regions because of subtle pre-existing depositional relief. In large, highly efficient systems, the lateral tracing of these two facies does not show any gradual transition into each others thus providing evidence of their tabular geometry over distances up to several and even tens of km (Ricci Lucchi and Valmori, 1980; Casnedi, 1983; Mutti et al., 1999; Tinterri and Tagliaferri, 2015, among others) and, most importantly, casting doubt on their common origin. TNB facies observed are essentially the same plumites as in LS settings. However, Type-2 and Type-3 plumites, and their intergradational expressions, tend to predominate comprising packets of extremely regular and closely spaced alternations (Fig. 15 A,B), commonly showing an internal higher-frequency cyclicity.

At small scale, particularly in lobe regions, TNB packages herein interpreted as plumites, consisting of a limited number of beds (commonly up to 10-15), typically occur as finer-grained and thinner bedded partings separating individual thick beds or groups of thick beds (Fig. 16). The facies contrast is quite abrupt suggesting that the two kinds of deposit have a different origin.

6. DISCUSSION AND CONCLUSIONS

The genetic relations between TKBs and TNBs are difficult to understand in simple terms of proximal and distal deposits of turbidity currents, or more generally in terms of basal sand-laden flows accompanied by more dilute turbulent flows. This relationship certainly exists and does explain many depositional settings, but fails to explain the pervasive occurrence of TNBs in turbidite systems and especially the enormous number of thin beds and events leading to their deposition. If, for example, we consider an ideal, 10 m- thick facies sequence in a lobe

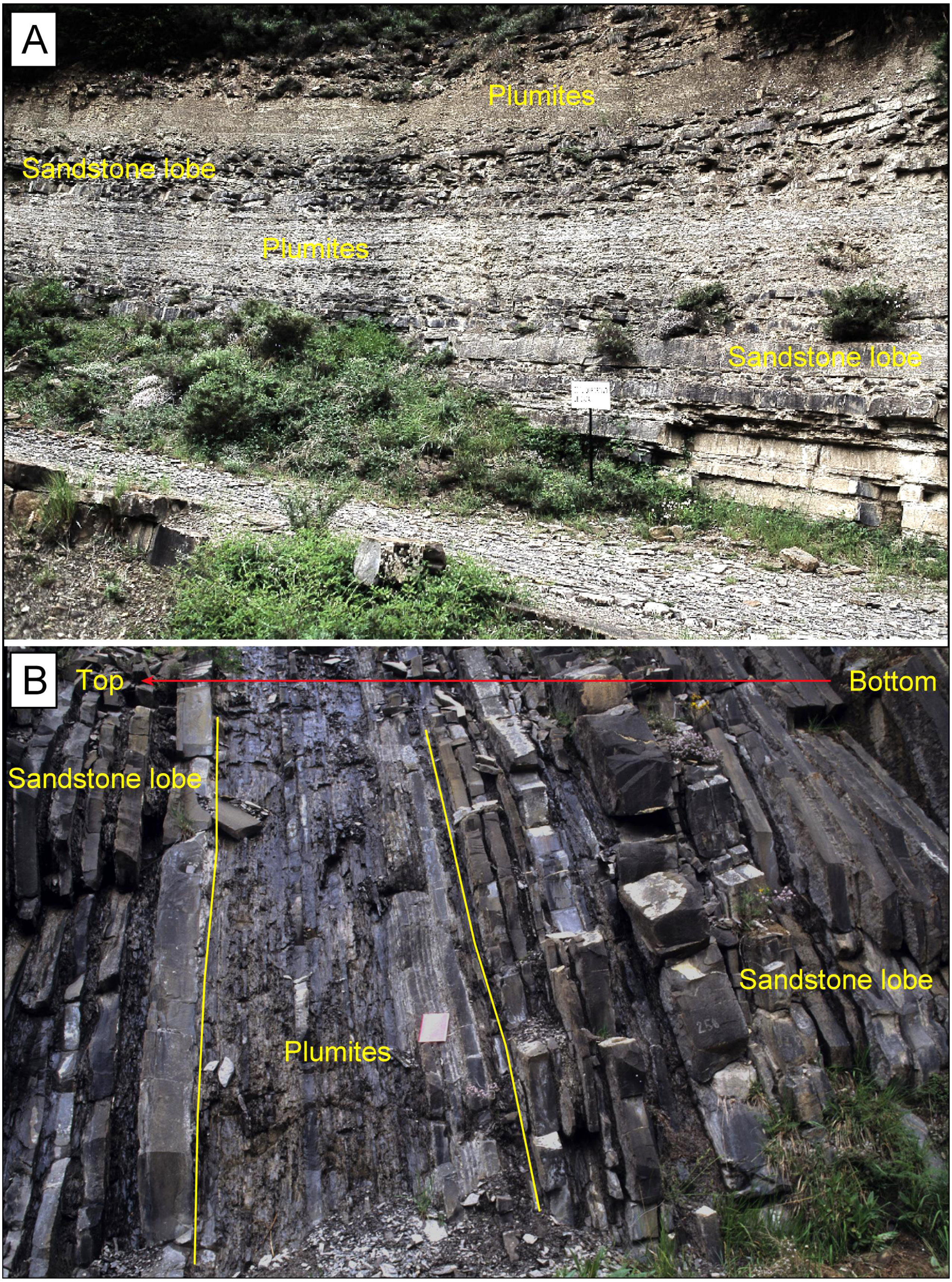

Fig. 15 - A) and B), transitional contact of plumites with medium-bedded sandstone lobes. Eocene Broto system, south-central Pyrenees.

Fig. 16 - Medium-bedded turbidite sandstone beds alternating with packets of thin-bedded plumites. Eocene Broto system, south-central Pyrenees.

element, consisting of a lower 5-m thick TKB facies and an equally thick upper TNB facies, only a few beds (say 5 beds, each 1-m thick) and related turbidite events are needed to form the sandstone lobe, whereas some 33 to 165 beds (for individual bed thickness of 15 cm or 3 cm, respectively) and related events are needed to form the upper TNB facies. The first and most simple conclusion that can be drawn is that thin beds are the product of events with a frequency of an order of magnitude higher than that of TKBs.

To partly understand the above problems, it is here suggested that hyperpycnal flows be partly redefined. In their original definition (Mulder and Syvitski, 1995; Mulder et al., 2003), hyperpycnal flows are strictly viewed as the product of plunging plumes forming at river mouths and loaded with fine-grained sediment (finer than medium sand) transported by the flow as suspended load. If this definition is accepted, then hyperpycnal turbidites should be only fine grained, unless the somewhat unlikely assumption is made that bed erosion can add gravel and coarse sand to the flow during its early basinward motion. This assumption would hardly explain the abundance of coarse-grained sediment (conglomerates and pebbly sandstones), which are common in the proximal elements of many turbidite systems.

As documented by Mutti et al. (1996, 2003) from ancient fluvio-deltaic systems, substantial amounts of coarse-grained sediment are directly transferred to the sea by dense gravelly and sandy flows (debris flows, hyperconcentrated flows, composite sediment gravity flows, high-density turbidity currents: see Mutti et al., 2003 for more details) essentially moving as "bedload". These fluvial outflows, which propagate in seawater as highly hyperpycnal flows, account for the deposition of coarse-grained shelfal lobes in many fan deltas and coarse-grained deltas of tectonically-active basins.

The figure 17 shows a general scheme indicating how fluvial outflows behave when entering a marine basin (fresh water basins are here omitted from the discussion). The scheme includes: (1) coarse-grained dense flows (CGDFs) (Fig. 17A) that, because of their density, keep moving in seawater as underflows with minor modifications suffered at the shoreline, (2) turbulent flows sufficiently dense to produce plunging plumes (PPs) at river mouths (hyperpycnal flow s.s.) (Fig. 17B); and (3) dilute suspensions that propagate in seawater as hypopycnal plumes (HP) (Fig. 17C). Contrary to the opinion of Mulder et al. (2003, p. 3), the failure of lower-discharge mouth bars induced by sudden river outflows, as described by Bornhold et al. (1994) from British Columbia fjiords, and the incorporation of their sediments into the flow, increasing its density, is here thought to be an important element in the generation

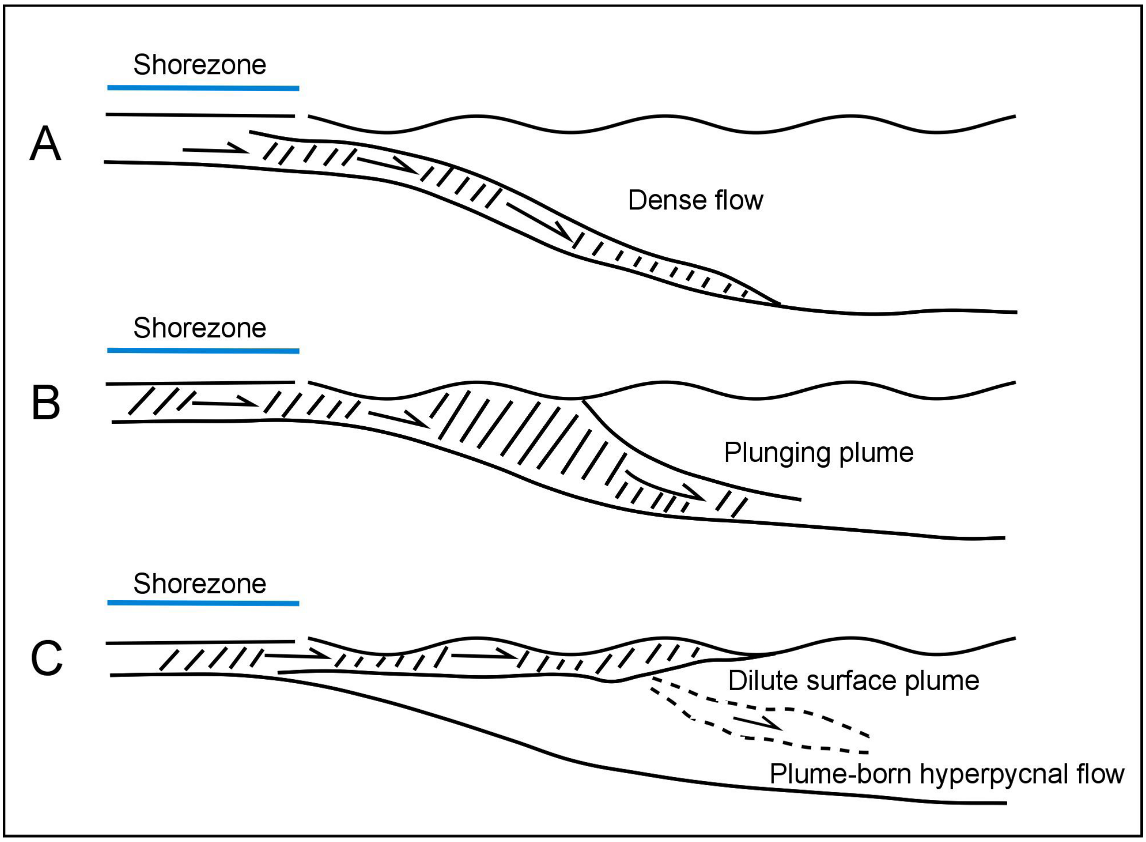

Fig. 17 - Main types of fluvial outflows. Dense flows (A) and plunging plumes (B) are primary hyperpycnal flows, while plume-born hyperpycnal flows (C) are secondary flows produced by dilute surface plumes.

of hyperpycnal flows. The process is probably mainly limited to dense river outflows and not to plunging plumes that become hyperpycnal flows seaward of river mouths.

The textural composition of the original river outflows and that of the sediment added by bed erosion determine what kind of process will predominate during transport and deposition in seawater. If basin configuration allows for the direct transfer of sediment to deep water, and therefore the ignition of turbidity currents (in the broad sense of Mutti and Ricci Lucchi, 1972; Lowe, 1982, and Mutti, 1992), CGDFs and PPs will move downslope and deposit their load in the basin as coarse grained and fine-grained turbidites respectively. HPs will propagate in surface water and eventually die out after losing their load due to particle settling or convection processes. However, these convection processes, if affecting large volume plumes with relatively high sediment concentration, may become an additional and effective mechanism through which large amounts of thin-bedded sandstone can be deposited in slope and basinal settings.

Individual floods behave in a similar way. Entering seawater, an ideal flood, containing all the grain-size populations and being accelerated in a high-gradient system, will basically split into three parts: (1) a dense and coarse-grained basal flow moving along the bed; (2) a finer-grained dense to turbulent flow mainly evolving into a plunging plume; and (3) a dilute hypopycnal flow floating on seawater and propagating as long as it is fed by the river (Fig. 18). This is probably the fate of fluvial outflows entering seawater as composite flows in fandeltas and coarse-grained deltas (for more details see Mutti et al., 2000, and Tinterri, 2007). During subaerial transport, the leading edge of the flow is most commonly an inertia-driven, coarse-grained frictional dense flow, which is followed by a bipartite flow consisting of a dense basal flow sheared by an overlying sand-laden suspension; a more dilute and slower turbulent flow carrying fine sediment in suspension forms the trailing part of the flow. The scheme, inspired from the fundamental model envisaged by Sohn et al. (1999), implies deposition showing the downcurrent inversion of the deposit of the different parts of the flow.

Along with many other factors, the relative proportions of the basic grain-size populations within the flow (gravel, coarse sand, fine sand and coarse silt, and mud) strongly control the final characteristics of the resulting bed and more generally the facies characteristics of an entire system. The resulting great variability of flood-related turbidite systems, contrasts dramatically with the simple and widespread blanketing of plumites, which are only composed of suspended fine-grained sediment undergoing fractioning through settling. As shown in figure 19, the facies scheme that summarizes an ideal

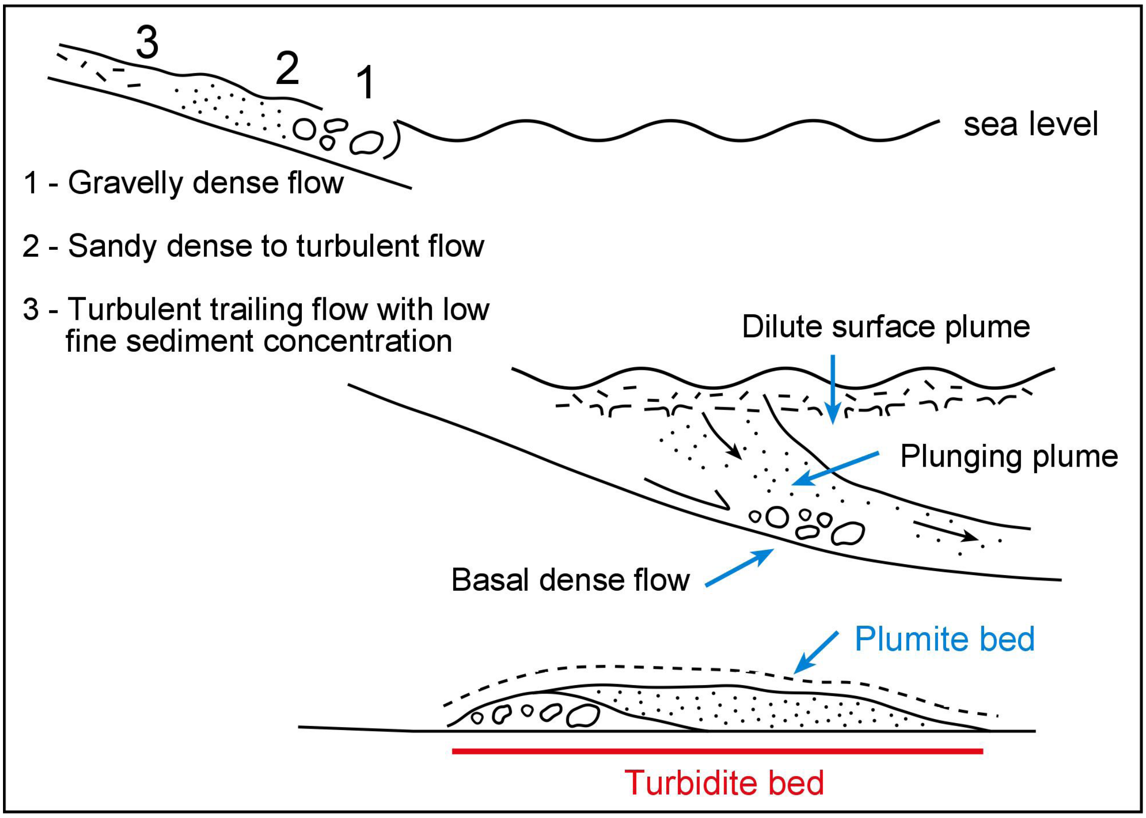

Fig. 18 - Ideal transition of a composite fluvial outflow into a hyperpycnal turbidity current and associated surface plume (the scheme assumes direct transition of river outflow to deep water).

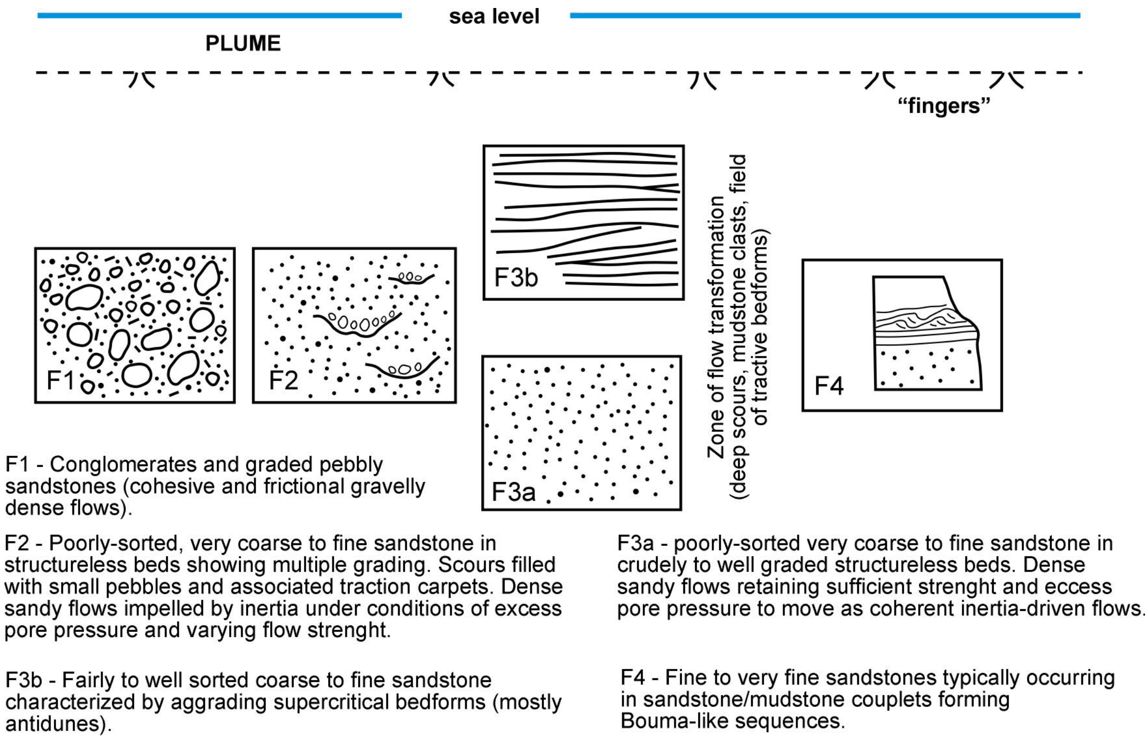

Fig. 19 - Facies scheme that summarizes an ideal turbidite system. Facies types can greatly vary based upon the relative proportions of the different grain-size populations within the flows. Some facies can be suppressed, others may become dominant. Plumites are quite an exception, in that dilute hypopycnal plumes are common to most rivers, except for those that are very deficient in fines. Turbidite facies scheme slightly modified from Mutti (2017).

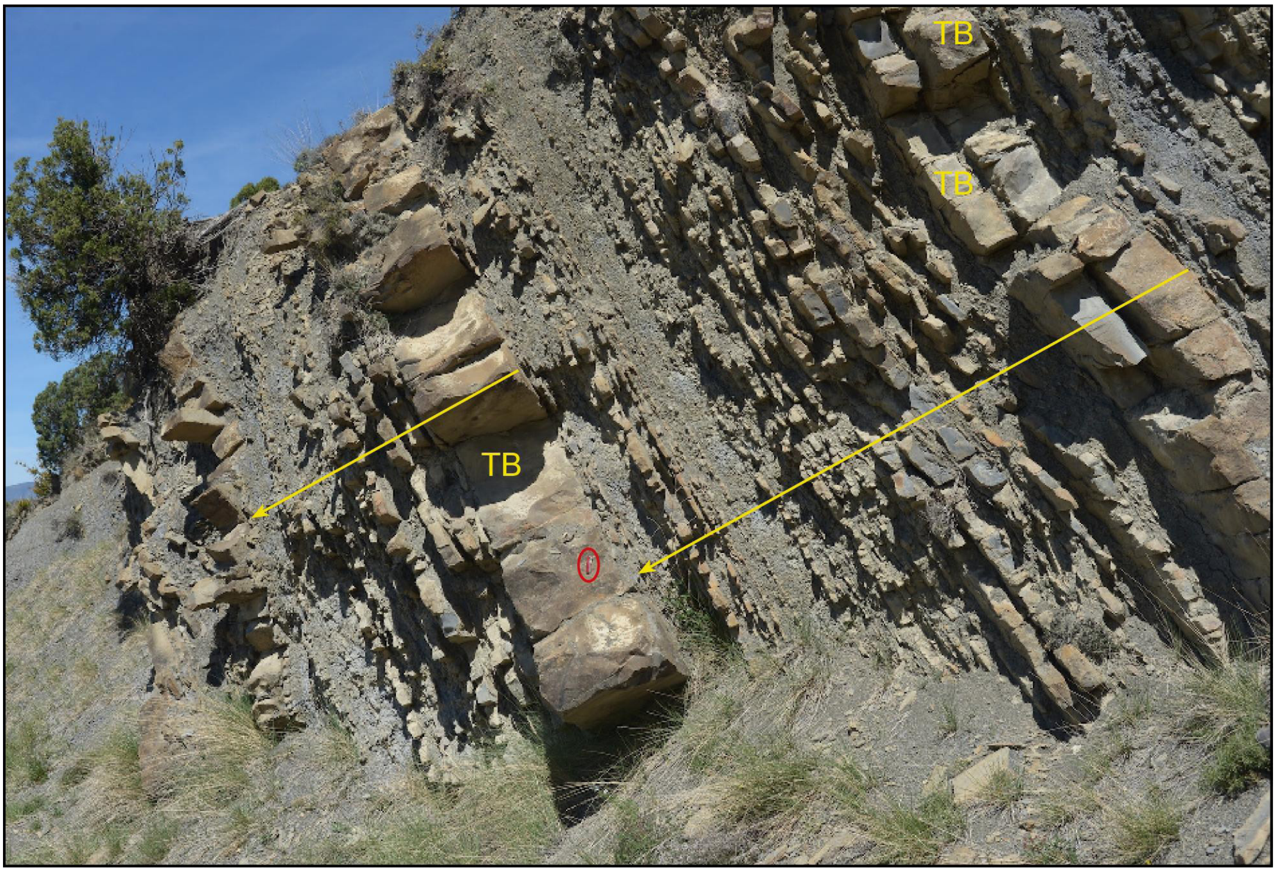

Fig. 20 - Thick, fine-grained turbidite beds (TB) transitionally capped by plumites and forming two overall thinning-upward facies sequences. Because of their fine-grained texture, also the three thick turbidite beds could have been deposited by "plume-triggered" events. Eocene Figols Group,south-central Pyrenees. Swiss Army knife for scale (red ellpse).

turbidite system can greatly vary based upon the relative proportions of the different grain-size populations within the flows. Some facies can be suppressed, others may become dominant. All other things being equal, the original textural composition of the flows (including that acquired through bed erosion) will ultimately control not only the types of facies and facies associations, but also the entire architecture of the system. We can say that, assuming again that all other things should be equal, each flood-generated deep water turbidite system can only develop in the way dictated by its feeder fluvial system. Plumites are quite an exception, in that dilute hypopycnal plumes are common to most rivers, except for those that are very deficient in fines.

Parson et al. (2001) have discussed at length hyperpycnal flows resulting from finger-like or leaking convection affecting an unstable hypopycnal plume and suggested that more than half the sediment could be lost by the plume to a dense, bottom-riding turbidity current. In flume experiments, many of these turbidity currents can transfer sand to the lobe region. This process is very likely, though no direct evidence can be found from field studies. In particular, no evidence has been found of substantial bed erosion features or residual sediment indicating the early erosional stages of these flows. Beds produced by this process have probably gone unnoticed until now and should, however, be mainly fine grained. Their recognition should be mainly based on the local facies association. A possible example is tentatively shown in figure 20.

A final comment is needed about cyclicity. From field observations, it appears that a basic motif emerges from the stacking patterns of turbidites and associated plumites. The pervasive occurrence of thinning- and fining-upward facies sequences strongly suggests that an initial stage of turbidite deposition is transitionally or abruptly followed by a mixed stage of turbidite/plumite deposition, in turn capped by a stage of plumite deposition produced by plumes of decreasing sediment concentration (Fig. 20). The sequence ideally ends with mudstones recording the cessation of fluvial floods and a resumed "normal" (clear water) fluvial regime. This sequence further supports the close links between the two kinds of sedimentation, though these links are certainly limited to turbidite systems of tectonically active basins where high-gradient fluvial systems and proximity of the catchment zones to the shoreline favour the role of floods (Mutti et al., 1996, 2003). The cyclicity seems therefore the result of alternating periods of low to high fluvial discharge with different sediment concentration, ultimately controlled by

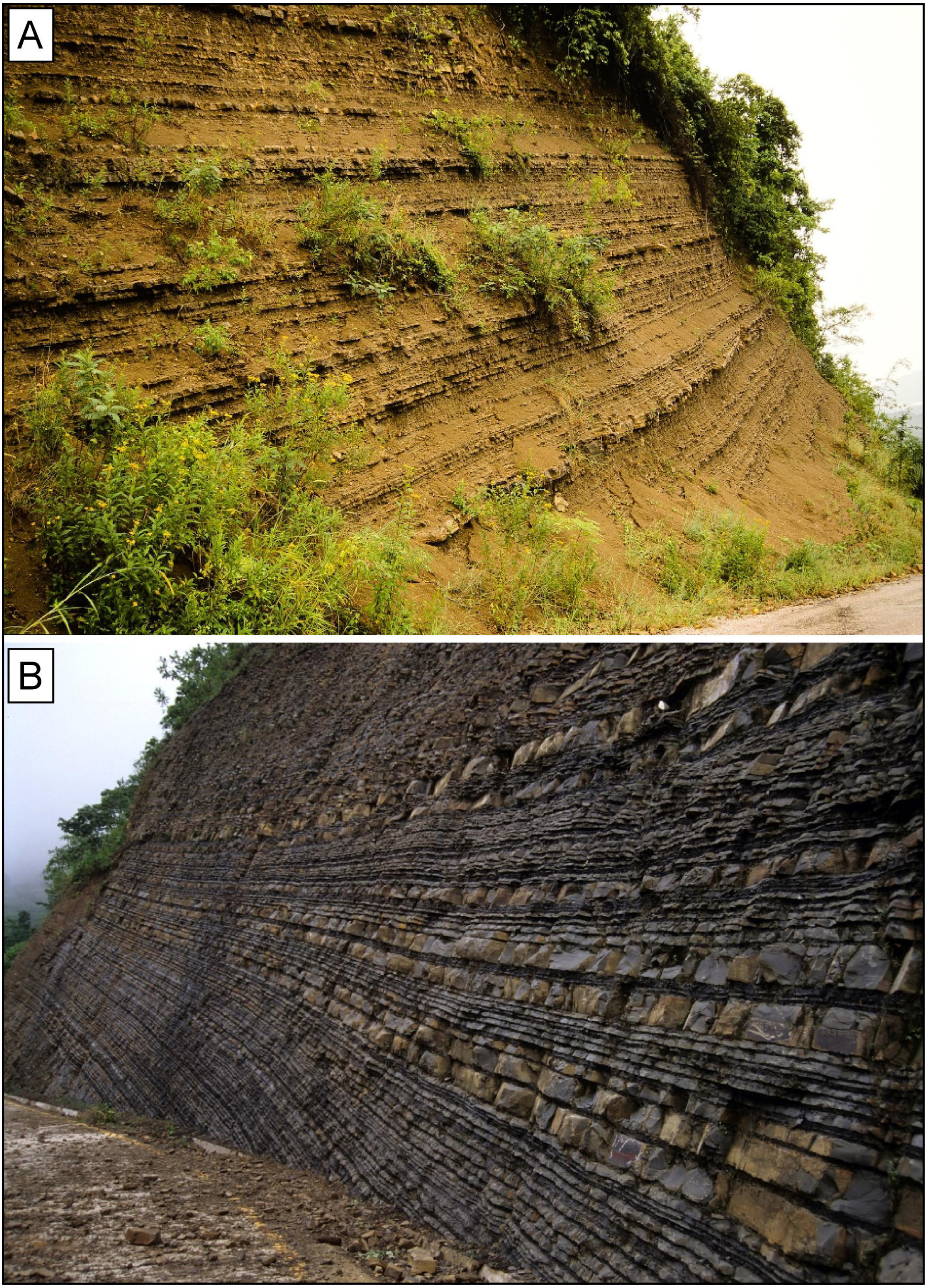

Fig. 21 - Cyclic stacking pattern of plumites. A and B) Both examples consist of an alternation of very-fine grained sandstone with ripple laminae and mudstones. In B, thicker sandstone beds gradually thin out to the left. Paleocene-Eocene Chicontepec Formation, Sierra Madre, Mexico.

climate variations. Cyclicity is a pervasive and impressive feature of plumite successions (Fig. 21).

Plumites are the only direct signature of a fluvial process ending in deep water. Their correct recognition is the only tool for directly linking fluvial and turbidite deposition and widening our approach to turbidite basin analysis. Plumites are obviously important also in terms of hydrocarbon exploration and production, acting essentially as permeability barriers at scales ranging from seismic-scale prodeltaic wedges down to that of reservoir geology. A great improvement in our understanding of these problems certainly resides in more careful core analyses. Cores are where plumites appear in all their beauty.

POSTSCRIPTUM AND AKNOWLEDGEMENTS - Most of this research was carried out long after retiring from university and it has been motivated by reasons of personal curiosity, primarily by the interpretation of a beautiful exposure of turbidites in the Spanish Pyrenees. I found the exposure (Fig. 16) more than 50 years ago and I could never understand why such different beds could be alternating so regularly and without transitional members. This paper is probably the long-waited answer. In addition to field work, research involved a long re-examination of thousands of photographs of rocks that I took during my career. It was amazing to realize how old photographs can actually take you back to the exposures you saw many years ago and how you can see them with fresh eyes. Based on my experience, I would thus strongly advise young students to carry with them a good camera when they go to the field and carefully preserve the photographs. Sometime they may turn out to be useful.

My sincere thanks go to Salvatore Milli who kindly agreed to critically review the manuscript and patiently spent many weeks with me in the field discussing supercritical flows in the Pyrenees and in the Laga mountains. I'm also grateful to Franco Ricci Lucchi and Roberto Tinterri for their critical reading of the manuscript and useful suggestions. Special thanks go to Luci Maria Arienti for introducing me to the fascinating world of the Maceiò Formation many years ago.

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