Received: 8 August 2023 | Revised: 15 December 2023 | Accepted: 30 December 2023

DOI: 10.1002/dep2.266

The Depositional Record
A journal of the International Association of Sedimentologists
Open Access
IAS
WILEY

ORIGINAL RESEARCH ARTICLE

Deltas: New paradigms

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Abstract

Deltas are deposits directly accumulated by land-generated gravity flows in a standing body of water. The paradigm of deltaic sedimentation has dramatically changed during recent years, from the popular very simplified ternary models of marine littoral deltas towards more realistic and comprehensive models, considering the importance of sediment-laden river discharges. Ternary delta models were designed for clean rivers, where a stream flow drags the sediments. Depending on the basin dynamics, these littoral deposits can be modified, forming tidal-dominated, wave-dominated or fluvial-dominated littoral deltas. In recent years, a new classification of delta systems was proposed, based on contrasting the salinity of the receiving water body with the bulk density of the incoming fluvial discharge. Rivers are highly dynamic systems, and their discharges can be very variable in terms of flow duration and sediment concentration. Additionally, the salinity of the receiving water body can exhibit significant variability, especially in closed lakes and epicontinental seas, ranging from freshwater to brines. This scenario allows the distinction of three major delta categories (hypopycnal, homopycnal and hyperpycnal deltas) which can be in turn subdivided, defining seven delta types. Hypopycnal deltas form when the bulk density of the incoming flow is lower than the density of the water in the basin, allowing the definition of three delta types, corresponding to hypersaline littoral deltas, marine littoral deltas and brackish littoral deltas. Homopycnal deltas form when the bulk density of the incoming flow is similar to the density of the water in the basin, defining a delta type termed homopycnal littoral deltas. Hyperpycnal deltas form when the bulk density of the incoming flow is higher than the density of the water in the basin, allowing the definition of three categories termed hyperpycnal littoral deltas, hyperpycnal subaqueous deltas and hyperpycnal fan deltas.

KEYWORDS

deltas, gravity flows, hyperpycnal flows, turbidites

1 | INTRODUCTION

According to some estimates, rivers currently supply *ca* 36,000 km^3 of freshwater to the ocean every year, enabling the transfer of between 18.5 and 25 gigatons (GT) of sediments (Holeman, 1968; Milliman & Meade, 1983; Syvitski, 2003; Chakrapani, 2005; Liu et al., 2009; Milliman & Farnsworth, 2013). This sediment supply represents about 95% of the total flux of sediments from land (Syvitski, 2003). These fluvial-derived sediments are primarily stored in different kinds of deltas, from where they can be partially eroded and redistributed by diffusion processes and ocean currents (Barrell, 1912). The most popular assumption is that most of these river-supplied sediments are accumulated as littoral deltas (Coleman & Wright, 1971; Galloway, 1975; Wright, 1978; Gani & Bhattacharya, 2005; Bhattacharya, 2006, 2010; Syvitski et al., 2022). Orton and Reading (1993) defined deltas as 'discrete shoreline protuberances formed where an alluvial system enters a basin and supplies sediment more rapidly than it can be redistributed by basinal processes'. More recently, Syvitski et al. (2022) made an extended revision, defining deltas as 'subaerial landforms that cap underlying deposits with subaqueous extensions that result from a river feeding sediment directly into a standing body of water at a rate that overwhelms any effective dispersal processes derived from the ambient basin'. Littoral deltas form when bedload-dominated diluted river flows enter a standing body of water. In these circumstances, the river flow is forced to stop due to the combined effect of friction and a decrease in flow confinement (Winsemann et al., 2021). According to this paradigm, deltas are essentially considered as coastal forms, extending a few kilometres from the coastline. Probably, this narrow and oversimplified geomorphological view of delta sedimentation was a consequence of our historically poor understanding of offshore processes, river dynamics and sea-level changes during the Holocene. This paradigm of littoral (coastal) deltas could be considered valid for bedload-dominated clean-water streamflows during 'normal' (non-flood) conditions. In this situation, sediment transport is controlled by shear forces provided by river stream flow. In contrast, during floods, there can be a substantial increase in the concentration of suspended sediments in the river discharge (Mulder et al., 2003) resulting in sediment-laden dirty rivers. In these circumstances, river sediments may not necessarily accumulate at the river mouth. Instead, they can bypass coastal areas and transfer sediments deeper into the basin (Kao et al., 2010). Since during floods, river flow capacity and competence are at their maximum, the volume of terrigenous sediments transferred basinward during a single flood can be enormous (Mulder et al., 2003), typically hundreds to thousands of times higher than that during 'normal' discharge conditions. Only a small part of all the sediment load transported by rivers may be retained in coastal areas (Syvitski, 2003; Liu et al., 2009), and consequently understanding the characteristics and distribution of these deltaic sediments in the offshore becomes a hot topic.

The problem of exploring the real significance and the possible basinward extension of deltas was excellently discussed in the pioneer work of Moore (1969), who proposed a new paradigm for delta sedimentation. For Moore (1969), the common association of a river (with or without a delta) with a submarine canyon and an abyssal fan implies a genetic relationship. These elements composed his 'dynamic system', which includes the river, its delta, the related submarine canyon and the submarine fan. Later, Moore and Asquith (1971) proposed a wider and more sedimentological definition of deltas, considering a delta as 'the subaerial and submerged contiguous sediment mass deposited in a body of water (ocean or lake) primarily by the action of a river'. For these authors, all sediments reworked by forces other than the depositing river, but not transported away from the main mass of the delta, are considered as delta deposits. However, sediments that moved a significant distance from the original delta, such as barrier islands, shelfal bars or detached deep-sea fans (the intrabasinal turbidites of Zavala & Arcuri, 2016), are not considered as part of the delta. Consequently, delta deposition (in a broad sense) refers to all those sediments accumulated in largely more complex systems, which cannot be classified and analysed using the simple geomorphological ternary diagrams (Galloway, 1975) designed for coastal deltas.

In an effort to better understand the subaqueous extension of deltas, Postma (1990) proposed a new disruptive delta classification contrasting the alluvial feeder system, basin depth and river mouth processes. From this analysis, Postma (1990) recognised 12 prototype deltas, being eight shallow water and four deep-water deltas. One of the most important concepts introduced in this contribution was the recognition of river-fed submarine fans as part of the delta system.

During the last few decades, detailed oceanographic studies were conducted in shelfal areas located in front of large deltas (Kineke & Sternberg, 1995; Nittrouer et al., 1996; Kuehl et al., 1997; Walsh & Nittrouer, 2009; Cummings et al., 2015). These studies suggest that deltas are considerably more complex than previously considered (Bhattacharya, 2010). In shelfal areas, a number of studies recognised the existence of multiple subaqueous clinoforms extended hundreds of kilometres basinward (Steel & Olsen, 2002; Swenson et al., 2005; Helland-Hansen & Hampson, 2009; Patruno et al., 2015) termed 'subaqueous deltas' (Kuehl et al., 1986), detached from the classical 'subaerial delta'. The origin of these clinoforms is at present poorly understood. Most studies propose subaqueous deltas originate via fluid muds affected by ocean currents like tides, waves and ocean waves (Kineke & Sternberg 1995), advection–diffusion of suspended sediments (Pirmez et al., 1998), or hyperpycnal flows (Plink-Björklund & Steel, 2004; Olariu et al., 2010; Ahmed et al., 2014; Wilson & Schieber, 2014). Additionally, in recent years, a new type of turbidite (deposits of turbid flows) directly supplied by rivers, termed 'extrabasinal turbidites' (Zavala & Arcuri, 2016), was recognised in both ancient and recent systems.

Based on the above considerations, it appears that we can apply 'Gestalt' psychology to deltas. This implies that we may not fully understand deltas as a whole by solely studying their single parts. This new understanding requires building a new classification comprehensively integrating littoral, shelfal and deep-water elements as parts of a new paradigm of delta sedimentation.

The purpose of this paper is to discuss the rational classification of delta systems recently proposed by Zavala et al. (2021), focussing in a detailed analysis of some poorly known new delta categories. In this contribution, the definition proposed by Moore and Asquith (1971) will be broadly followed with slight modifications, considering a delta as *the deposit directly accumulated by a land-generated gravity flow in a standing body of water*. Please note that this definition does not consider water depth, diffusion processes (wave & tides), buoyancy or distance from the coast, but instead focusses on primary accumulation by an extrabasinal flow.

2 | METHODS

This paper explores and discusses the characteristics of delta deposits according to some fundamental understanding acquired by the senior author during the last 30 years through the study of different outcrop and subsurface (core) examples of delta systems from a number of stratigraphic units analysed in different sedimentary basins from Argentina, Brazil, Venezuela, Colombia, Trinidad & Tobago, Mexico, Italy, Spain, Russia and China (Table 1). These stratigraphic units and their deposits were analysed through extensive outcrop/subsurface studies applying different branches of sedimentology and stratigraphy, like facies analysis (both descriptive and genetic), core studies, well log analysis and correlation, electrofacies analysis, sequence stratigraphy, seismic stratigraphy, seismic attributes, analysis of photohorizons, analysis of architectural elements, biostratigraphic studies and trace fossil analysis. The age of the studied units ranges from Palaeozoic to Quaternary. Since the stratigraphy, sedimentology and internal characteristics of all these units cannot be fully discussed in this paper, some selected references are also provided in Table 1, providing some complementary information about the units under consideration.

As can be seen in Table 1, a single unit can include deposits accumulated by different delta types. The last is a direct consequence of the highly dynamic characteristics of the associated fluvial systems and salinity changes in some restricted basins over time.

3 | A NEW PARADIGM ABOUT THE ORIGIN AND SIGNIFICANCE OF DELTA DEPOSITS

A broader approach concerning deltaic sedimentation was initially proposed by Bates (1953). Bates (1953) defined a delta as a sedimentary deposit built by a jet flow into or within a permanent body of water. Analysing the contrast between the bulk density of the incoming river flow (ρ_r) and the density of the water in the reservoir (ρ_w), Bates (1953) recognised three types of deltas: (i) marine littoral deltas (MLDs), (ii) lacustrine Gilbert littoral deltas and (iii) submarine deltas (Figure 1). Conceptually, these three situations correspond to the three different behaviours for jet flows generated when the bulk density of the incoming jet is similar or differs with respect to that of the receiving standing body of water, defining pure jets (equal density), buoyant jets (lower density) and stratified jets (higher density). Although these categories of jet flows can happen also in sediment-free flows (i.e. due to differences in temperature or salinity), the most interesting situation occurs when incoming jet flows are sediment laden, since this sediment load (transported as bedload and suspended load) will be accumulated in deposits showing potentially distinctive characteristics and stacking patterns.

According to Bates (1953), MLDs (Figure 1A) form when a river discharges a fluid having a lower bulk density with respect to that of ocean waters ($\rho_r < \rho_w$), thus generating a hypopycnal flow (or buoyant jet). Due to the combined effect of flow unconfinement and friction with basin waters, the river flow velocity will be dramatically reduced at coastal areas resulting in a rapid decrease in flow capacity and competence. Consequently, coarse-grained sediments transported as bedload by the fluvial stream will be forced to accumulate at coastal areas forming a mouth bar (or delta front). In marine settings, the incoming freshwater, together with fine-grained materials transported in turbulent suspension (mainly silt-clay and eventually plant remains), commonly develops a buoyant jet (or buoyant plume), from where sediment fallout contributes to form prodelta deposits. In some settings, these buoyant jets can be deflected by coastal

TABLE 1 Some of the stratigraphic units and related delta systems considered in this paper.

				Delta types according to this work							
				Hypopycnal deltas				Hyperpycnal deltas			
Unit	Age	Basin	Country	BLD	MLD	HSLD	HOLD	HLD	HSD	HFD	References
Los Molles	Early-Middle Jurassic	Neuquen	Argentina					C	C	R	Almeida Junior et al. (2020)
Lajas	Middle Jurassic			C	C			C	C	R	Zavala and González (2001)
Challacó	Middle Jurassic			R				R	C		Zavala et al. (2020)
Lotena	Middle Jurassic				C			R	C		Zavala (2005)
Mulichinco	Early Cretaceous			C				C	C	R	Zavala (2000a)
Agrio	Early Cretaceous			?	?			C	C		Irastorza et al. (2021)
Centenario	Early Cretaceous			?				R	C		Iñigo et al. (2019)
Rayoso	Early Cretaceous			C		C		R	C		Zavala et al. (2006)
Springhill	Early Cretaceous	Austral			?				C		Schwarz et al. (2011)
Magallanes	Late Cretaceous				?			R	C		Buatois et al. (2011)
Cabo Viamonte beds	Miocene								C		Ponce and Carmona (2011)
La Lola	Ordovician	Ventania							C	R	Zavala et al. (2000)
Tunas	Permian			C				C	C		Zavala et al. (2019)
Rio Blanco	Triassic	Cuyo					C				Barredo and Sharkov (2012)
Carapebus	Miocene	Campos	Brazil		?				C		Machado et al. (2004)
Carbonera	Palaeogene	Eastern Llanos	Colombia		C				?		Torrado et al. (2020)
Guadalupe	Late Cretaceous				?				C		Martinez Aparicio et al. (2020)
Guarico	Eocene	Guarico	Venezuela		?				C	C	Arcuri and Zavala (2018)
Merecure	Miocene	Maturín			?				C		Zavala et al. (2011a)
Naricual	Oligocene				C					C	Zavala et al. (2011a)
Carapita	Miocene			?	C				C		Gamero et al. (2007)
Misoa	Eocene	Maracaibo			C			C	C		Gamero et al. (2005)
Carbonera	Eocene				C						Torrado et al. (2020)
Pampatar	Eocene	Tortuga-Blanquilla			?				C		Guzmán and Campos (2008)
Herrera	Miocene	Columbus	Trinidad & Tobago		?				C		Gamero et al. (2007)
Mayaro	Pliocene				?				C		Zavala and Arcuri (2016)
B4 S&stone	Pliocene				?				C		Gamero et al. (2011)

TABLE 1 (Continued)

Unit	Age	Basin	Country	Delta types according to this work							References
				Hypopycnal deltas				Hyperpycnal deltas			
				BLD	MLD	HSLD	HOLD	HLD	HSD	HFD	
Aliano	Pliocene-Pleistocene	Sant'Arcangelo	Italy	?					C		Zavala (2000b)
Achimov	Early Cretaceous	West Siberia	Russia	?					C		Zavala (2020)
Vikulovo	Early Cretaceous	West Siberia		?				C	R		Zavala et al. (2016)
Leushinska	Early Cretaceous	West Siberia		?				C	R		Zavala et al. (2016)
Bobrik	Carboniferous	Volga-Ural			C				C		Ulmishek (1988)
Nenjiang	Cretaceous	Songliao	China	C					C		Pan et al. (2017)
Yanchang	Triassic	Ordos		C			C	C	C		Zavala et al. (2022)

Abbreviations: BLD, Brackish littoral deltas; C, common; HFD, hyperpycnal fan deltas; HLD, hyperpycnal littoral deltas; HOLD, homopycnal littoral deltas; HSD, hyperpycnal subaqueous deltas; HSLD, hypersaline littoral deltas; MLD, marine littoral deltas; R, rare; ?, possible.

diffusion processes like tides, waves and longshore currents (Wright, 1977).

Gilbert deltas (Figure 1B) form when a river discharges a fluid having a similar bulk density with respect to that of the water in the basin ($\rho_r = \rho_w$), corresponding to a homopycnal flow generated by a pure jet flow (or fully turbulent jet, Wright, 1977). The typical situation of a homopycnal flow occurs when a clean-water bedload-dominated fluvial stream enters a freshwater lake. Because of its similar density, the incoming flow will be rapidly mixed with the ambient water at the river mouth (Wright, 1977), resulting in a drastic drop in flow velocity and related flow capacity/competence, forming a littoral deposit (mouth bar). In bedload-dominated rivers, clasts are forced to accumulate in the upper leeside of delta foresets, from where inertia-dominated gravity avalanches develop (Nemec, 1990). The result are steep littoral Gilbert deltas (Gilbert, 1885), which are very common in proglacial lakes.

Finally, submarine deltas (also called subaqueous deltas) form when a river discharges a fluid having a higher bulk density with respect to that of the water in the reservoir ($\rho_r > \rho_w$), resulting in a hyperpycnal flow (generated by a stratified jet flow). When this happens, the river discharge plunges in coastal areas and travels basinward as an extrabasinal (land-generated) turbidity current. Since rivers discharge freshwater, the flow bulk density can be only significantly increased by the excess of load provided by fine-grained sediments transported in turbulent suspension. According to Mulder and Syvitski (1995), a minimal concentration of 35 to 45 kg/m^3 of suspended sediment is required in a fluvial discharge to produce a hyperpycnal plume in normal-salinity marine settings. Nevertheless, this threshold can be substantially lowered in coastal areas having a high freshwater influx, resulting in marine brackish conditions (Bhattacharya & MacEachern, 2009). In the case of freshwater lakes, the required sediment concentration is very low, about 1 kg/m^3 (Mulder & Syvitski, 1995).

The three situations outlined by Bates (1953) represent just three possible conditions within a continuum. The bulk density of a river discharge can be highly variable depending on the size of the drainage network, climate, volume of available loose sediments, flood magnitude, flow duration and coastal relief (Zavala, 2020). In nature, the bulk density of a river discharge (ρr) can range from 998.20 kg/m^3 (for sediment-free freshwater at 20°C) up to more than 2153.20 kg/m^3 (for a 70% by volume in cohesive debris flows with sediments having an averaged density of 2.65 gr/cm^3, Zavala, 2020). On the other hand, the surface density of the receiving water body mainly depends on the water salinity and temperature, ranging from less than 1 PSU (Practical Salinity Units) in freshwater lakes up to more than 300 PSU for concentrated brines. Consequently, the final scenario

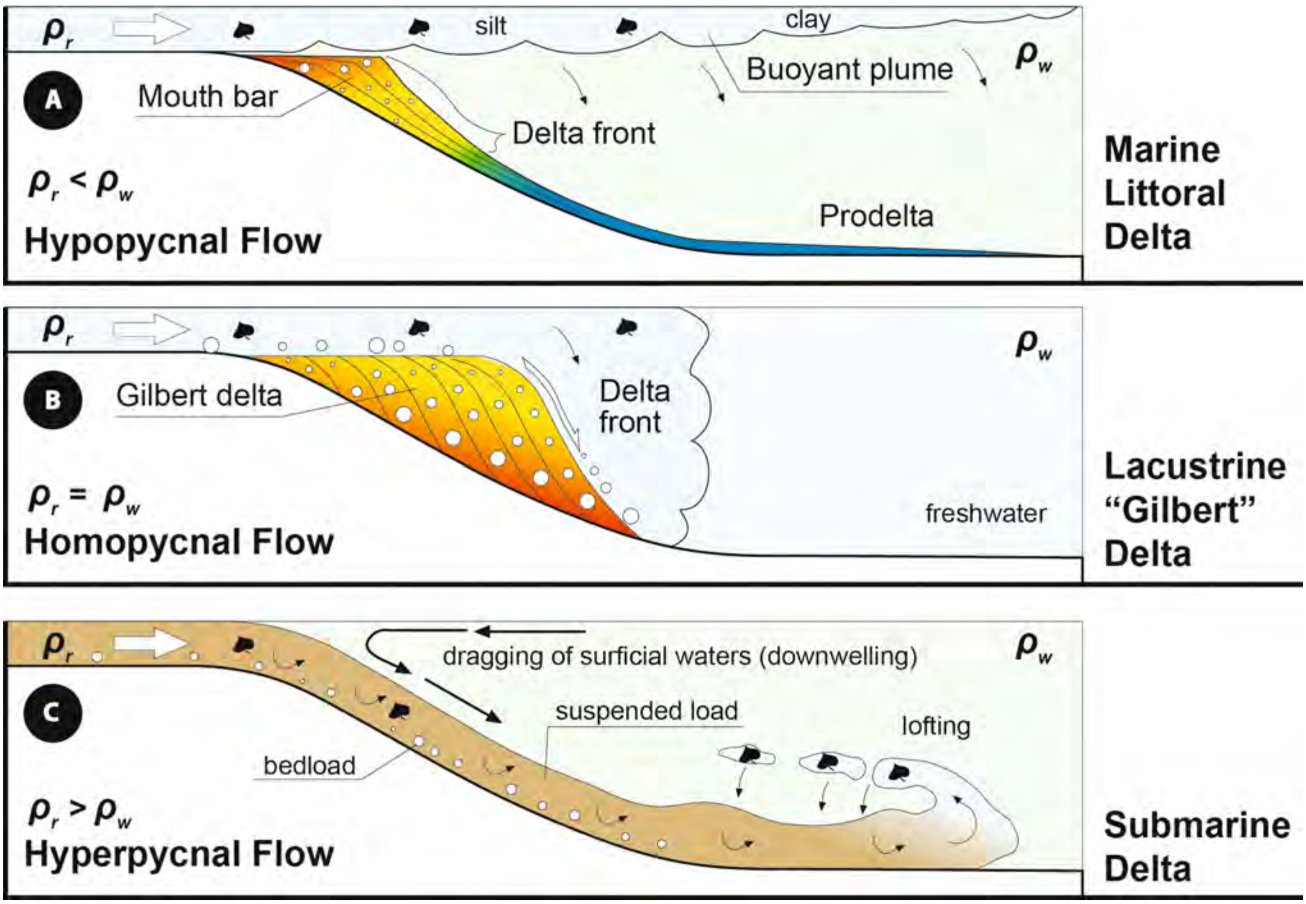

FIGURE 1 Three different delta types recognised by Bates (1953) according to the density contrast between an incoming fluid and the water in a reservoir. (A) Marine littoral deltas, generated by hypopycnal flows ($\rho_r < \rho_w$). (B) Lacustrine littoral 'Gilbert' deltas, generated by homopycnal flows ($\rho_r = \rho_w$). (C) Submarine deltas, generated by hyperpycnal flows ($\rho_r > \rho_w$). Modified after Zavala and Pan (2018). ρ_r = Bulk density of the river discharge. ρ_w = Density of the water in the reservoir.

for deltaic sedimentation will define multiple fields, allowing us to understand the origin of deltas and associated deposits from a more rational point of view.

Following Bates's concepts and fundamental understanding of jet flows (Jopling, 1963; Wright. 1977; Fischer et al., 1979; Kim, 2001; Hoyal et al., 2003; Winsemann et al., 2021), a new classification of deltas was recently proposed by Zavala et al. (2021). This delta classification is based on the different possible natural density contrasts existing between a land-generated density flow and the water in the receiving basin, and the characteristics of their related deposits. The most important aspect of this classification is that it can be applied to both present and ancient systems, since each delta type is characterised by a distinctive physical morphology, facies association, internal architecture and stacking pattern. The conceptual classification scheme is shown in Figure 2. The *X*-axis (in logarithmic scale) shows the range of salinities (in PSU) for lacustrine and marine basins (from freshwater lakes to brines close to saturation) and the range of water densities (ρ_w) considering the averaged marine salt composition at 20°C. Water densities have been calculated using the Oceanlife (2017) Water Salinity Converter. The common range of normal sea surface salinity is also indicated (ranging from 30 to 40 PSU according to the results of the Aquarius mission, NASA). The *Y*-axis (logarithmic scale) shows the different density flows produced by natural river discharges (Zavala, 2020), their corresponding sediment concentrations (kg/m^3) and flow bulk densities (ρ_r, considering a 20°C interstitial freshwater and an averaged sediment density of 2.65 gr/cm^3). The interaction between these two densities (incoming flow and basin water) allows the definition of three main fields for delta sedimentation (hypopycnal, homopycnal and hyperpycnal delta fields) and seven different delta types (Figure 2).

Some selected case examples of ancient systems (studied by the senior author during the last 30 years) are shown in Table 1 and were classified according to these new proposed delta categories. It should be addressed that a single river system can build different delta types over time, depending on the characteristics, dynamic and efficiency of the associated drainage network.

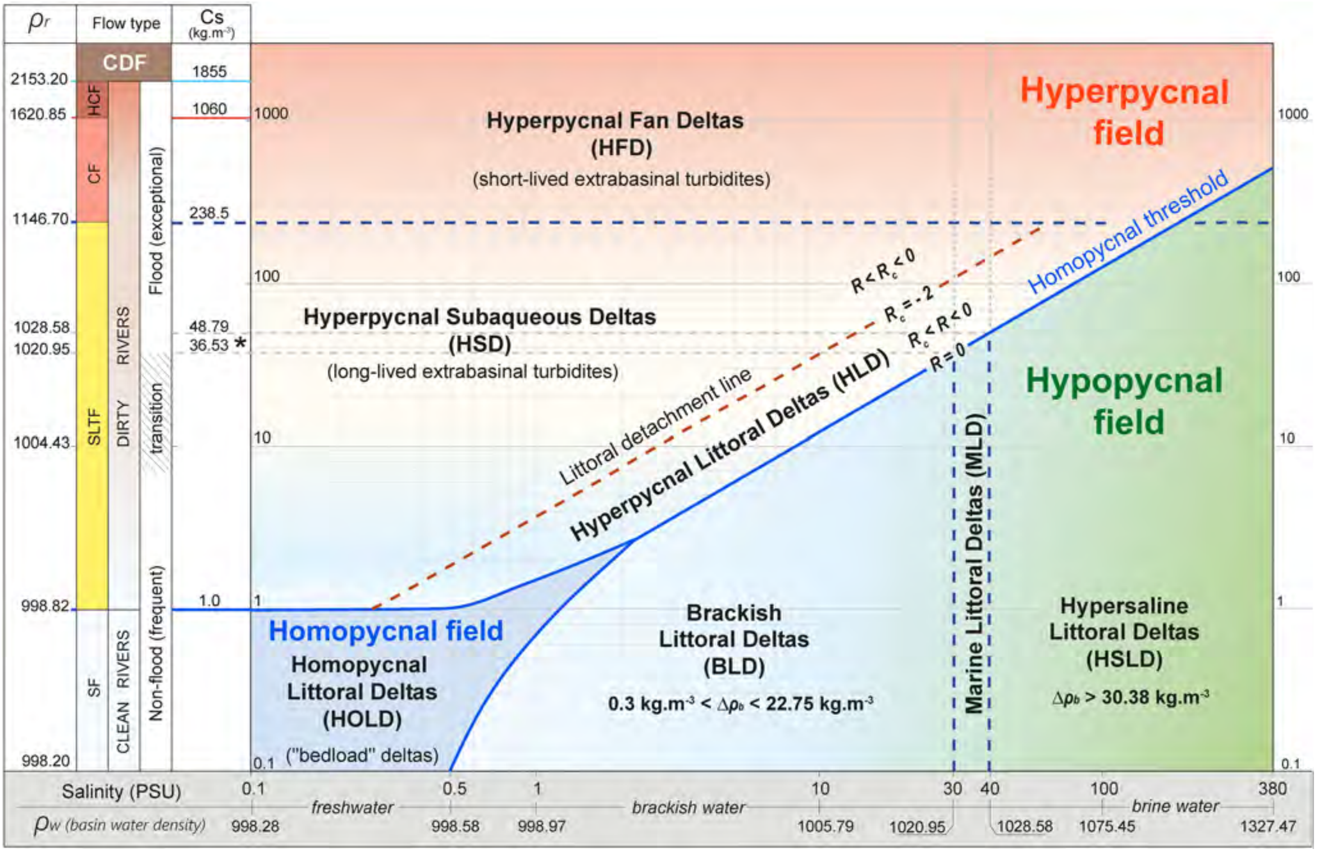

FIGURE 2 Classification of deltas expanding Bates's concepts of density contrast between the bulk density of the incoming flow and the density of water in the receiving basin. Three main fields are recognised, corresponding to hypopycnal, homopycnal and hyperpycnal delta fields. The hypopycnal delta field comprises brackish, marine and hypersaline littoral deltas. The homopycnal delta field includes homopycnal littoral deltas. Finally, the hyperpycnal delta field is integrated by hyperpycnal littoral deltas, hyperpycnal subaqueous deltas and hyperpycnal fan deltas. $\Delta\rho_b$, differential buoyancy. R = non-dimensional density parameter. R_c = critical value for a non-dimensional density parameter. *Critical range of necessary sediment concentration to produce a hyperpycnal flow in normal-salinity marine waters. After Zavala et al. (2021).

3.1 | Hypopycnal deltas

Hypopycnal deltas form when the bulk density of the incoming flow (ρ_r) is lower than the density of the water in the reservoir (ρ_w). All hypopycnal deltas constitute constructive littoral forms, since the incoming subaerial flow (due to its lower bulk density) is forced to stop at coastal areas (Wright, 1977). This results in the near-immediate accumulation at the shoreline of all sediments transported by the river as bedload, forming a mouth bar (also referred as delta front deposits). The characteristics of these mouth bar deposits will depend on the grain size of the sediments transported in bedload and on the interaction with coastal diffusion processes (Jopling, 1963; Galloway, 1975; Wright, 1977). The forced accumulation at the delta front often results in an unbalanced deposition and the construction of steep delta slopes, typically affected by gravity avalanches (Rajchl et al., 2008). In coarse-grained systems, these steep high gradient deltas (especially in fiords) have been wrongly termed as 'Gilbert deltas', based on the existence of large-scale foresets (Nemec, 1990; Longhitano, 2008). In fact, the term Gilbert deltas should be restricted only for those deltas originated by true homopycnal flows.

An important constituent of hypopycnal deltas is the prodelta. The prodelta is mainly composed of fine-grained materials carried as suspended load in the fluvial discharge, which are transported basinward by buoyant jets and related buoyant plumes. The capacity of coastal buoyant plumes for transporting suspended load sediments basinward will depend on the volume and grain size of the suspended sediments, and (fundamentally) on the differential buoyancy ($\Delta\rho_b$) provided by the negative density contrast between the incoming river water (ρ_{rw}) and the water in the receiving basin (ρ_w). The differential buoyancy $\Delta\rho_b$ is an indication of the suspended sediment load (kg/m^3) that the buoyant plume can sustain and is expressed by following Equation (1):

$$\Delta\rho_b = \rho_w - \rho_{rw}, \quad (1)$$

where ρ_w is the density of water in the receiving basin and ρ_{rw} the density of water (typically freshwater) in the fluvial discharge.

The $\Delta\rho_b$ is critical for the development (or not) of extensive sediment-laden buoyant plumes, which will effectively control the characteristics (extension, grain size and slope) of the associated prodelta deposits. In general, a high $\Delta\rho_b$ will be associated with extended prodeltas with near-flat slopes. In contrast, a low $\Delta\rho_b$ is characterised by narrow and steep prodelta slopes. The transport capacity of buoyant plumes progressively decreases from the river mouth, resulting in a basinward-graded profile primarily accumulated by fallout processes from the overflow (Scruton, 1960; Wright, 1977; Levy, 1981; Herut et al., 2002). The collapse of buoyant plume sediments along the prodelta slope can trigger muddy sediment gravity flows (also termed fluid mud flows, Kineke & Sternberg, 1995), which constitute an alternative origin of intrabasinal turbidites (Parsons et al., 2001; Zavala & Arcuri, 2016; Hage et al., 2019).

A common characteristic of most hypopycnal littoral delta deposits is the accumulation of progradational metre-thick coarsening-upward and thickening-upward successions (Wright, 1978; Coleman & Prior, 1982; Allen & Mercier, 1987; Gani & Bhattacharya, 2005; Bhattacharya, 2006; Bhattacharya & MacEachern, 2009). This coarsening-upward trend is the result of the vertical stacking of an energy-increasing succession (from offshore-prodelta to upper delta front) as the mouth bar progrades due to the limited accommodation available at coastal areas with a near-stable water level. An exception happens in coarse-grained bedload-dominated hypopycnal deltas, affected by gravity (inertia dominated) avalanches along steep-slope delta fronts. In this context, inertial flows transport the coarsest fraction towards the lower slope, commonly resulting in fining-upward delta front successions (Larsen & Crossey, 1996; Kleinhans, 2005; Longhitano, 2008; Winsemann et al., 2018).

Hypopycnal littoral deltas are typically point sourced, since coarse-grained sediments transported by bedload are physically attached to the river mouth, forming the mouth bar (delta front and delta plain). The local accumulation of sediments at the river mouth often results in unbalanced sedimentation in coastal areas, which are commonly characterised by limited accommodation. In this situation, the littoral delta system is forced to manage the accommodation to store the sediments, commonly resulting in the lateral shift of delta lobes (Frazier, 1967; Figure 3).

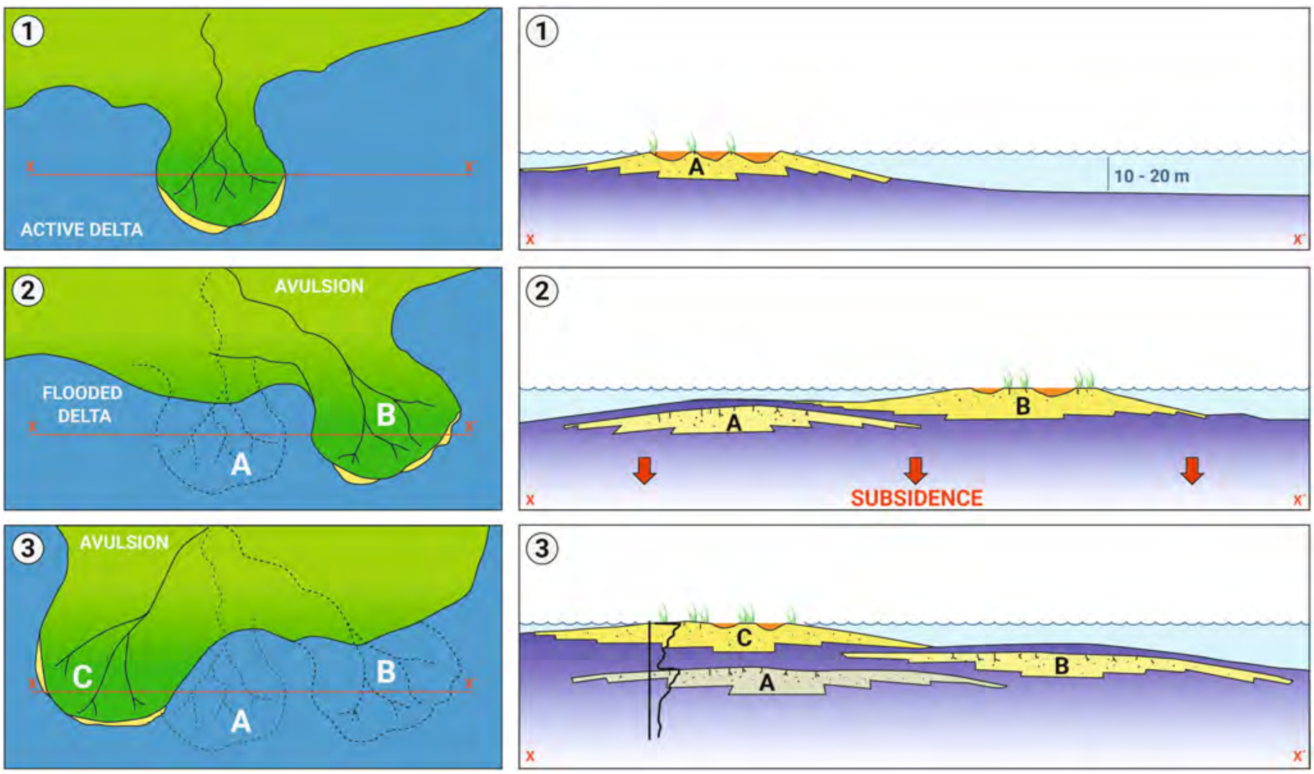

FIGURE 3 Lateral shift (autocyclic control) in littoral delta successions (from 1 to 3). Changes in the local rate of sediment supply from a point source (river) result in a differential progradation. The interplay between sediment supply, subsidence and accommodation space allows the accumulation of metre-thick coarsening and thickening-upward cycles. Since progradation is gradual and avulsion is near instantaneous, these autocyclic progradational facies successions are sharply bounded. Palaeosols with root traces and coal deposits are common at the top of the delta front, corresponding to delta plain deposits.

The lateral shift of delta fronts was documented in detail by the pioneering work of Kolb and Van Lopik (1958) in recent Mississippi delta deposits. The stacking of these coarsening-upward littoral mouth bar deposits is controlled by autocyclic processes (Beerbower, 1964) generating small-scale progradational facies successions (3 in Figure 3) bounded by local relative flooding surfaces (Allen & Mercier, 1987). These sharp-bounded coarsening and thickening-upward successions originate because the gradual progradation of littoral deltas is punctuated by a near-instantaneous river avulsion.

The coastal characteristics of hypopycnal littoral deltas allow the common preservation of delta plain and associated distributary channel-fill deposits at the top of progradational prodelta–delta front successions. Nevertheless, the long-term preservation of delta plain and distributary channel deposits will depend on regional subsidence, since delta plain areas are essentially bypass (transfer) areas that connect the fluvial system with the coeval delta front. Typical delta plain deposits include thin sandstone and mudstone levels with rooted intervals and coal beds. The existence of delta plain deposits at the top of progradational delta front successions is a distinctive characteristic that allows a clear differentiation of hypopycnal littoral deltas from hyperpycnal littoral deltas (HLD's, see later), which commonly lack delta plain deposits due to their extreme basinward extension. Figure 4 provides an example of a detailed subsurface correlation showing internal facies changes in MLD's from the Bobrik Formation (Carboniferous) in the Volga-Ural Basin, Russia (Table 1). At marginal positions (wells 1, 2 and 3 in Figure 4), these metre-thick progradational successions end with rooted/coal levels from the delta plain (Figure 5D). At inner basin positions (wells 4, 5 and 6 in Figure 4), these littoral deltas grade into massive sandstone lobes, related to hyperpycnal subaqueous deltas (HSDs, see later). The internal stacking of a littoral delta succession from the Bobrik Formation can be seen in Figure 5, together with some examples of their constituent facies. These deposits form metre-thick progradational facies successions starting with massive to laminated shale from the offshore-prodelta (Figure 5A), sometimes showing hyperpycnal channel/lobe deposits (subaqueous deltas). The succession continues with heteroliths showing a progressive increase in sandstone content, accumulated in a prodelta to lower delta front setting (Figure 5B). The upper interval is dominated by laminated to cross-bedded sandstones (Figure 5C) from the upper delta front. The succession commonly ends with clay-rich sandstones with root traces (Figure 5C) and coal intervals, indicating an accumulation in a delta plain setting. Due to delta shifts (by distributary channels avulsion), this deltaic succession is sharply overlain by offshore mudstones from the next succession (Figure 5C). As previously discussed, the existence of delta plain (subaerial) deposits at the top of progradational facies successions is considered a diagnostic characteristic that allow the recognition of hypopycnal littoral delta deposits, since it documents deposition very close to the shoreline.

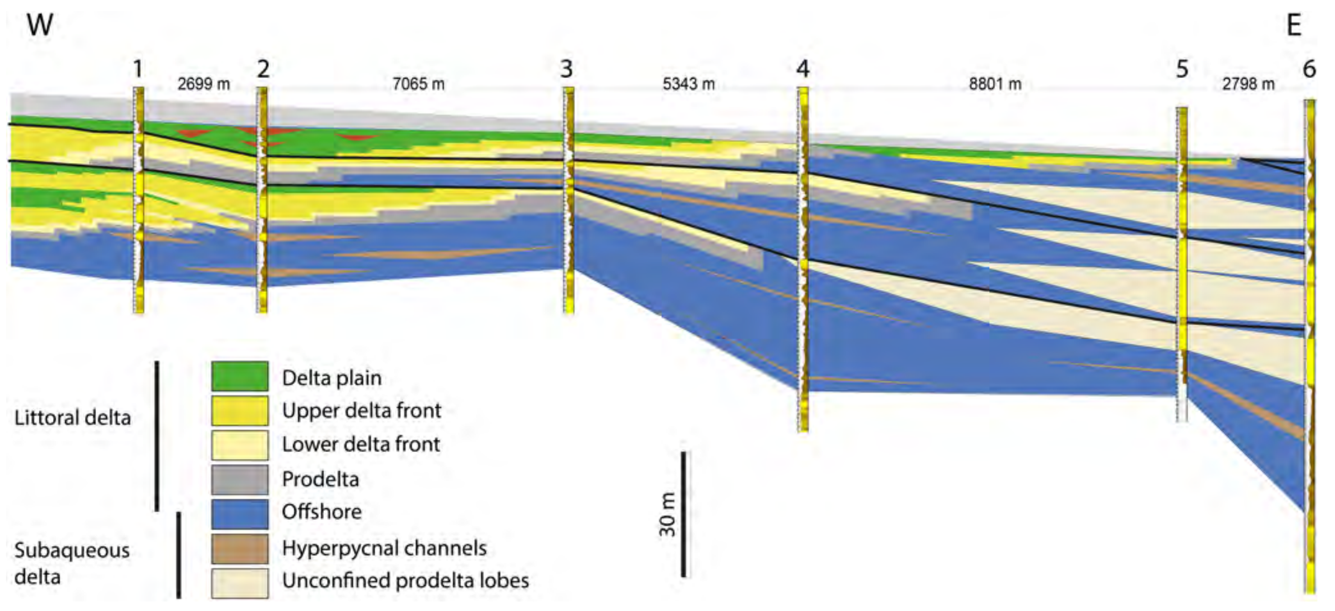

FIGURE 4 Detailed cross-section of delta deposits from the Bobrik Formation (Lower Carboniferous) along 26.7 km. Note the coarsening-upward stacking of littoral delta deposits and the overall deltaic progradation towards the east. These littoral delta deposits have related massive sandstone beds (shelfal sandstone lobes) basinward, which correspond to hyperpycnal subaqueous delta deposits. West Saneco field, Volga-Ural Basin, Russia.

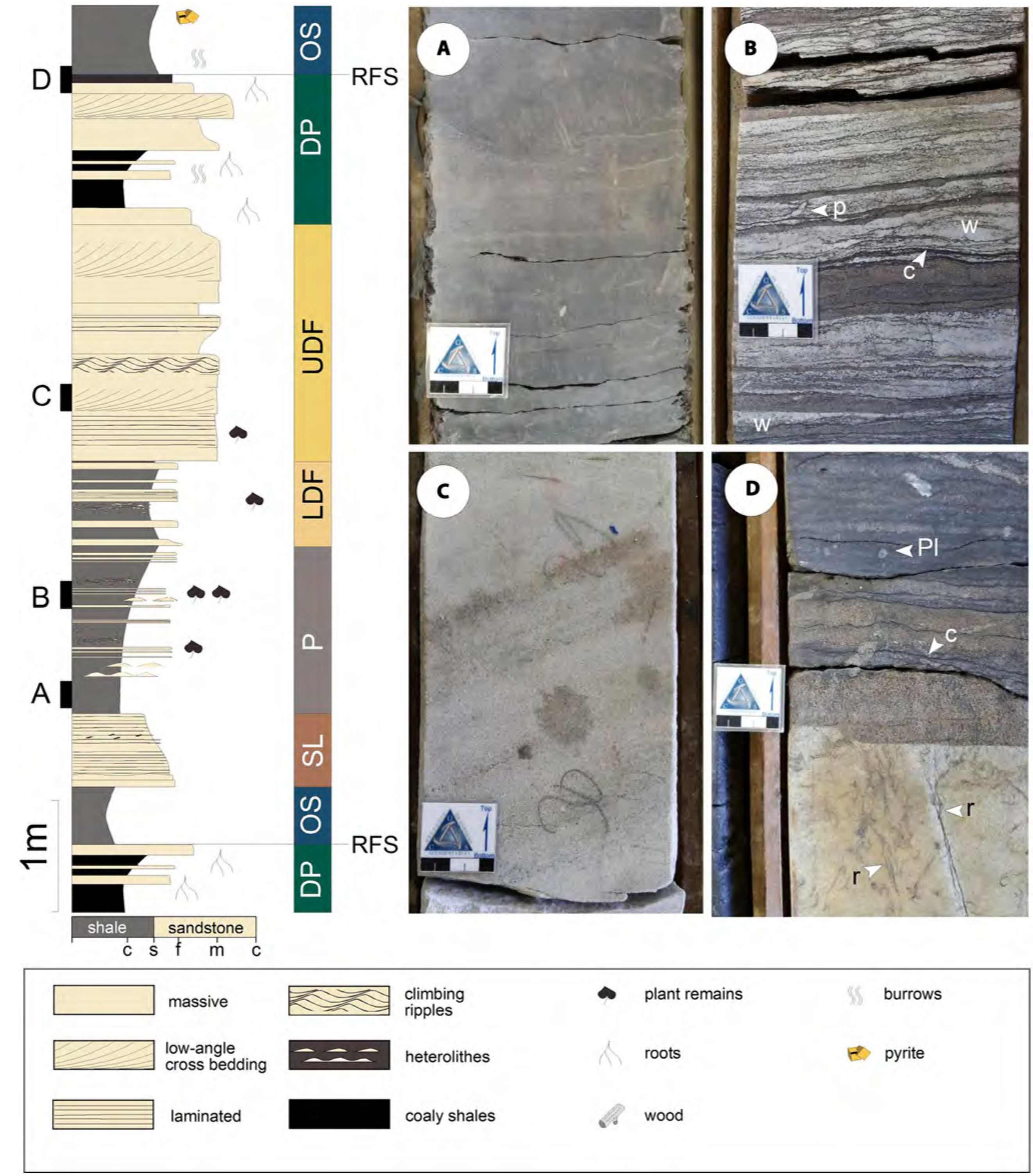

FIGURE 5 A typical coarsening-upward facies succession recognised in marine littoral delta deposits from the Bobrik Formation (Lower Carboniferous) in the Saneco field, Volga-Ural Basin, Russia. The letters on the left show the location of the selected examples. These small-scale progradational facies successions are controlled by autocyclic processes related to the lateral shift of marine littoral deltas. (A) Massive shales from offshore-prodelta setting. (B) Fine-grained heteroliths ('prodelta rhythmites') with abundant plant remains from the prodelta–lower delta front transition. Note the wave bedding (w), carbonaceous remains (c) and *Palaeophycus* burrows. (C) Cross-bedded sandstones from the upper delta front. (D) Detail of the boundary between a delta plain rooted (r) interval followed by carbonaceous (c) muddy sandstones sharply flooded by offshore shales. Note some *Planolites* burrows (Pl) in the offshore shales. Os, offshore; SL, shelfal lobes; P, prodelta; LDF, lower delta front; UDF, upper delta front; DP, delta plain; RFS, relative flooding surface.

The characteristics and geometry (depositional slope) of delta front and prodelta deposits in hypopycnal deltas will depend on the basin physiography, magnitude and duration of the associated discharge, grain size of the river-supplied sediments, basin diffusion processes and $\Delta\rho_b$ (differential buoyancy). According to the magnitude of this differential buoyancy, three categories of hypopycnal deltas (Zavala et al., 2021) are recognised (Figures 2 and 6): (i) hypersaline littoral deltas (HSLDs), (ii) MLDs and (iii) brackish littoral deltas (BLDs).

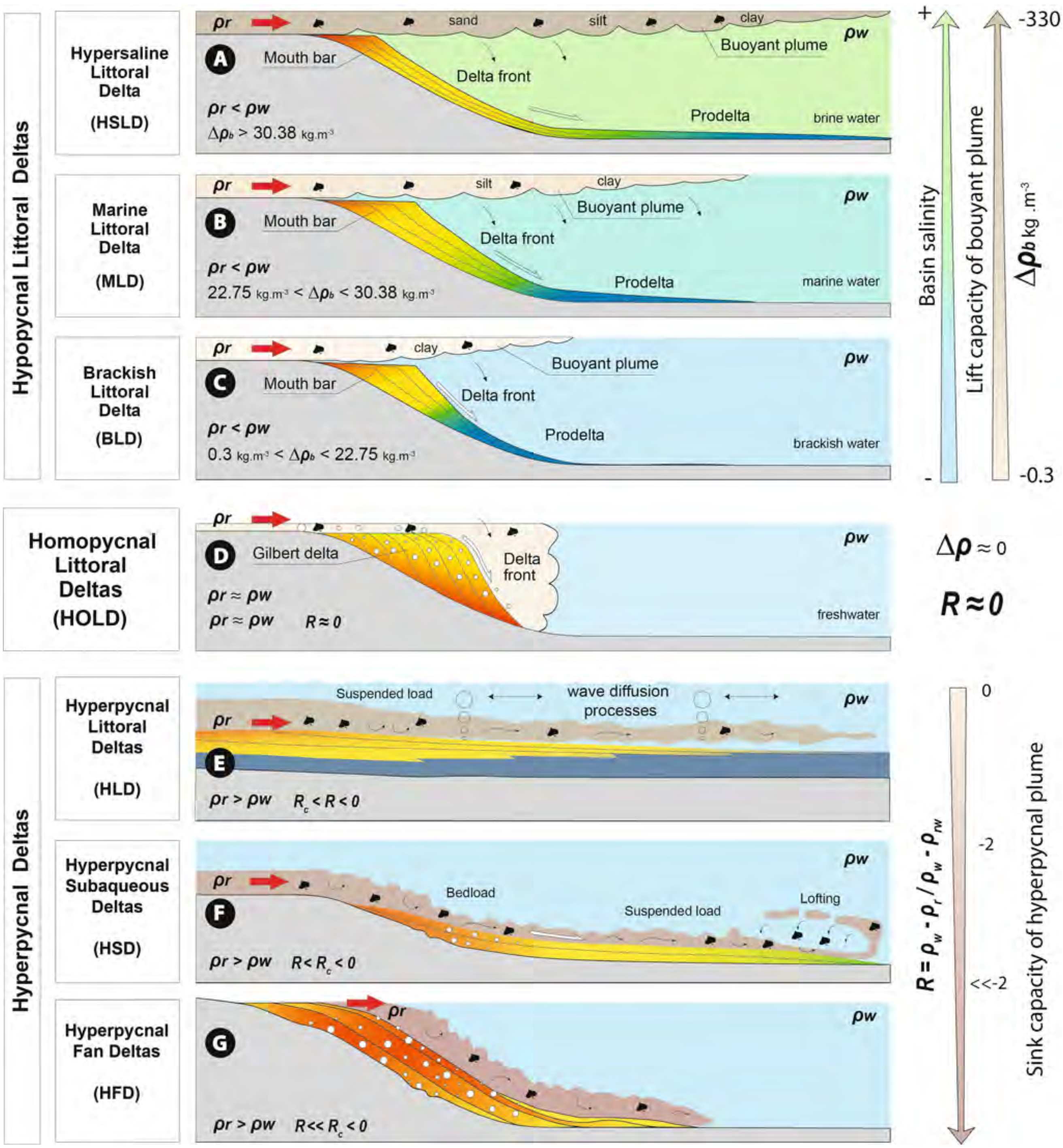

FIGURE 6 Diagram showing the seven different categories of deltas proposed in Zavala et al. (2021), which are controlled by the interplay between the density of the water within the basin and the bulk density of the incoming fluvial discharge. Modified from Zavala et al. (2021).

3.1.1 | Hypersaline littoral deltas

Hypersaline littoral deltas are associated with underfilled hypersaline lakes and partially closed hypersaline seas (Figures 2 and 6A). These deltas are rare, since one of the characteristics of hypersaline basins is a negative water balance (associated with a low run-off) that favours salt concentration due to an intense evaporation mainly in tropical and subtropical areas. The HSLDs have a high $\Delta\rho_b$ (typically higher than 30.38 kg/m^3) allowing the development of extensive buoyant jets and plumes during river discharges that can transport basinward relatively coarse-grained suspended materials (up to fine-grained to medium-grained sands).

The excess buoyancy provided by the high $\Delta\rho_b$ allows for the transfer of part of the river's momentum to the overflow, resulting in narrow and elongated buoyant plumes (Figure 7). The ability to transport these relatively coarse-grained materials along the buoyant plume will depend on how far the buoyant jet flow can be maintained. Consequently, lower delta front and prodelta deposits will be dominated by sediments accumulated by fallout processes (mainly composed of prodelta rhythmites), resulting in very gentle delta slopes (Figure 6A). In the Lower Cretaceous Rayoso Formation (Zavala et al., 2006; Table 1), prodelta rhythmites are interbedded with hypersaline lacustrine deposits like stromatolites, chicken-wire gypsum and halite.

Recently, Lu et al. (2022) described and analysed in detail a 457 m core (ICDP Core 5017-1) drilled in the Dead Sea. With an actual water density of 1240 kg/m^3, the Dead Sea is the largest and deepest hypersaline lake on Earth. This core is located about 30 km away from the present Jordan River and was drilled under a water depth of 297.5 m during 2010–2011. From the core analysis, these authors propose two different depositional scenarios related to glacial and interglacial periods that deeply influenced the lake dimensions and salinity. During glacial periods, the lake-level rose and lake water salinity was reduced to around 70 to 130 PSU (Torfstein, 2019) favouring the development of hyperpycnal flows and related turbidites during sediment-laden floods. In contrast, during interglacial periods the salinity increased up to 300 PSU, allowing buoyant plumes to transfer suspended sediments more than 30 km basinward (Lu et al., 2022), which were accumulated by fallout processes as graded beds. During these hypersaline conditions, hyperpycnal discharges are extremely rare. One of the consequences of having these sediment-laden overflows is the construction of an extended and gentle prodelta area.

Since hypersaline basins are typically developed on underfilled (closed) lakes, the lake level is commonly highly variable depending on the water balance. Consequently, large fluvial discharges can cause not only a progressive dilution of basin waters but also an overall lake-level rise increasing basin accommodation and resulting in transgressive (retrogradational) littoral delta deposits, with stacking patterns that can depart from classical coarsening-upward successions.

3.1.2 | Marine littoral deltas

Marine littoral deltas (Figure 1A, see also Figures 2 and 6B) are the best-known type of littoral deltas. According to the dominant marine diffusion process recognised in coastal areas, MLDs have been classified by Galloway (1975) into three categories: fluvial-dominated, wave-dominated and tide-dominated deltas. This classification scheme was later expanded by Orton and Reading (1993), who added the overall grain size of the

FIGURE 7 Buoyant plume of the Jordan River over the Dead Sea: Note that, because of the excess of buoyancy induced by the high $\Delta\rho_b$, part of the river momentum is transferred to the overflow, resulting in a narrow and elongated buoyant plume. Image from Google Earth, June 2019.

sediments. The high-density contrast between marine waters and incoming freshwater results in a $\Delta\rho_b$ ranging between 22.75 and 30.38 kg/m^3. Consequently, fine silt and clay materials (and even plant debris) transported as suspended load often form part of buoyant jets (buoyant plumes). The collapse of these sediments (through flocculation and suspension fallout 'rain') results in the accumulation of well-developed laminated and graded prodelta deposits (Nemec et al., 1995) or 'prodelta rhythmites' (Figure 5B). Due to the small volume and grain size of the sediments carried in the buoyant plume, the slope of the delta front–prodelta transition in MLDs tends to be steeper than in HSLDs. In shelf margin deltas (Porębski & Steel, 2003), prodelta slopes can dramatically increase, favouring sediment failures and avalanches (Plink-Björklund & Steel, 2005). Coarse-grained MLDs are also termed 'fan deltas', due to the centripetal distribution of coarse-grained sediments from the feeder channel. These subaerial-littoral fan-deltas are mainly built by clean-water river discharges, where sediments are mainly transported as bedload. The last results in steep delta fronts commonly affected by gravity avalanches. These MLDs are often wrongly termed 'marine Gilbert-type deltas' (Colella, 1988; Falk & Dorsey, 1998), and confused with the true Gilbert deltas, related to homopycnal flows in freshwater lakes.

3.1.3 | Brackish littoral deltas

These deltas are commonly developed in underfilled/balanced filled lakes and partially closed (inland or epicontinental) marine basins with reduced salinity due to a limited connection with the open sea and an important influx of freshwater (Figures 2 and 6C). In BLDs, the $\Delta\rho_b$ is low (typically ranging between 0.3 and 22.75 kg/m^3), allowing only the existence of weak and diluted buoyant plumes. These deltas form at the mouth of bedload-dominated rivers with limited suspended load. Prodelta deposits are poorly developed and dominantly composed of clay levels with plant debris. The dominant accumulation of coarse-grained sediments at the upper delta front produces an unbalanced sedimentation that often results in steep delta front deposits affected by frequent gravity avalanches.

One of the best actual examples of a marine brackish basin (epicontinental sea) is the Baltic Sea. The poor connection of the Baltic Sea with open ocean waters results in a low salinity that can highly fluctuate due to the freshwater influx by seasonal run-off. As an example, the salinity in the Baltic Sea can be very variable, from 13 PSU at the bottom in the central Baltic, up to 2 PSU at the surface in the Bothnian Bay (Kniebusch et al., 2019). An example of a recent BLD is the Vistula Delta located at the Polish coast (Mojski & Kawińska, 1995) in the Baltic Sea. This small BLD is wave dominated and is characterised by a steep delta front slope.

Another excellent example of a brackish sea with an associated BLD is located in the Black Sea. Black Sea waters are characterised by a marked salinity stratification. In the upper 50 to 90 m of the water column, the salinity is relatively low (mean annual value between 17 and 20 PSU) due to the high freshwater influx, estimated at 350 km^3/year (Giosan et al., 2005). In contrast, below 90 m the salinity is similar to that of the Mediterranean, about 39 PSU (Mertens et al., 2012). The main fluvial delta entering the Black Sea is the Danube River, which supplies about 77% of the total fluvial input with a very low averaged suspended sediment concentration (0.3 kg m^{-3}, Mulder & Syvitski, 1995). In the present conditions, the Danube delta is a wave-dominated BLD and is characterised by a relatively steep delta front resulting from a weak buoyant plume (Giosan et al., 2005). In the geological past, the Danube River also formed HLDs and HSDs, as evidenced by the existence of an associated extended shelf and submarine canyon (Popescu et al., 2004).

Some beautiful examples of fossil BLD's were provided by Gani and Bhattacharya (2005) in their seminal paper. In this contribution, it is interpreted that the steep deltas from the Cretaceous Ferron Sandstone (Utah) illustrated in their fig. 4, and that from the Upper Cretaceous Frontier Formation (Wyoming) shown in their fig. 5 correspond to BLDs developed at marginal positions of the Cretaceous seaway of the North America brackish sea (Bhattacharya & MacEachern, 2009).

Brackish littoral deltas are very sensitive to variations in the bulk density of the related river discharge. The incoming flow can easily go hyperpycnal if the sediment concentration increases seasonally, thus transforming BLDs into hyperpycnal (ramp) littoral deltas. As an example, the salinity of the Rio de la Plata Estuary in Argentina is very low, remaining below 10 PSU 100 km away from the present mouth of the Parana River (Fossati et al., 2014; Moreira & Simionato, 2019). The high suspended load supplied by the Parana River (about 160 million tons year^{-1} of fine-grained sand, silt and clay) does not allow the construction of a BLD, but an extended shallow ramp related to a HLD system.

3.2 | Homopycnal deltas

Homopycnal deltas form when the bulk density of the incoming flow is similar to that of the water in the receiving basin (Figures 2 and 6D). This condition restricts the existence of homopycnal littoral deltas (HOLDs) to clean bedload-dominated rivers entering freshwater lakes (Bates, 1953). Bedload sediments are transported by shear forces at the base of the streamflow until reaching the river mouth. At this point, the flow slows down due to the loss of confinement, and sediments transported as bedload are forced to accumulate at the upper delta front (Gruszka & Zieliński, 2021). This unbalanced sedimentation often results in the periodical collapse of previously accumulated sediments in a series of gravitational avalanches produced when the critical depositional slope angle is exceeded at the upper delta front (Winsemann et al., 2018). The characteristics of homopycnal deltas will depend on the grain size of the associated bedload and the critical slope to produce a gravity instability at the depositional slope. Coarse-grained (gravelly) homopycnal deltas are steeper, and are dominated by sediment avalanches at the delta front. These avalanches are essentially inertia flows, where the coarsest-grained sediments travel at the front of the flow (Nemec, 1990). Consequently, gravely homopycnal delta deposits are the only type of littoral delta capable of building fining-upward successions (Flores, 1990). Fine-grained fallout-generated prodelta deposits, very common in hypopycnal deltas, are absent in HOLDs, since these deltas lack buoyant plumes due to their equal density conditions. In consequence, in gravelly homopycnal deltas, prodelta deposits are coarse grained, and often composed of resedimented deposits or hyperpycnal fan deltas (HFDs) generated during extreme floods when the density threshold is exceeded. The better known examples of HOLDs are Gilbert deltas (Gilbert, 1885; Gruszka & Zieliński, 2021), which are gravelly littoral deltas mostly developed on proglacial lakes. The progradation of Gilbert deltas over poorly developed prodelta deposits can result in very high and steep delta foresets (Kleinhans, 2005). Some beautiful examples of recent Gilbert deltas with exposed steep foresets were documented by Bell (2009) in the balanced-fill General Carrera Lake, southern Chile.

The development of homopycnal Gilbert deltas in non-freshwater lakes is almost impossible since it will require a critical balance of suspended sediment concentration to be maintained in the fluvial discharge to achieve exactly the same density to that of the water in the receiving basin. Nevertheless, in some contributions, the term 'Gilbert deltas' has been wrongly extended to denote steep gravelly fan deltas in marine settings (Postma & Roep, 1985; Colella et al., 1987; Breda et al., 2007; Longhitano, 2008), which in fact represent coarse-grained MLDs related to hypopycnal rather than homopycnal conditions. These steep gravelly marine fan deltas are originated by bedload-dominated hypopycnal river discharges, where sediments are widely distributed from the river mouth by debris flows (avalanches) and intrabasinal turbidity currents generated by slope instability (Orton & Reading, 1993).

In the overfilled interval of the Upper Triassic Yanchang Formation in Ordos Basin (Zavala et al., 2022), sandy HOLDs are common (Figure 8). These deltas are characterised by relatively steep delta fronts with well-defined clinoforms that pass from upper to lower delta front. The rapid

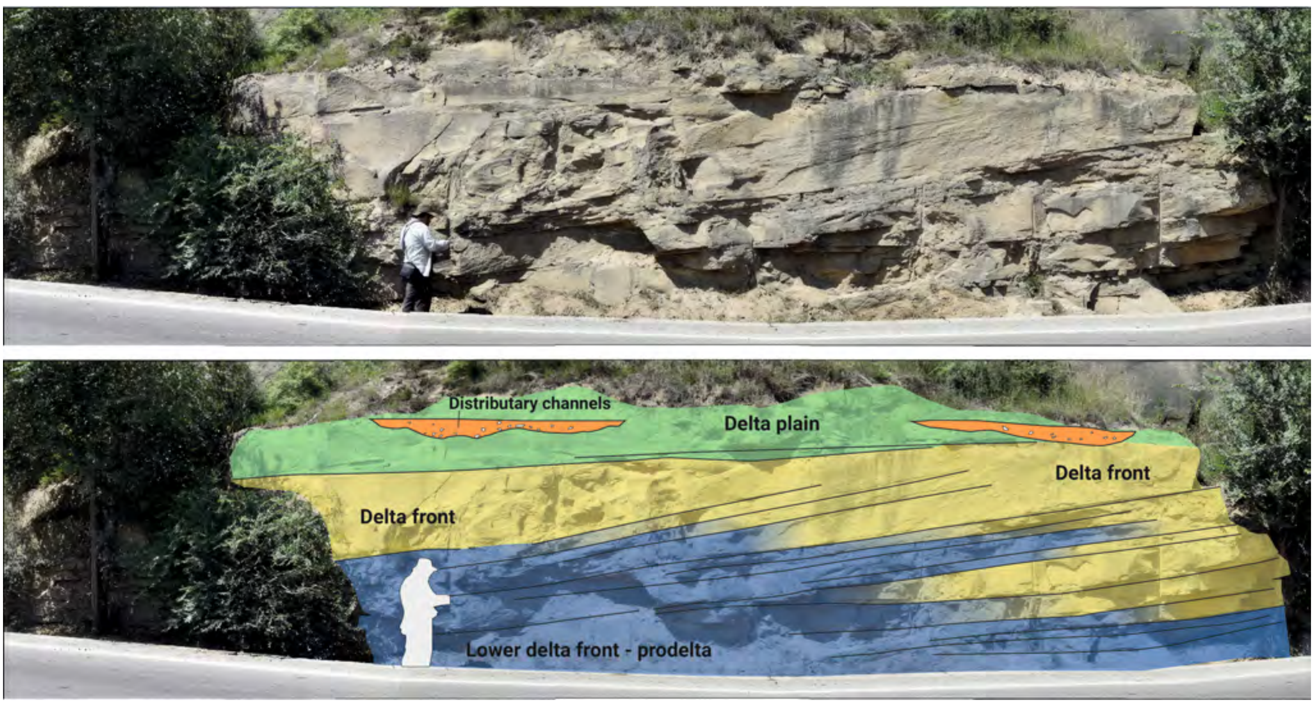

FIGURE 8 Example of homopycnal littoral deltas from the overfilled stage of the Yanchang Lake. Upper Triassic Yanchang Formation, Ordos Basin, China. Note the relatively steep delta slope and the rapid facies change between upper (yellow) and lower (blue) delta front facies. Chang 3 member near Xizhencun.

facies change observed in the outcrop is a consequence of the drastic deceleration of the river flow when entering the lake that forces the accumulation of sandy materials transported by shear at the base of the stream flow. The rapid accumulation results in massive, laminated and (climbing) rippled sandstones, marking the transition from upper to lower delta front (Figure 8).

Another excellent example of sandy HOLDs is present in the Triassic (Norian) lacustrine overfilled section of the Cacheuta depocenter, Cuyo Basin, Argentina (Figure 9). These deposits belong to the Rio Blanco Formation and are composed of relatively steep (*ca* 13°) delta foresets showing a rapid facies change along short distances between cross-bedded and rippled medium to fine-grained sandstones. Homopycnal littoral deltas represent a critical equilibrium condition that can be easily broken when rivers increase the suspended sediment load during floods, allowing the system to become hyperpycnal.

3.3 | Hyperpycnal deltas

Hyperpycnal deltas (Figure 1C) form when the bulk density of the incoming river flow (ρ_r) is higher than the density of the water in the reservoir (ρ_w). The excess of density provided by the suspended load results in a negative differential density ($\Delta\rho_s$) that forces the flow to sink below basin waters at coastal areas (Mulder & Syvitski, 1995; Mulder et al., 2003). This $\Delta\rho_s$ is equivalent to the fractional density difference (R_t or $\Delta\rho/\rho$) used in the analysis of jet flows (Cantelli et al., 2008). The value of this differential density depends on the contrast between the sediment concentration of the incoming flow (typically ranging from sediment-laden turbulent flows up to cohesive debris flows; Zavala, 2020) and the density of the water in the reservoir (Figure 2), which mainly depends on the salinity. This differential density can be calculated by following Equation (2):

$$\Delta\rho_s = \rho_r - \rho_w, \tag{2}$$

where ρ_r is the bulk density of the fluvial discharge, and ρ_w is the density of water in the reservoir.

$\Delta\rho_s$ represents the relative load of the incoming flow and potentially controls the effectiveness of shear forces and finally the erosional capacity of stratified jet flows associated with hyperpycnal discharges. In stratified jets (having a high bulk density with respect to that of ambient water) composed of a light interstitial fluid with an excess

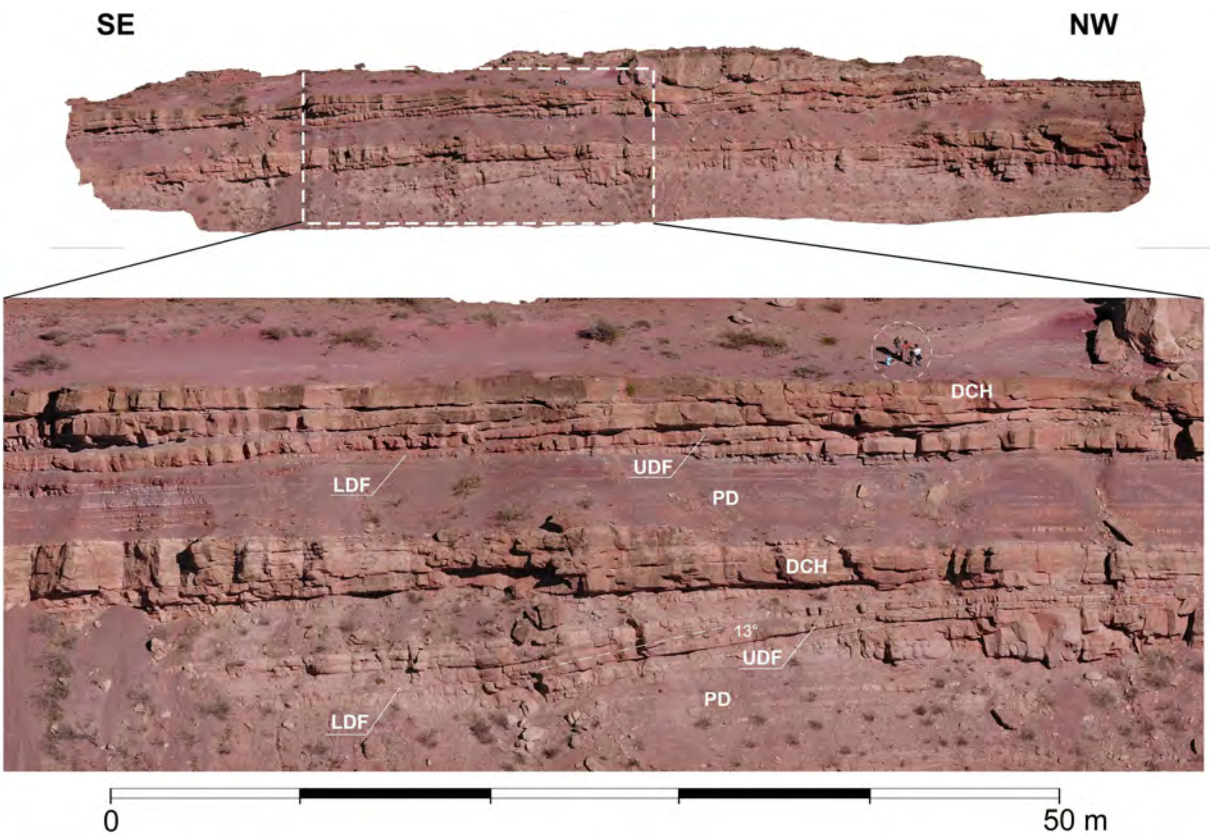

FIGURE 9 Two sets of stacked homopycnal littoral deltas from the Upper Triassic Rio Blanco Formation, Cuyo Basin, Argentina. Note the steep delta front (*ca* 13°) and the rapid facies change. Encircled persons for scale. Cerro Cocodrilo section, near Potrerillos, Mendoza. PD, Prodelta; LDF, lower delta front; UDF, upper delta front; DCH, distributary channels.

of load provided by suspended particles, the progressive loss of weight produced by the settling of part of the suspended load can result in a flow density reversal or 'lofting' (Simpson, 1982; Sparks et al., 1993; Zavala et al., 2008; Pritchard & Gladstone, 2009). The density contrast between the incoming jet flow and the receiving water body was discussed by Turner and Huppert (1992) and Kim (2001), who introduced a non-dimensional density parameter R. The rheological significance of this parameter is similar to that of the $\Delta\rho_s$ since it provides an indication of the relative load of the incoming flow. The main difference is that the R parameter is non-dimensional and takes into consideration the buoyant effect of the incoming freshwater contained in the fluvial discharge. The density parameter R is expressed by following Equation (3):

$$R = \frac{\rho_w - \rho_r}{\rho_w - \rho_{rw}}, \tag{3}$$

where ρ_w is the density of water in the receiving basin, ρ_r the bulk density of the fluvial discharge and ρ_{rw} the density of the water in the fluvial discharge.

In sediment-laden jets, $R<0$. In this situation, a critical value R_c was proposed, which separates light plunging jets ($R_c<R<0$) from heavy plunging jets ($R<R_c<0$). In light plunging jets, the flow originally plunges, but the density difference between the incoming flow and the reservoir water is not enough to allow substantial shear and erosion at the flow bottom (Figure 10A). This small density contrast makes the suspended cloud easy to maintain by normal marine diffusion processes (like tides,

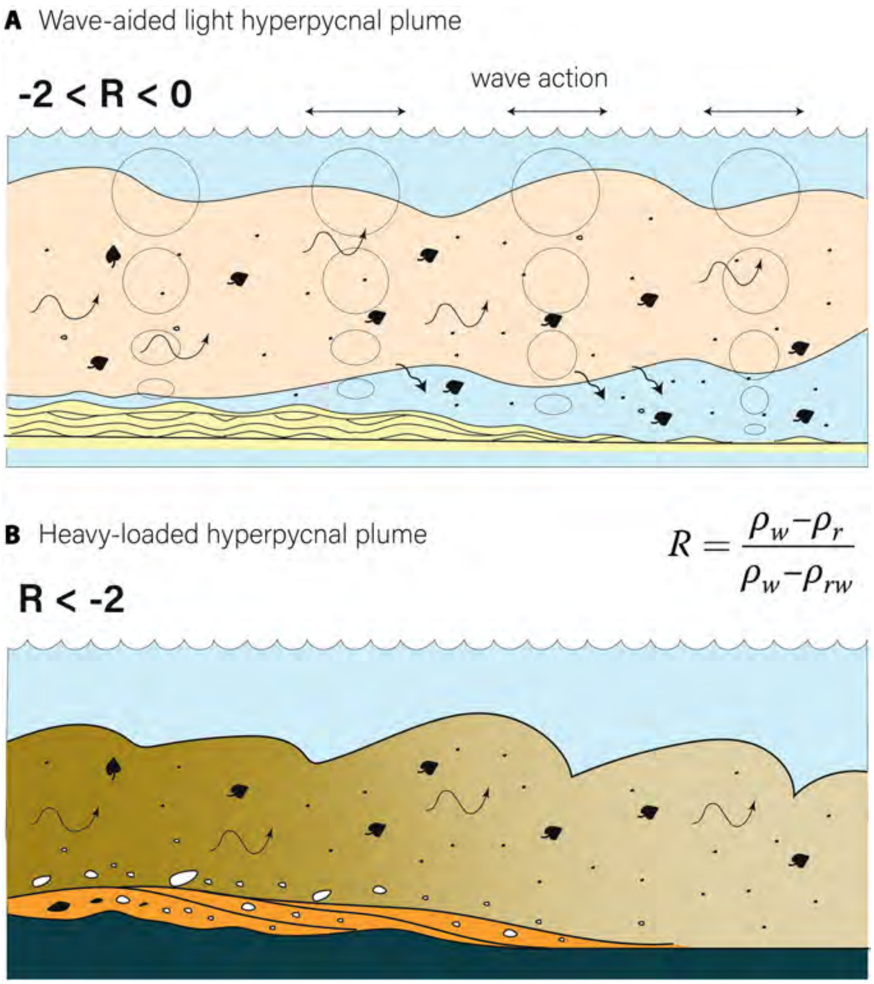

FIGURE 10 Diagram showing some contrasting characteristics between light (R_c −2 < 0) and heavy-loaded (R_c < −2) hyperpycnal plumes. (A) Light hyperpycnal plumes can only transport fine-grained (sand-silt) sediments in turbulent suspension for long distances aided by waves, tides and ocean currents. The resulting deposit is often dominated by sedimentary features associated with the dominant diffusion process (e.g. truncated wave bedding or even tidal bundles) and consequently its origin can be commonly misinterpreted. A key element for recognising its deltaic origin is the presence of plant remains that suggest a direct supply from an extrabasinal source (river). (B) Due to its high excess load, heavy-loaded hyperpycnal plumes can travel attached to the basin floor for large distances, locally eroding the bottom and transporting intrabasinal and extrabasinal bedload. The facies tract resulting from heavy-loaded hyperpycnal plumes was discussed in Zavala et al. (2011a).

waves and ocean currents). In contrast, heavy plunging jets (Figure 10B) are denser and can interact with the flow bottom as a land-generated density current (or extrabasinal turbidite), capable of eroding the basin floor and allowing transfer of the sediments farther basinward throughout a system of subaqueous channels and lobes (Lihong et al., 2020). Shear forces at the bottom enable the transport of extrabasinal and intrabasinal clasts as bedload. The critical value R_c for generating heavy plunging jets was estimated as −2.0, after a series of flume experiments performed by Kim (2001). According to the non-dimensional density parameter R (above or below the critical value R_c), basin physiography and rheology of incoming flows, three types of hyperpycnal deltas are recognised (Figures 2 and 6); (i) HLDs, (ii) HSDs and (iii) hyperpycnal fan deltas (HFDs).

3.3.1 | Hyperpycnal littoral deltas

Hyperpycnal littoral deltas are very low gradient littoral deltas (Figure 6E) which are partially equivalent to 'subaqueous deltas' (Kuehl et al., 1986), ramp deltas (Overeem et al., 2003), prodeltaic shelves (Bhattacharya & MacEachern, 2009), muddy prodeltaic hyperpycnites (Wilson & Schieber, 2014), river-dominated deltaic parasequences (Ahmed et al., 2014), storm-flood-dominated deltas (Lin & Bhattacharya, 2020) and shelf hyperpycnites (Olariu, 2023). These deltas form when sediment-laden (dirty) rivers enter brackish (lacustrine or marine) or normal-salinity marine basins. The HLDs are formed by weak plunging jets (Kim, 2001) resulting in light hyperpycnal plumes. Weak plunging jets form when the non-dimensional density parameter R is between 0 and −2. Flume experiments (Kim, 2001) show that in these conditions, diluted hyperpycnal flows do not have enough weight to interact with the basin bottom (erode), and sediments can be easily maintained in suspension by adding some additional energy, like that provided by tides, waves or ocean currents (Figure 10). This interaction between light hyperpycnal flows and basin dynamics allows fine-grained (sand-silt-clay) sediments to be transported and accumulated very far (typically hundreds of kilometres) from the river mouth. This makes HLDs one of the most important 'shelf builder' systems in nature. In this interpretation, HLDs provide a rational explanation for the growth of subaqueous clinoforms often recognised in front of large deltas (Nittrouer et al., 1996; Patruno et al., 2015). These clinoforms compose progradational sandy parasequences and consequently are not conveniently explained by fluid mud flows, mainly composed of mud and silt (Kineke & Sternberg, 1995). Sediment concentration and water salinity vertical profiles suggest that fluid mud flows are not hyperpycnal in origin, since they develop under the buoyant plume of hypopycnal deltas, probably due to the collapse of the sediment cloud (Parsons et al., 2001; Kineke & Sternberg, 1995).

Most HLDs form when moderate dirty river discharges enter in brackish (lacustrine or marine) basins. As pointed out by Mulder and Syvitski (1995), a number of dirty rivers have an averaged suspended load between 1 and 40 kg/m^3 during normal (average) annual discharges. In normal-salinity marine waters these 'dirty' river discharges commonly result in classical hypopycnal MLDs since the bulk density of the river discharge is commonly below the required threshold to become hyperpycnal. Nevertheless, in brackish basins (Figure 2) these incoming long-lived sediment-laden river inflows could have enough density to plunge in coastal areas, thus generating a light hyperpycnal plume. Such HLDs can also develop in normal-salinity marine basins.

According to Mulder and Syvitski (1995), it is assumed that a minimal sediment concentration of 35 to 45 kg/m^3 of suspended sediment is required in a fluvial discharge to produce a hyperpycnal plume in marine settings. Nevertheless, this minimal concentration is largely below the necessary critical concentration R_c required to produce a HSD (characterised by extrabasinal channel-lobe complexes) in marine settings. For example, the Yellow (Huanghe) River delta (Wang et al., 2006; He et al., 2022) in the Bohai Sea is considered a hyperpycnal-dominated delta (Gao et al., 2015; Shanmugam, 2018). The low averaged sediment concentration in the related fluvial discharge results in the generation of a low gradient progradational shallow and extended clastic ramp (Gao et al., 2015; He et al., 2022). Most of the time, the Yellow River generates low-density hyperpycnal plumes that can be easily deflected by littoral currents (like in the Yangtze delta, Luo et al., 2017) forming extended HLD deposits. This situation is common to other large river deltas like the Amazon (Nittrouer et al., 1986), Ganges- Brahmaputra (Kuehl et al., 1997) and Han (Cummings et al., 2015) deltas, all characterised by extended (hundreds of kilometres) low gradient HLDs. The Han River is considered a moderately dirty river (Mulder & Syvitski, 1995), and the interaction between weak hyperpycnal flows and tidal action can explain its very low gradient (<0.2°) delta foresets (Cummings et al., 2015), which is typical of HLDs.

Tide-dominated HLD deposits

The interaction of light hyperpycnal plumes and tidal action can be an efficient mechanism for sediment distribution. The Middle Jurassic Lajas Formation (Neuquén Basin, Argentina) in the Picún Leufú Sub-Basin is a world-class example of the interaction between hyperpycnal flows and tidal action (Zavala, 1996; Rossi & Steel, 2016).

In this unit, delta front deposits compose a very thick (near 200 m thick) succession of tidally modulated sediments interbedded with massive and cross-stratified sandstone beds with common imbricated clay clasts (Figure 10) and abundant plant remains.

In this succession, shales are uncommon, since the permanent winnowing by tidal action prevents the 'normal' fallout of fine-grained sediments. Additionally, bioturbation and body fossils are scarce, probably suggesting a stressed environment due to turbid water conditions and a high freshwater influx, which contribute to decreasing the water salinity. Massive and cross-stratified beds (Figure 11D) are here interpreted as the result of heavy-loaded ($R_c < -2$) hyperpycnal flows, forming part

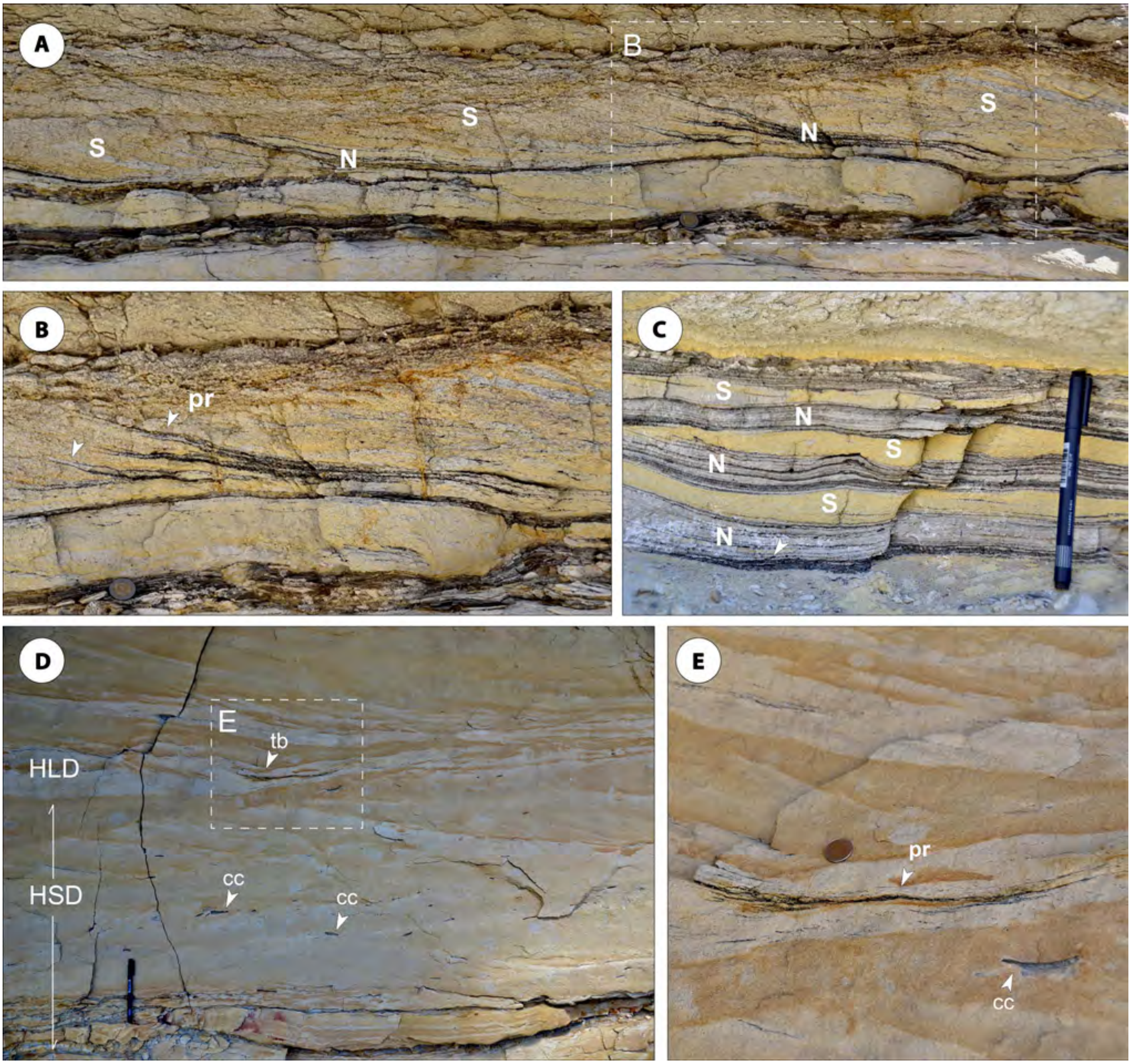

FIGURE 11 Examples of tide-dominated delta front deposits from HLDs. (A) Neap-spring cycles evidencing energy fluctuations during the lunar day (28 terrestrial days approx.). (B) Detail of 'A', showing the characteristic discontinuous 'mud' drapes accumulated during neap tides. These fine-grained fallout deposits are made of plant remains (pr). (C) Tidal rhythmites with cyclical grain size variations related to neap-spring cycles. Plant remains are abundant in neap deposits. (D) Outcrop showing the interaction between heavy-loaded and light hyperpycnal plumes. Heavy-loaded hyperpycnal flows accumulate massive to cross-stratified sandstones with aligned and imbricated clay clasts (CC) and plant remains, as part of HSD deposits. On top of this succession, tide-modulated light hyperpycnal flow deposits can be recognised by the presence of tidal bundles (tb) with abundant plant remains. (E) detail of d, showing the characteristics of tidal bundles with plant remains (pr), sharply overlying massive sandstones with clay clasts (cc). Lajas Formation in the Bajada de Los Molles Locality, Neuquen Basin, Argentina.

of a subaqueous delta (or HSD, see later). These deposits are interbedded with intervals of fine-grained sandstones showing characteristic tidal bundles with spectacular neap-spring cycles (Figure 11A). These tide-modulated deposits are interpreted as the result of the interaction of light hyperpycnal plumes and tidal action in tide-dominated HLDs. Unlike conventional tidal bundles, in these tide-modulated delta front deposits, mud drapes generated during slack water periods are not composed of 'mud', but of plant debris (Figure 11B,C), indicating accumulation in a delta front setting. In tide-dominated HLDs, tidal action can effectively control the extension of the light hyperpycnal plume. During spring tides, strong tidal currents contribute to increase the distribution of fine-grained sandstones. In contrast, during neap tides, sand distribution is limited, favouring the fallout of plant remains along sandy wave foresets.

Wave-dominated HLD deposits

An example of the interaction between hyperpycnal flows and wave diffusion processes (Figures 6E and 9) is wave-enhanced hyperpycnal flows (Lamb et al., 2008; Macquaker et al., 2010; Guy Plint, 2014; Schieber, 2016; Wilson & Schieber, 2017), also called storm-flood-dominated deltas (Lin & Bhattacharya, 2020). In a series of flume experiments, Smith et al. (2019) proved that the addition of surface waves in gravity-driven currents (e.g. hyperpycnal flows) resulted in a 7 to 8.5% increase in the downslope transport of suspended sediments. Wave-dominated HLDs are very common in extended shelfal deposits from the Lower Cretaceous in the Neuquén Basin (Argentina), especially in the Agrio and Mulichinco formations. The occurrence of HLDs was probably favoured by the lower salinity (brackish) conditions that existed during the Early Cretaceous in the Neuquén Basin (Lazo et al., 2008).

In the Mulichinco Formation, metre-thick wave-dominated low-angle clastic ramps can be traced for tens to hundreds of kilometres basinward. The common occurrence of wave-reworked sandstones along the entire ramp supports shallow water conditions associated with a very gentle (near flat) slope. Figure 12 provides an example of

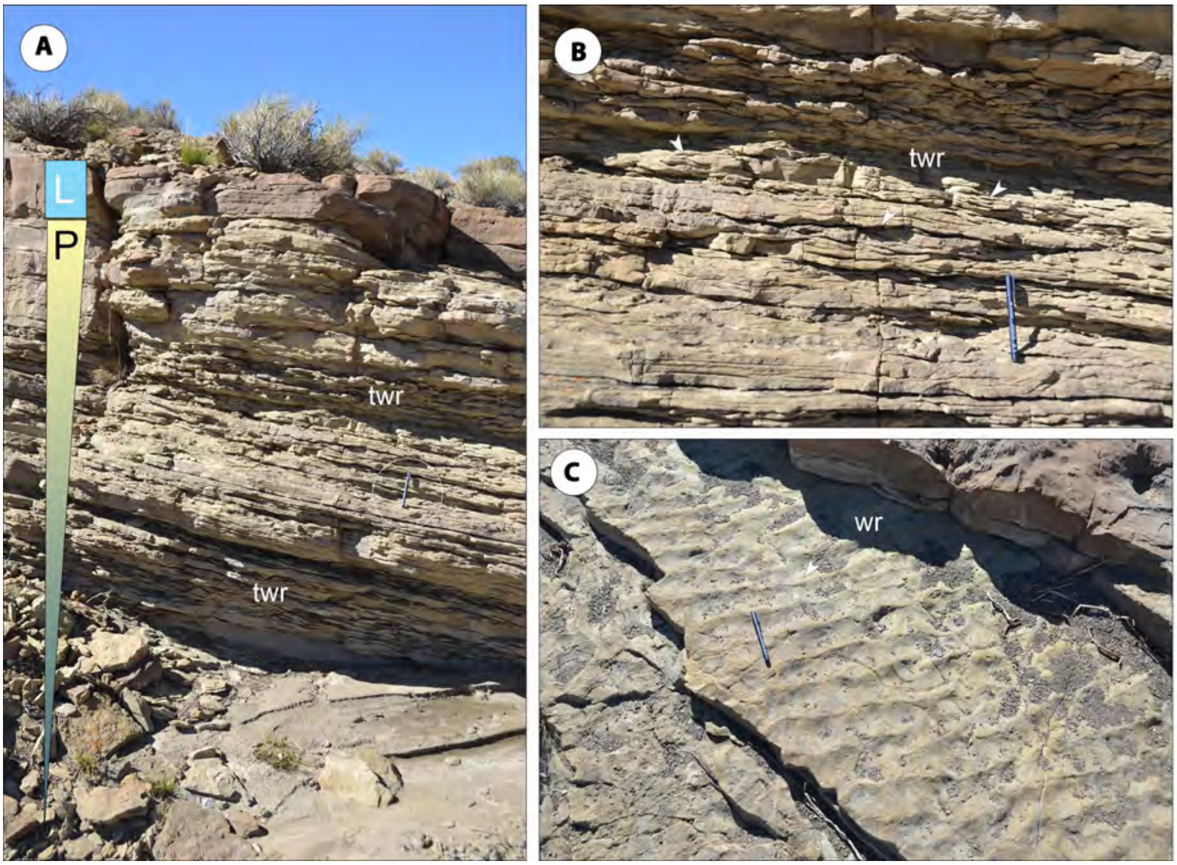

FIGURE 12 Example of wave-dominated hyperpycnal littoral delta deposits. (A) Progradational wave-reworked fine-grained sandstones (p) ending with a limestone bed (L), the last representing a condensed interval. (B) Fine-grained sandstones with truncated wave ripples (twr), accumulated by fallout from a turbulent suspension in a wave-dominated (shoreface) ramp. (C) Detail of a depositional surface with well-preserved wave ripples (wr) and some horizontal trace fossils. Mulichinco Formation at Mina San Eduardo Locality, Neuquén Basin, Argentina.

these deltaic wave-dominated deposits forming extended coarsening-upward clastic ramps. In many shallow marine successions, these HLD deposits are often wrongly interpreted as shoreface parasequences.

Internal organisation and stacking pattern of HLDs

Ancient HLDs consist of progradational shallow clastic ramps extending for hundreds of kilometres basinward in brackish lakes, partially closed epicontinental seas and marine shelves (Overeem et al., 2003; Zavala et al., 2016; Gao et al., 2018). During the Cretaceous, the high global sea level favoured the existence of partially closed shallow inland seas, like those present at the Western Interior Seaway (USA), the West Siberian Basin (Russia) and the Neuquén Basin (Argentina). In these epicontinental seas, the salinity was substantially lowered due to an increasing contribution of freshwater by riverine run-off. Petersen et al. (2016) estimated salinity to be lower than 11 PSU for coastal environments in the Western Interior Seaway during the Cretaceous, which is less than one third the normal salinity of open seas. In the Lower Cretaceous Agrio Formation (Neuquén Basin, Argentina), the deposits of HLDs are made up of metre-thick wave-dominated coarsening-upward and thickening-upward successions (Irastorza et al., 2021; Figure 13).

These progradational facies successions (or parasequences) start with massive mudstones that are gradually followed by wave-modified heterolithic deposits (lenticular, wave and flaser bedding) as the fine-grained sandstone content increases upwards. At proximal areas, the upper section can also show sandstone beds with planar lamination, hummocky cross stratification and asymptotic cross-bedding (Figure 13). These progradational successions commonly lack body fossils and show scarce bioturbation. Nevertheless, bioturbation becomes very abundant near the top of the sandy succession, where these deposits are sharply overlain by a regionally extensive bioclastic oolitic limestone bed (Figure 13). It is interpreted that these changes along progradational cycles and the sharp boundary with the bioclastic limestones could be related to changes in the

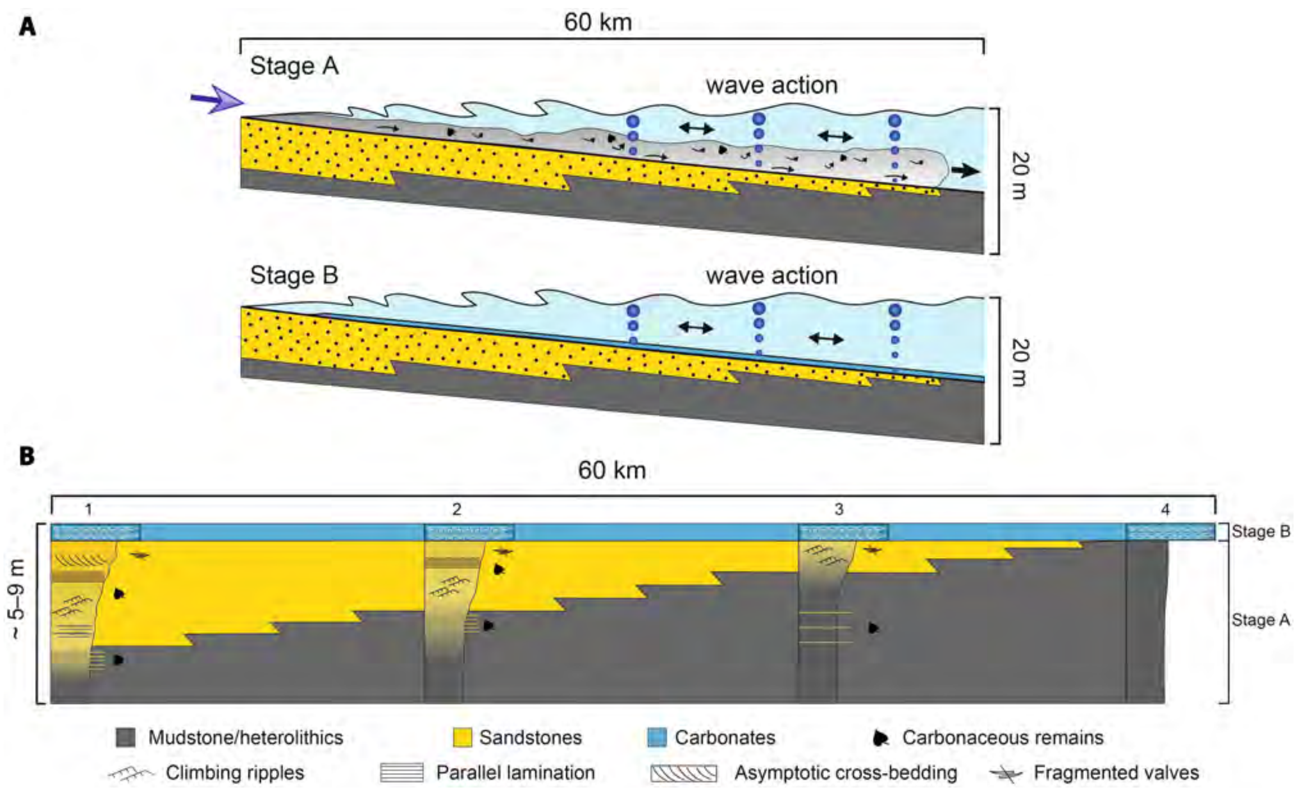

FIGURE 13 Origin and internal stacking pattern of wave-dominated hyperpycnal littoral delta deposits in the Lower Cretaceous Agrio Formation, Neuquén Basin, Argentina. (A) Hyperpycnal littoral deltas compose very low gradient progradational ramps of regional extent, generated by light wave-aided hyperpycnal flows supplied during rainy (humid) periods (Stage A). Progradational events are punctuated by periods of very low sediment supply (arid), with condensed intervals made of bioclastic limestones (packstones) that laterally grades into massive limestones (mudstones). (B) Facies changes recognised along tens of kilometres in hyperpycnal littoral delta deposits. The bioturbation of these progradational facies successions is low, due to the stress provided by turbid and brackish waters. Modified from Irastorza et al. (2021).

palaeoenvironmental conditions induced by fluctuations in suspended sediment concentration and water salinity (Irastorza et al., 2021). Evidence from oxygen isotopes and palaeoecological analysis (Lazo et al., 2008) suggest brachyhaline conditions for most of the Agrio Formation, probably resulting from a high freshwater influx by associated delta systems. At a small scale, the dramatic increase in bioturbation towards the top of these progradational facies successions could suggest a gradual return to near-normal marine salinity conditions, as the supply of freshwater decreased, controlled by allocyclic processes. When sediment supply and associated sediment-laden plumes progressively disappear, marine organisms colonised this well-oxygenated and extended shallow clastic ramp still affected by wave action in the photic zone (Irastorza et al., 2021). Sediment-starved conditions associated with long-term basin subsidence probably contribute to the gradually increasing relative water depth, thus returning to offshore conditions before the next progradational HLD. Consequently, these limestone levels can be considered as 'condensed intervals', since the time involved in their origin is probably similar (or even longer) to that required for HLDs to prograde basinward. The allocyclic control on the origin of these limestones seems evident from the stacking pattern and regional correlation (Figure 13), since limestones commonly sharply overlie progradational clastic deposits accumulated in a range of water depths, from shoreface (sandy) up to offshore (muddy) deposits (Sections 1–4 in Figure 13). In contrast to HSDs, which are commonly characterised by bedload and suspended load deposits detached from the river mouth (Zavala & Pan, 2018), HLDs are attached to the shoreline forming littoral deposits accumulated by the collapse of suspended load (bedload deposits are uncommon and limited to proximal positions). The depositional slope of HLDs is extremely low, typically ranging between 0.2 and 0.003° (Overeem et al., 2003; Bhattacharya & MacEachern, 2009; Wilson & Schieber, 2014; Cummings et al., 2015; Zavala et al., 2016; Gao et al., 2018). The common reworking by wave diffusion processes, the low gradient of the delta front and the overall progradation shown by HLDs make it possible to wrongly interpret these deltaic deposits as storm-dominated shoreface deposits/strand plains or wave-dominated parasequences (Colombera & Mountney, 2020). Parasequences are upward-shoaling facies successions bounded by flooding surfaces, the last interpreted as caused by a relatively rapid sea-level rise (Van Wagoner et al., 1988, 1990; Arnott, 1995). Nevertheless, the real origin of these upward-shoaling successions has never been addressed, since a 'shoreface' refers to a position along the coast where wave action can effectively rework the sediments, but never a depositional environment. A wider discussion about the origin and concepts related to parasequences was recently provided by Colombera and Mountney (2020), which agrees with an allocyclic control by Milankovitch cycles. Probably, most shoreface parasequences described in the literature are in fact different expressions of shelf-progradational HLDs (Zavala et al., 2021), controlled by long-term climate changes instead of high-frequency eustatic sea-level changes.

A spectacular example of HLDs can be found in the Lower Cretaceous of the West Siberian Basin in clastic shallow marine deposits from the Leushinskaya and Vikulovo formations (Zavala et al., 2014, 2016). These units conform two unconformity-bounded progradational sequences, each one showing a thickness of about 100 m. Each sequence is in turn composed of several shallowing-upward wave-dominated elementary depositional sequences (sensu Mutti et al., 2000) or parasequences. In these HLDs, single sandstone beds are centimetres-thick, commonly showing a normal grading from fine-grained sandstones to mudstones. These beds accumulate over a basal erosional surface and internally show sedimentation dominated by traction-plus-fallout processes from waning sediment-laden turbulent flows affected by wave diffusion processes (Figure 14).

The step-by-step analysis of the accumulation of these single beds (Figure 14) allows the recognition of at least five stages: (1) erosion by wave action, (2) flow waxing-bypass, (3) initial sand accumulation by wave-modified traction plus fallout, (4) fallout of silt-clay from waning flows and (5) starvation and bioturbation (mostly by *Palaeophycus* traces). It is interpreted that during the starvation period, mudstones evolve into a firm ground that can resist erosion by wave action until some threshold is exceeded.

The detailed analysis of these beds and their stacking patterns at different scales, like beds, composite beds, bedsets, composite bedsets (or parasequences) and sequences, allows a deep comprehension of the origin and significance of HLD deposits. Figure 15 shows the different hierarchical orders recognised in the Cretaceous of Russia and their main internal characteristics (modified from Zavala et al., 2016).

Beds, composite beds and bedsets (Campbell, 1967) are up to 30 cm thick, and are internally composed of fine-grained sandstones and heterolithics showing a fining-upward and thinning-upward stacking, where bioturbation increases upwards (A, B and C in Figure 15). These characteristics suggest climatically/controlled waning flows, where periods of low sediment supply are characterised by a high bioturbation index.

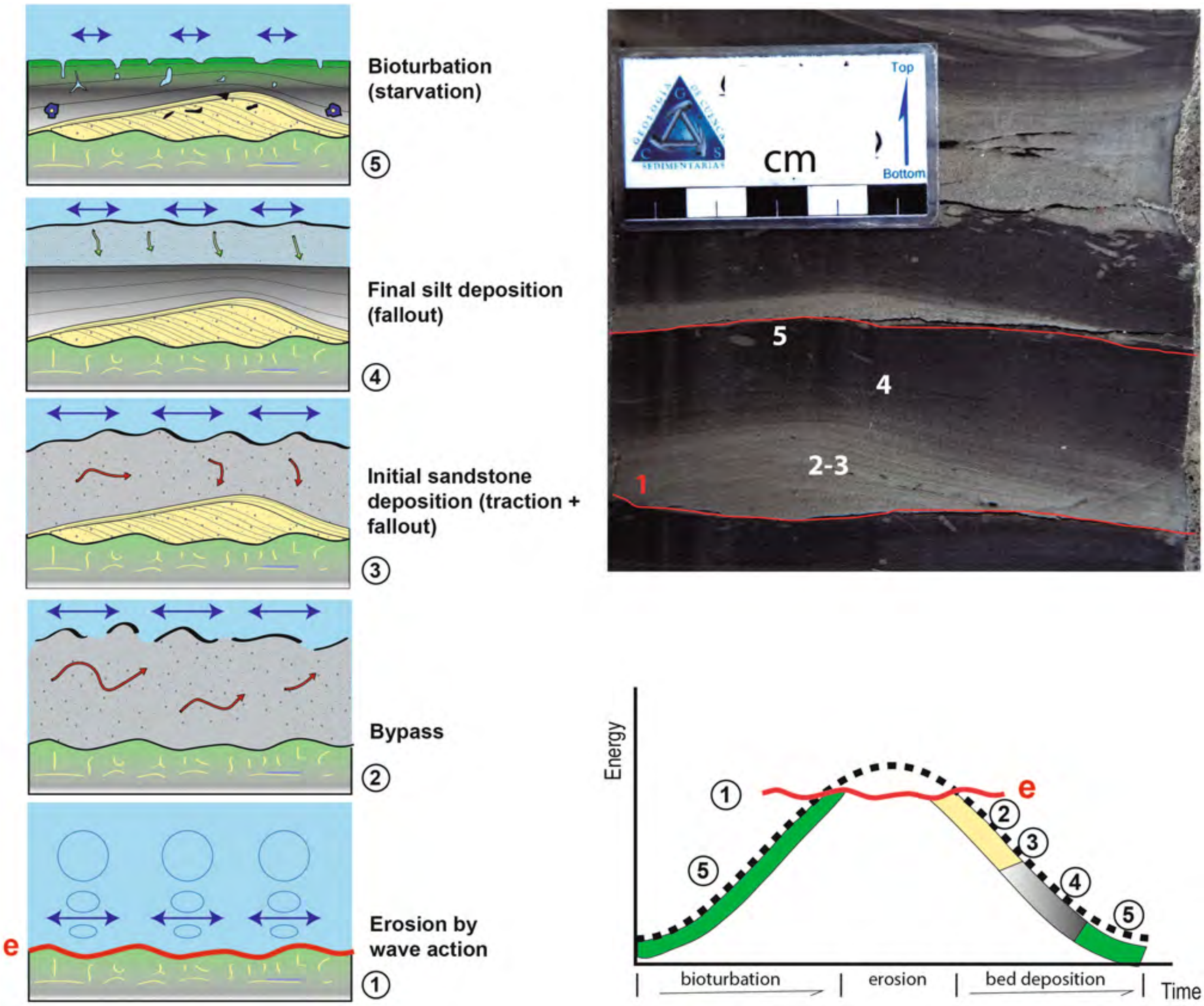

FIGURE 14 Step-by-step analysis of the accumulation of single sandstone beds in hyperpycnal littoral deltas from the Lower Cretaceous Vikulovo Formation, West Siberian Basin, Russia. The accumulation of each bed includes at least five stages comprising (1) erosion, (2) sediment bypass, (3) initial deposition by traction plus fallout, (4) final silt deposition and (5) starvation and bioturbation. After the deposition, muddy deposits conform a firm ground that can resist wave action until some threshold is exceeded. Modified after Zavala et al. (2016).

In contrast, composite bedsets (or parasequences) and sequences compose metre-thick to decimetre-thick cycles. These cycles display an overall coarsening and thickening upward trend, where bioturbation gradually decreases upward. This decrease in bioturbation is interpreted as resulting from the progradation of coastal systems, with the associated decrease in salinity towards more littoral areas.

The development of HLDs is very sensitive to changes in the sediment concentration of the associated fluvial discharge. If the sediment concentration of river discharges decreases, these deltas can evolve into conventional wave-dominated MLDs. In contrast, if the sedimentary load substantially rises during floods, a *R* parameter below the critical number of −2 can make these deltas seasonally evolve into detached HSDs.

3.3.2 | Hyperpycnal subaqueous deltas

Hyperpycnal subaqueous deltas constitute the most commonly recognised type of hyperpycnal delta (Mutti et al., 1996, 2000, 2003; Mulder et al., 2003; Nakajima, 2006; Zavala et al., 2006; Petter & Steel, 2006; Zavala & Arcuri, 2016; Zavala & Pan, 2018; Grundvåg et al., 2023) generated by relatively high-density flood river discharges in marine and lacustrine basins. To generate a HSD, the incoming fluvial discharge should have a *R* density parameter below the critical R_c of −2 (Figures 2 and 3F), corresponding to the field of long-lived sediment-laden turbulent flows (SLTF, Zavala, 2020). The SLTF's are pure turbulent flows with a suspended sediment concentration up to

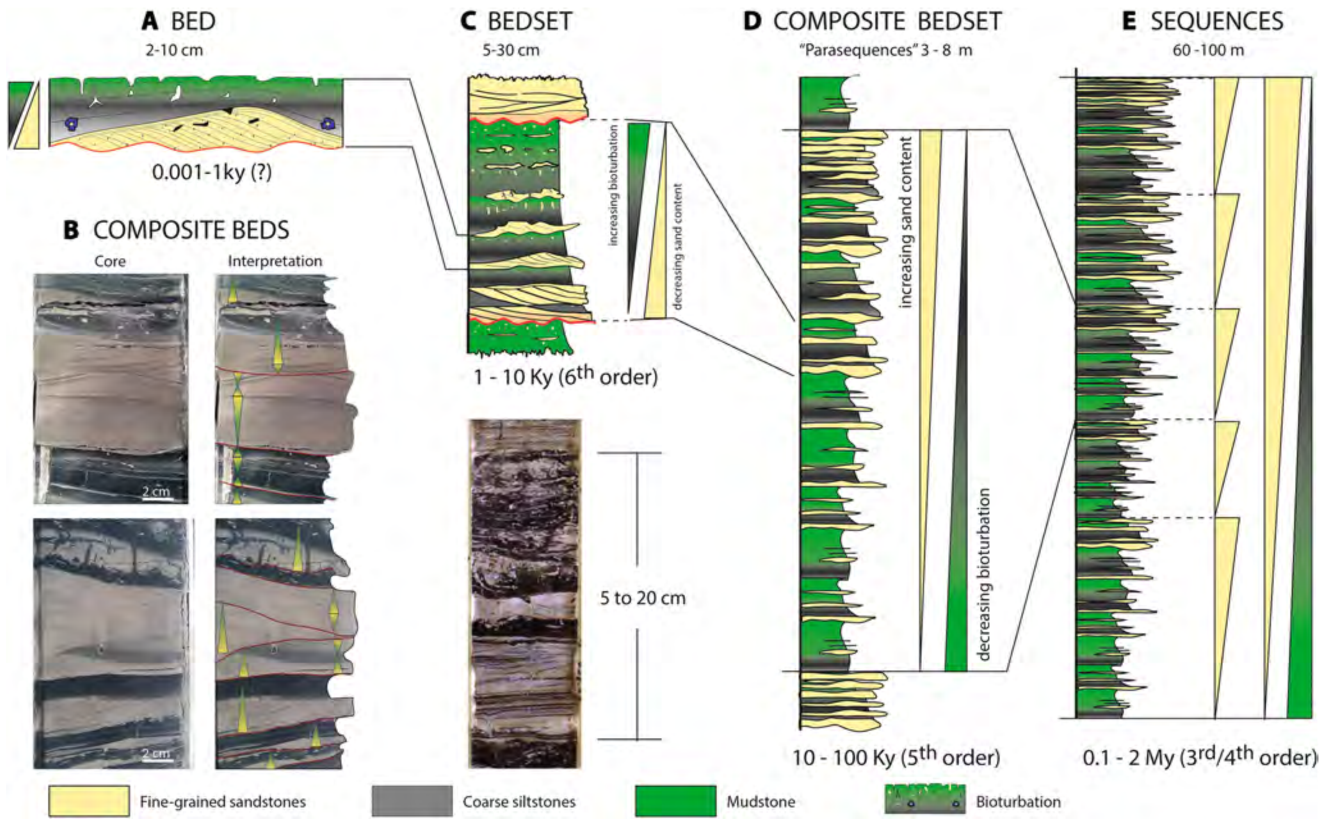

FIGURE 15 Different time-hierarchical units in hyperpycnal littoral delta deposits from the Lower Cretaceous (Aptian) Karabashskiy Oil & Gas field, West Siberian Basin, Russia. Note that beds (A), composite beds (B) and bedsets (C) compose fining-upward and thinning-upward facies successions in which bioturbation increases upward. In contrast, composite bedsets or parasequences (D) and sequences (E) are characterised by an overall coarsening and thickening-upward stacking, where bioturbation decreases upwards. This progressive upward decrease in the bioturbation index is probably caused by the approaching coast, where an increase in the freshwater influx results in stressed conditions. The step-by-step analysis of bed deposition is shown in Figure 14. Inverse-then-normal grading is also common in composite beds (B). Modified after Zavala et al. (2016).

238.5 kg/m^3 (Figure 2; Zavala, 2020), this is below the Bagnold's limit (9% vol., Bagnold, 1962) that guarantees fully turbulent conditions. Due to its relatively high bulk density, the river discharge plunges and bypasses coastal areas generating a coastal-detached subaqueous channel-lobe system (Zavala & Pan, 2018). The associated deposits show the characteristics of extrabasinal turbidites (Zavala & Arcuri, 2016). In brackish (lacustrine or marine) settings, the density threshold to generate a HSD is easily achieved by most dirty rivers (Figure 2). In contrast, in normal-salinity seas, the generation of HSDs requires a density contrast produced by a suspended sediment concentration much higher than the minimum of 35 to 45 kg/m^3 proposed by Mulder and Syvitski (1995). Theoretical concepts and flume experiments (Kim, 2001) suggest that the required suspended sediment concentration in the incoming flow to produce a HSD in the ocean should be over 100 kg/m^3 (Figure 2). Consequently, hyperpycnal flows produced by dilute hyperpycnal discharges (<100 kg/m^3) in normal salinity seas (related to some dirty rivers often affected by coastal diffusion processes, Shanmugam, 2018) commonly result in HLD and cannot be considered as analogues of HSDs. These high-density hyperpycnal discharges are commonly composed of suspended load often carrying associated bedload (Figure 16). Bedload can be composed of extrabasinal clasts inherited from the original fluvial discharge, intrabasinal clasts eroded during the travel basinward (mostly clay clasts and valves) or a mixture thereof (Zavala & Arcuri, 2016; Zavala 2020). Bedload deposits are common in proximal settings (Lai & Capart, 2007), typically characterised by either extrabasinal and/or intrabasinal conglomerates embedded within massive sandstone deposits (Griggs et al., 1970; Zavala et al., 2011a, 2011b). Suspended load deposits are dominantly composed of massive sandstones followed by laminated and ripple-drift cross-laminated sandstones (Zavala et al., 2011a).

In marine and saline basins, the density reversal induced by the interstitial freshwater contained in the parent flow results in the generation of lofting plumes (Figure 16B) that lead to the accumulation of lofting

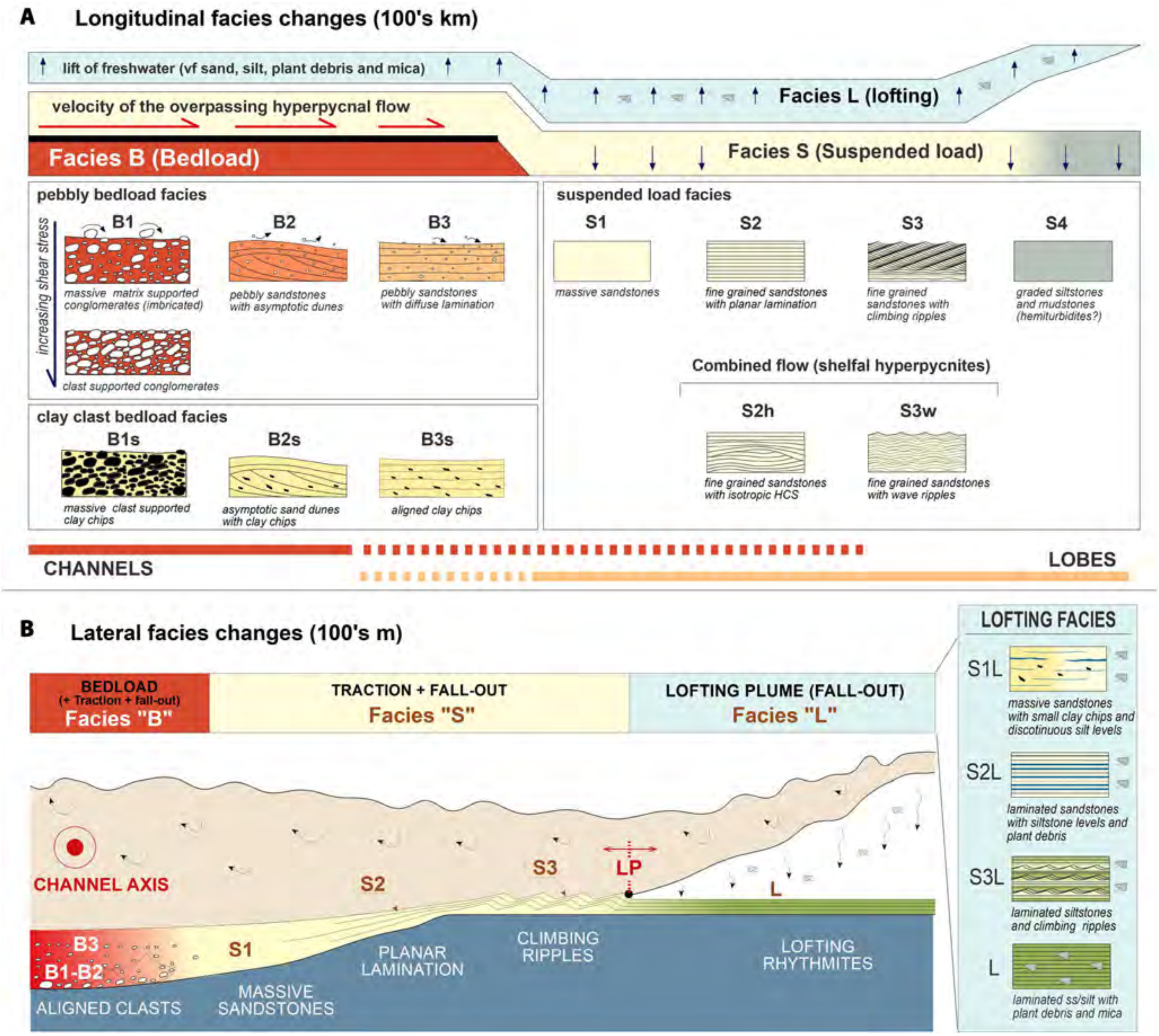

FIGURE 16 Genetic facies tract for the analysis of sustained hyperpycnal flows with associated bedload in hyperpycnal subaqueous deltas (HSDs). (A) Facies association along the depositional system. (B) Lateral facies changes towards flow margins. Modified after Zavala and Arcuri (2016).

rhythmites (Zavala et al., 2008; Zavala & Arcuri, 2016; Siwek & Wendorff, 2019). The deposits of HSDs commonly show abundant plant remains, microfossils and fossil debris eroded from the basin bottom at different water depths (Griggs et al., 1970). The HSDs are typically associated with medium to large-size rivers characterised by long-lived and quasi-steady fluvial discharges (Khripounoff et al., 2003). The continuous pumping of the fluvial discharge allows these flows to travel considerable distances also along near-flat basin bottoms (Zavala et al., 2006; Bourget et al., 2010).

Depending on the duration of the incoming flow and the basin physiography, HSDs can develop on the shelf as channel fills and shelfal sandstone lobes (Mutti et al., 1996, Sections 5 and 6 in Figure 4), or at inner basin areas as basin-floor fan complexes (Zavala & Arcuri 2016). One of the most spectacular examples of a recent HSD corresponds to the Bengal Fan, which is the largest submarine fan on Earth. The Bengal Fan (also known as the Ganges Fan) is about 3000 km long, 1430 km wide and has a maximum accumulated thickness of 16.5 km (Curray et al., 2002). Recently, the International Ocean Discovery Program Expedition 354 (Lee et al., 2019) discovered abundant woody debris in recent extrabasinal turbidites recovered at 3700 m water depth, *ca* 2000 km away from the river mouth. These deposits enhanced the importance of hyperpycnal flows in building very thick subaqueous delta linked successions as basin-floor fans.

3.3.3 | Hyperpycnal fan deltas

Hyperpycnal fan deltas are a special kind of hyperpycnal delta generated in high gradient settings by small mountainous rivers (Figure 4). During high-peak floods, these rivers produce short-lived high-density discharges (typically concentrated flows, hyperconcentrated flows and exceptionally, cohesive debris flows). The high sediment concentration of these flows results in a very low non-dimensional density parameter *R* (Figures 2 and 6G) that forces the flow to plunge in coastal areas and to travel basinward as a high-density inertia-dominated flow (Liu et al., 2013). These inertial flows require a steep slope to maintain their complex internal sediment support mechanism (matrix cohesion, buoyancy, water escape and dispersive pressure). If the slope decreases, these flows can transform into more dilute density flows (Zavala, 2020). Due to their short duration, deposits associated with these flows constitute residual conglomerates and fan-shaped lobes accumulated close to the depositional slope break (Prior & Bornhold, 1990; Liu et al., 2013). These flows are often affected by multiple flow transformations and hydraulic jumps (Mutti, 1992; Piper & Normark, 2009; Felix et al., 2009), losing all original lightweight extrabasinal components. Consequently, final deposits can resemble those typical of intrabasinal turbidites (Zavala & Arcuri, 2016; Zavala, 2020). Well-documented examples of HFD systems correspond to the Eocene Battfjellet Formation in the Central Tertiary Basin on Spitsbergen, Svalbard (Henriksen et al., 2011; Mellere et al., 2002) and the Eocene Santa Liestra Group fan-delta system (Mutti et al., 1996, 2003). In the Neuquén Basin (Argentina), there are numerous examples of HFDs from the Jurassic Cuyo (Mosquera et al., 2008) and Lotena (Zavala et al., 2002) groups. In Venezuela, HLDs are very common in systems accumulated close to growing ranges, like in the Palaeocene-Eocene Guarico Formation (Zavala, 2020) and the Lower Miocene Naricual Formation (Zavala et al., 2011b).

A highly comprehensive description of Holocene HFDs from fjords in British Columbia was introduced by Prior and Bornhold (1990) in their milestone contribution. These Holocene fan deltas have associated HFDs built by a combination of high-density flows including debris avalanches, inertia flows (hyperconcentrated and concentrated flows) and sediment-laden turbulent flows, extending several kilometres from the coast. Additionally, Bornhold and Prior (1990) provided a detailed description of a recent HFD associated with the subaqueous extension of the Noeick littoral (fan) delta in British Columbia. The lower delta slope of the HFD extends up to 4.5 km from shore, reaching a water depth of 250 m. The slope of this system averages 4–5° along the first 2 km.

4 | DELTAIC SYSTEMS AS LITTORAL, SHELFAL AND DEEP-WATER SYSTEM BUILDERS

This study suggests that deltaic systems are more complex and significant than previously recognised in the geological literature. Traditionally, deltas were considered as littoral systems and classified along with estuaries, tidal flats, strandplains and lagoons (Boyd et al., 1992), as partially subaerial geomorphological forms shaped by coastal diffusion processes such as tides and waves. However, this contribution proposes a broader perspective on deltaic sedimentation (inspired by Moore & Asquith, 1971), considering as deltas *all clastic deposits directly transferred by land-generated gravity flows into coeval marine or lacustrine basins*, *regardless of their grain size*, *shape or water depth*. Consequently, the key concept of this new approach is that deltas can exhibit varying levels of efficiency (Figure 17), and a single river system can build different types of deltas (products) throughout geological history. The concept of efficiency considered here is similar to that proposed by Mutti et al. (2003) for hyperpycnal flows exiting river mouths. Mutti et al. (2003) defined flow efficiency as the ability of a density flow to carry its sediment load basinward, primarily controlled by its momentum, sediment concentration, discharge and duration.

River discharges can be highly variable in terms of duration and sediment concentration, and their related deposits (deltas) have played a significant role in the construction of the thick stratigraphic successions found in the geological record. All terraces in present fluvial systems are Pleistocene or younger in age. This suggests that rivers periodically shape and clean their valleys, transferring basinward all temporarily stored sediments (Schumm, 1977).

A synthesis of the main types of marine deltaic systems recognised in this study and their distribution is shown in Figure 17. This diagram is inspired by the concept of the 'Dynamic System' proposed by Moore (1969). The types of deltas depicted in the figure are primarily influenced by the characteristics of the associated fluvial discharge, which in turn governs the efficiency of the deltaic system as a whole. Considering an increasing degree of flow efficiency, a single source-to-sink system can accumulate MLDs, HLDs and HSDs (Figure 17).

Marine littoral deltas result from bedload-dominated clean-water fluvial discharges (streamflows) and represent the lower level of delta efficiency. These deltas are point-sourced littoral systems, and due to the limited accommodation, they often show lobe switching (Figure 3; 1–4 in Figure 17) controlled by autocyclic processes. One diagnostic characteristic of these deposits is the existence

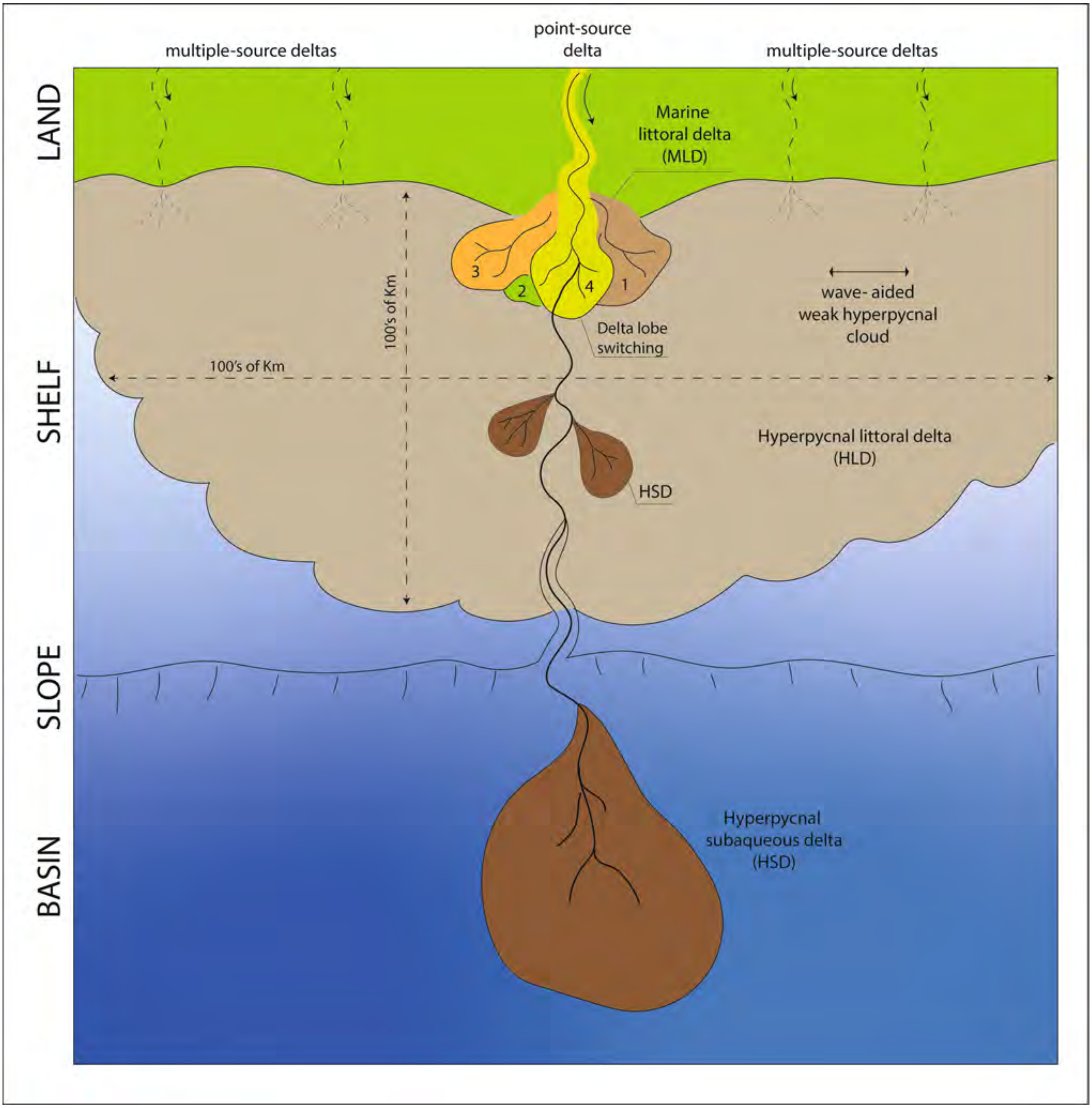

FIGURE 17 The different scales of delta deposits in marine settings are linked to the flow efficiency of the parent fluvial discharge. Marine littoral deltas (MLDs), hyperpycnal littoral deltas (HLDs) and hyperpycnal subaqueous deltas (HSDs) represent an increasing level of efficiency of the delta system.

of delta plain (often rooted coal-rich) deposits on top of coarsening and thickening upward metre-thick successions (Figure 5), which is possible because of their coastal position. The autocyclic control on these progradational littoral delta successions limited the importance of coarsening-upward cycles for performing regional correlations. These MLDs are very important for building any kind of other littoral systems, since marine diffusion processes can distribute the sediments along the coast forming strandplains, lagoons, tidal flats, beaches, etc. Since these systems and their deposits were not primary accumulated by a river, they should not be considered as part of the MLD.

If river discharges increase their sediment concentration, rivers can eventually supply a diluted turbid mixture of water and sediments (mostly fine-grained sand, silt and clay) that plunge in coastal areas and can be widely distributed aided by coastal diffusion processes. These deltas, corresponding to HLDs, have a wider (regional) distribution and can be eventually multiple-sourced. Their deposits compose coarsening and thickening metre-thick successions controlled by allocyclic processes. One typical characteristic of these progradational facies successions is the absence of delta plain deposits on top, since the time-equivalent coastal area can be tens to hundreds of kilometres away. In contrast, the top of these progradational clastic successions (or parasequences) is often bounded by time-condensed (starved) deposits like ash levels, bioturbated horizons (hardgrounds) or limestone beds. The last makes upper bounding surfaces of coarsening-upward and thickening-upward HLDs very useful for performing regional correlations (Elder et al., 1994; Colombera & Mountney, 2020). The extended distribution of HLD deposits makes them one of the most important 'shelf builders' in nature. In fact, sediments supplied by these HLDs can be eventually eroded and transported by tides and ocean currents, forming different shelfal bars (e.g. tidal sand bars) depleted of extrabasinal elements. Since these deposits are not accumulated by a direct fluvial discharge, they cannot be considered as part of these HLD systems.

Finally, when rivers discharge heavy-loaded turbulent suspensions, the hyperpycnal flow can bypass littoral areas forming detached hyperpycnal channels and lobes on the shelf (shelfal sandstone lobes of Mutti et al., 1996), slope (transient fans, Adeogba et al., 2005) and deep water (basin floor fans, Lihong et al., 2020; Grundvåg et al., 2023). Although sequence stratigraphic models (Van Wagoner et al., 1988, 1990) relate the origin of basin floor fans with lowstand periods (eustatic control), growing evidence suggests that many basin floor fans can effectively grow also during highstands due to a direct sediment supply by climatically driven extreme (hyperpycnal) fluvial discharges. As an example, the Early Eocene was a hyperthermal characterised by a sea level 70 to 100 m above present (Miller et al., 2020). Despite these highstand conditions, at least 59 deep-water turbidite systems were recognised worldwide (Burton et al., 2023) in both active and passive margins. Evidently, triggering of flood-generated (extrabasinal) highstand turbidites is largely more common in depositional settings characterised by narrow shelves (Burton et al., 2023).

5 | STACKING OF DELTAS: PROGRADATIONAL VERSUS RETROGRADATIONAL DELTAIC SUCCESSIONS

The existence of metre-thick progradational (thickening and coarsening upward) stacking in clastic successions is often considered a distinctive feature that allows the recognition of mouth bars of littoral delta deposits (Miall, 1976; Bhattacharya & Walker, 1992; Reading & Collinson, 1996; Bhattacharya & Giosan, 2003; Bhattacharya, 2006). Nevertheless, in delta systems, this progradational pattern is only possible in shallow marine or in open (overfilled) lacustrine basin areas having a limited accommodation controlled by subsidence and a near-stable basin water level. In these circumstances, the continuous sediment supply (from a river discharge) forces the system to prograde basinward, forming a 'normal' or 'depositional' regression (Curray, 1964). This situation is common in littoral (hypopycnal, homopycnal and hyperpycnal) deltas developed along coastal and shelfal areas of shallow seas and overfilled lakes. In contrast, littoral deltas developed in underfilled lakes and subaqueous deltas in lacustrine and marine systems can show a substantially different stacking pattern (Pietras & Carroll, 2006; Bartov et al., 2012; Olariu et al., 2020; Gruszka & Zieliński, 2021).

Figure 18 depicts the situation during the late overfilled lake stage in the Triassic Yanchang Formation, Ordos Basin, China (Zavala et al., 2022). During this period (Chang 3 to Chang 1 members), the lake had a positive water balance that resulted in a permanent absolute lake level (ALL) limited by a water overflow (WO) at the spillpoint. Like in most overfilled lakes, the positive water balance is associated with a high river influx, which results in a freshwater lake (Carroll & Bohacs, 1999).

At a small scale, these delta successions are composed of stacked coarsening and thickening upward metre-thick progradational facies successions (coastline 1 to coastline 3, during time 1 to 3, Figure 18) controlled by mouth-bar switching. Although the ALL remains constant, relative lake- level falls due to sedimentation forming a forced regressive system tract (FRST). At a larger scale, these elementary depositional sequences (EDS, Mutti et al., 2000) are driven by allocyles, controlled by long term climate changes. During time 3–5, sediment supply decreases, resulting in an overall transgression (TST, coastline migrates from 3 to 5) due to a relative lake-level rise induced by basin subsidence. During time 5 to 7, the increasing sediment supply builds another progradational cycle during the next regression.

Sediment supply by rivers is accompanied by the incorporation of considerable quantities of water. Water typically constitutes 91 to 99% of river floods. In underfilled (closed) lakes, the incorporation of water results in a relative lake-level rise that contributes to increasing accommodation (Figure 19). Consequently, littoral delta deposits often compose fining-upward and thinning-upward successions (Zavala et al., 2022) of clastic deposits accumulated in different steps during the transgressive system tract (TST). Figure 19 depicts this situation in the lowermost (underfilled lake) section of the Yanchang Formation (Chang 10 to Chang 7 interval). As water and sediments

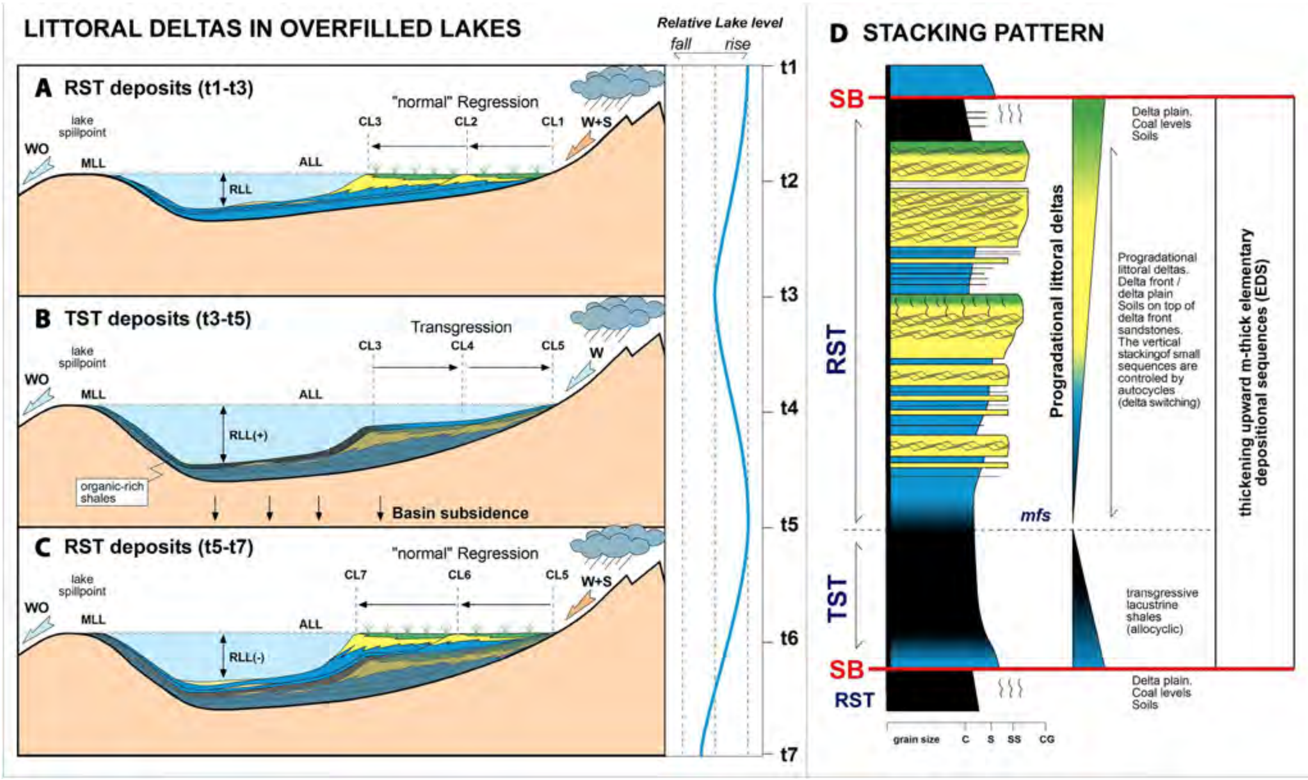

FIGURE 18 Different scales of coarsening and thickening-upward deltaic successions in the Yanchang Formation during the overfilled lake period (Chang 3 to Chang 1 members). (A) During time 1–3, sediment supply associated with a stable lake-level results in a progradation during the RST, with the accumulation of stacked thickening and coarsening upward successions controlled by mouth-bar switching. (B) During time 3–5, a decrease in the sediment supply results in a relative lake-level rise induced by subsidence. (C) During 5 to 7, a new progradation is registered. (D) Overall stacking of littoral delta deposits. Delta plain deposits are characterised by coal levels, which are very common in the uppermost members of the Yanchang Formation. Modified after Zavala et al. (2022).

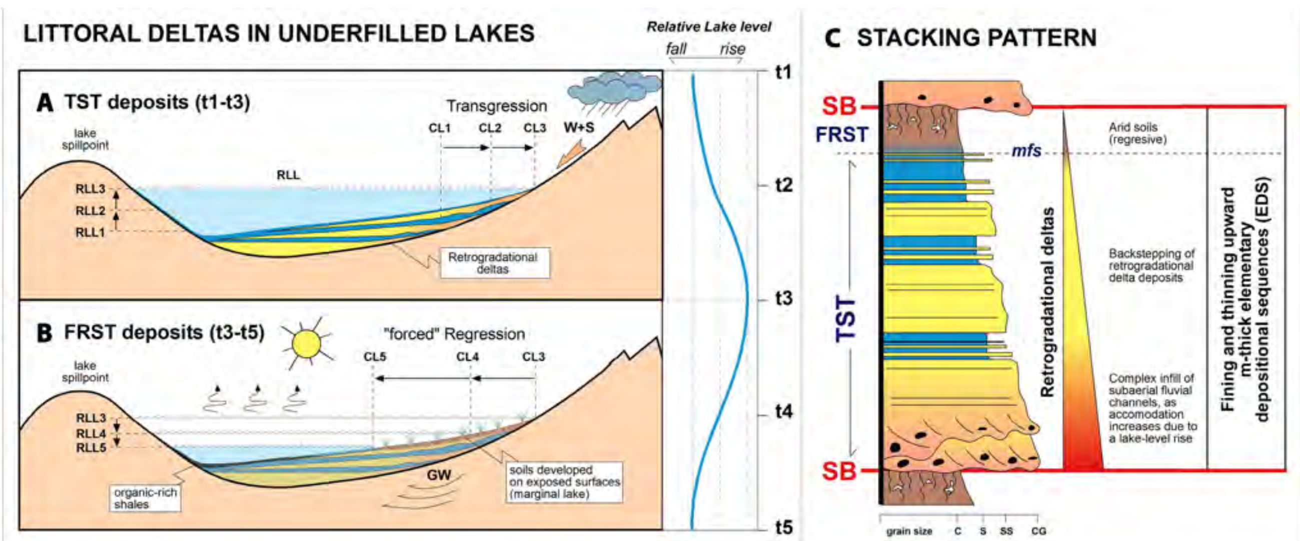

FIGURE 19 Different scales of fining-upward and thinning-upward deltaic successions in the Yanchang Formation during the underfilled lake period (Chang 10 to Chang 7 members). (A) During time 1 to 3, the sediment supply is associated with the introduction of a huge volume of water, which contributes to increasing the relative lake level (RLL1 to RLL3). This results in an overall transgression (coastline 1 to coastline 3) during the TST. Deltaic deposits during this period are characterised by an overall retrogradational trend. (B) During time 3–5, the decrease in water and sediment supply (allocycles) results in a climatically induced 'forced' regression, with a subaerial exposure and eventually arid soils developed during the FRST. (C) Overall stacking of retrogradational deltas during the TST of underfilled lakes. Modified after Zavala et al. (2022).

are supplied together during floods, the coastline migrates landward (CL1 to CL3 in Figure 19) resulting in the accumulation of fining-upward and thinning-upward delta front successions showing a retrogradational stacking mainly controlled by allocyclic changes. During time 3–5, the decrease in sediment and water supply induced a negative water balance, which provokes a relative lake-level fall (RLL3–RLL5, Figure 19B). In this situation, the minimum water level achieved by the lake is controlled by the interplay between the evaporation and the groundwater supply (Zavala et al., 2006). As a consequence of this lake-level fall, previous retrogradational delta successions are capped by a rooted interval (Figure 19C) generated during the forced regressive system tract (FRST), characterised by a marked subaerial exposure along lake margin areas. In a summary, progradational littoral deltas are uncommon in underfilled lakes, since the progradation of the littoral system will require near-stable lake-level conditions.

Finally, high accommodation in deep basins results in subaqueous delta deposits that often do not show other patterns than those driven by the long-term evolution of the related fluvial discharges and compensation cycles (Mutti & Sonnino, 1981). In most common situations, turbidite deposits are characterised by fining-upward and thinning-upward trends (Mutti et al., 1994; Amy et al., 2007), although thickening upward patterns are also registered (Prélat & Hodgson, 2013; Zhang & Dong, 2020).

6 | DISCUSSION

In geological sciences, deltas and their deposits have been recognised, defined and classified following both geomorphological and stratigraphic approaches. The geomorphological approach emphasised the shape and morphological characteristics of partially subaerial littoral deltas, and its relationship with the main active diffusion processes in the associated basin (Galloway, 1975). The authors believe that this approach and the resulting delta classification are risky and poorly relevant for the analysis of ancient successions, since it oversimplifies the importance of delta sedimentation. In contrast, the stratigraphic approach focussed on primary accumulation by a river (Bates, 1953; Moore & Asquith, 1971). This approach is very important for the stratigraphy and sedimentology of ancient successions, because the recognition of deltas focusses on the characteristics of the deposits, and it is not constrained by water depth. From a stratigraphic point of view, deltas are fundamental elements that allow the primary accumulation of a huge volume of clastic sediments in marine and lacustrine basins. Once accumulated in the basin, these deposits can be modified, eroded and redistributed by diffusion processes, drift currents and/or intrabasinal gravity flows. Nevertheless, field observations in a number of marine and lacustrine basins indicate that the primary source of clastic sediments in most basins is the direct supply and accumulation by rivers, specifically through different kind of poorly known delta types. The paradigm proposed in this paper suggests that fluvial systems and their associated deltas can work at different levels of efficiency over geological time (see also the 'dynamic system' of Moore (1969), and the 'fluvio-turbidite system' of Mutti et al., 1996). During inefficient periods, rivers mainly supply relatively clean-water discharges where sediments are mainly transported as bedload. The resulting deltas compose littoral forms as hypopycnal littoral deltas and HOLDs. During moderately efficient periods, suspended sediments in river discharges can generate diluted hyperpycnal plumes that distribute river sediments along extended areas commonly aided by waves, tides and ocean currents. These deposits constitute extended shallow progradational clastic ramps related to HLDs, often recognised as parasequences. Finally, during highly efficient periods, rivers can supply freshwater, sediments, organic matter and extrabasinal components to inner basin areas, allowing a rapid burial and long-term geological preservation (Kao et al., 2010; Zavala et al., 2012; Otharán et al., 2020; Cunningham & Arnott, 2023) in HSDs (shelfal lobes, slope and deep-water fans) and HFDs.

Since extrabasinal turbidity currents commonly transport relatively coarse-grained sediments, their deposits are assumed to be organic carbon poor compared with muddy marine deposits. Controversially, recent studies (Saller et al., 2006; Hage et al., 2020; Sarno et al., 2020; Hussain & Al-Ramadan, 2022; Ismail et al., 2023) suggest that land-generated (extrabasinal) turbidites often show higher total organic carbon with respect to the surrounding mudstones. Hyperpycnal flows have been proved to also be an important contributor to the flux of land-derived organic carbon towards distal, central basin areas (Zavala et al., 2012; Liu et al., 2013; Baudin et al., 2017, 2020; Furota et al., 2021; Hussain & Al-Ramadan, 2022; Otharán et al., 2022; Ismail et al., 2023).

In conventional models, littoral delta systems have been considered as one of the main contributors of coarse-grained (sand-gravel) sediments in coastal areas of related basins. Nevertheless, in many contemporaneous rivers, these coarse-grained sediments (transported as bedload) represent less than 10% of the total supplied sediments (Milliman & Meade, 1983; Liu et al., 2009). Milliman and Farnsworth (2013) estimated that rivers globally supply *ca* 19 GT of suspended sediment load per year, with 70% of this total attributed to large Asian rivers. In these rivers, about 30 to 50% of the suspended sediment load is trapped at the lower delta plain/river mouth, 20 to 30% accumulates on the shelf (adjacent to the river mouth), while

30 to 40% is transported far (600–1500 km) from the river mouth by hyperpycnal plumes aided by ocean currents and diffusion processes (Liu et al., 2009). These plumes are formed by the direct discharge of diluted hyperpycnal flows, and consequently their deposits should be considered as true deltaic (HLD) deposits. Hyperpycnal littoral deltas are here considered the real 'shelf builders' and provide a rational explanation for the extended distribution of graded fine-grained (mud-silt) deposits along the shelf (DeMaster et al., 1985; Nittrouer et al., 1986; Allison et al., 2000), often forming part of distal progradational parasequences. Understanding the relationship between mud-rich flows and deltaic diluted hyperpycnal plumes is challenging, and will require further studies.

7 | CONCLUSION

This paper introduces and discusses, in some detail, a new and broader definition and classification of deltas. In this contribution, all sediments primarily and directly supplied and accumulated by land-derived flows in a standing body of water are considered delta deposits, despite their shape and location along the depositional profile. In shallow water areas, the transport of land-derived sediments can be facilitated by diffusion processes such as tides and waves. In contrast, deposits eroded and substantially remobilized by intrabasinal processes like longshore currents, geostrophic currents, gravity instability, waves and tidal currents, among others, are not regarded as delta deposits.

A key point justifying the expansion of the delta definition is the consideration of the significance and variability of natural fluvial discharges, which can supply relatively dense mixtures of water and sediments. By contrasting the density of fluvial discharges with the density of basin waters, three main fields (hypopycnal, homopycnal and hyperpycnal) and seven types of deltas can be identified. Of particular interest are hyperpycnal deltas, as hyperpycnal processes enable the basinward transfer of a huge volume of sediments during river floods.

The results presented and discussed in this paper demonstrate that deltas are still poorly understood, and their deposits can be far more complex than previously considered.

ACKNOWLEDGEMENTS

Ideas and concepts introduced in this contribution are the result of more than 30 years of research in clastic sedimentology. During this time, a number of prominent geoscientists contributed with constructive field discussions. Our special thanks to Emiliano Mutti, Giancarlo Davoli, Eduard Remacha Grau, Marco Sanguinetti, Helena Gamero, Livan Blanco Valiente, José Carballo, Manuel Delgado, José Marcano, Juan José Ponce, Luis Buatois, Konstantin Zverev, Juergen Schieber, Xiangbo Li, Huaqing Liu, Shuxin Pan and Germán Otharán. We greatly appreciate the support of many oil companies that have invested in applied scientific research, particularly YPF, Perez Companc, Tecpetrol, Pluspetrol, CAPEX, Vista Oil & Gas, Enarsa, Repsol, Alrep, Eurotec-Yugra, PDVSA, PEMEX, CAYROS, TotalEnergies, Hocol, PetroChina and Gazprom Neft. Finally, the authors would like to express their sincere gratitude for the valuable comments and constructive criticism provided by Professors Ron Steel and Janok Bhattacharya during the peer review process. Their suggestions have significantly improved the quality of the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Zavala, C., Arcuri, M., Zorzano, A., Trobbiani, V., Torresi, A. & Irastorza, A. (2024) Deltas: New paradigms. *The Depositional Record*, 00, 1–37. Available from: https://doi.org/10.1002/dep2.266