

Research Article

Where Did All the Suspended Sediment Go?

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The Sedimentary Record

Studies of mud transportation and deposition in modern shelf settings indicate that fine-grained siliciclastic sediment is deposited from suspension in various ways. However, contemporary interpretations of ancient analogs (e.g., epeiric seaways such as North America's Cretaceous Western Interior Seaway, or Devonian Appalachian Basin) focus almost entirely on mud deposition from energetic bottom currents. If suspension deposits are not present in the rock record, but modern studies indicate those deposits should be present, it is appropriate to ask where all the suspended sediment went in the geologic past.

In this paper I argue that mud dispersal from a river mouth to the shelf is likely to be a multi-stage process that includes transportation in suspension and in bottom currents. Most or much silt and clay discharged at a river mouth is deposited on the shelf within a few tens of kilometers from hypopycnal plumes. Data from modern rivers suggests that hyperpycnal flows are relatively rare events. Plume deposits on the inner shelf can be reworked downslope by wave-enhanced sediment gravity flows. Other types of currents ensure that most mud deposited on a shelf is reworked and transported further offshore and along depositional strike by bottom currents. The sedimentary record preserves evidence only of the last phase of sediment transport, i.e. via bottom currents. Undisturbed muddy suspension deposits might be preserved in very proximal settings (associated with high sedimentation rates), interbedded with sandy storm deposits (as “fair-weather shales”) or in very distal settings as claystones or in marine snow.

INTRODUCTION

Defining sediment dispersal systems from rivers is important from many perspectives. That effort is necessary to understand the fate of contaminants, organic carbon, and sediments delivered to the sea, and it also helps us to interpret ancient depositional systems. Often, there is a need to link process and product, for example by inferring sediment transport mechanisms from sedimentary structures in cores or outcrops, or by studying modern depositional systems and inferring what their deposits might look like in the rock record.

In recent years, papers focused on shale¹ sedimentology in epeiric seas of the past (e.g., Bhattacharya & MacEachern, 2009; Li & Flaum, 2025; Moore et al., 2020; Percy & Pedersen, 2020; Wilson & Schieber, 2015) have referred to a paradigm shift in that field. These and other papers contrasted a traditional view that characterizes shale as consisting of mud deposited from suspension in quiet-water conditions with a newer conceptual model that emphasizes mud deposition as bedload under unidirectional currents.

It is indisputable that mud can be transported along the sea floor as bedload or various types of wave- or gravity-driven fluid mud flows. However, I argue herein that interpretations of ancient shallow-marine systems that do not recognize muddy suspension deposits are not actualistic and hence are untenable. I present my argument in two parts. First, I synthesize knowledge from studies of modern muddy depositional systems, focusing specifically on siliciclastic sediment delivered to shallow-marine environments by rivers. These studies illustrate the importance of suspended sediment transport of mud and provide clues as to what muddy suspension deposits should look like in the rock record. In the second part of the paper, I integrate learnings from the modern examples with the rock record to develop a depositional model.

SEDIMENT DISPERSAL AT RIVER MOUTHS – A REVIEW

In flowing rivers, silt- and clay-size particles (mud) are transported in suspension, forming the wash load of the flow. Cohen et al. (2022) suggested that approximately 80% of the global sediment flux from rivers is in the form of

¹ Like Schieber (2016), I use the term shale to refer to rocks sometimes referred to as mudstones or mudrocks.

wash load, and nearly 15% of the flux is in the form of sand suspended in the flow at high fluvial discharges. The general dominance of suspended load in modern fluvial systems was also noted by Mulder et al. (2003). The nature of an individual river's sediment discharge (volumes, grain size) is a function of drainage basin size, relief within the basin, geology of the basin, climate, runoff, vegetation, and trapping of sediment in lakes, on delta plains, and elsewhere (Syvitski, 2003).

As river enters the sea, fresh water interacts with ambient salt water in several ways that affect mud dispersal. Most noticeably from surface or satellite observations are sediment-laden hypopycnal plumes, buoyant but muddy fresh water issuing from the river mouth that enters the sea and overrides the denser salt water (Fig. 1). Interactions between a hypopycnal plume and ambient water are affected by influences such as waves or tides, suspended sediment concentrations, and bathymetry (e.g., Geyer et al., 2004; Horner-Devine et al., 2015; Wright, 2012). Oceanic fronts typically restrict the plume to the inner shelf less than a few 10s of kilometers from the river mouth while barotropic forcing combined with Coriolis force tends to deflect the plume along shore (to the right in the northern hemisphere).

Plume expansion reduces flow velocity, and suspended sediment carried by the river therefore settles as the flow enters the marine realm. Sediment deposition is affected by the interaction of multiple factors in ways that have long been documented and continue to be refined (e.g., Davarpanah Jazi & Wells, 2020; Wright, 1977; Zavala et al., 2021). In general, coarser sediments (including sand and silt) are deposited from suspension closest to the river mouth whereas clays and silt can be transported in the surface plume tens of kilometers from the river mouth (Figs. 1,2). Clays flocculate to form aggregates that settle through the plume more quickly than individual clay particles, but experimental work of Strom and Keyvani (2016) led those authors to conclude that flocs are carried basinward at least several kilometers from river mouths before beginning to settle from hypopycnal plumes. That experimental result is qualitatively supported by satellite imagery of muddy hypopycnal plumes extending tens of kilometers away from river mouths (e.g., Figs. 1,2).

Mud deposited from hypopycnal plumes is widely documented from studies of modern deltas (e.g., Barrie & Currie, 2000; Hart et al., 1995, 1998; Keller et al., 2017; Milligan et al., 2007; Wheatcroft et al., 1997; Yang & Liu, 2007). In the submarine portions of the Fraser Delta, suspension deposits form a basinward-tapering wedge that is mostly below storm wave base (Fig. 2) and drapes underlying topography (Hart et al., 1995). Although satellite images typically show the plume as being restricted to an area less than 20 kilometers from the river mouth, sediment settling from the plume is transported tens of kilometers more by ambient currents in the mid-water column (Hart et al., 1998). In other words, mud deposited from suspension covers an area that is considerably greater than the area of the hypopycnal plume defined in satellite images. Even muds deposited in > 100 m water depth are pervasively bio-



Figure 1. Satellite images of muddy hypopycnal plumes from medium-size rivers. In all cases, abrupt color changes at the plume margin define oceanic fronts that define the seaward movement of the plume. A) The mouths of the Tiber River, Italy entering the Mediterranean Sea. Image from European Space Agency. Coriolis force deflects the plume to the right in this northern hemisphere setting. Latitude/longitude of center of image approximately 41.74°/12.07°. B) Google Earth image of Zambezi River, Mozambique. Latitude/longitude of center of image approximately -19.04°/36.56°. Although collected in the dry season, and dams on river upstream restrict sediment load, the hypopycnal plume is dispersing mud tens of kilometers to each side of the river mouth and over 20 kilometers offshore. C) Satellite image of Burdekin River, Australia during low discharge. Coriolis force deflects the plume to the left in this southern hemisphere setting. Latitude/longitude of center of image approximately -19.65°/ 147.68° D) Same area as Part C but during high fluvial discharge. Comparison of the images in Parts C and D clearly demonstrates the fluvial discharge greatly affects our perception of the importance of hypopycnal plumes as mechanisms for transporting mud basinward.

turbated because bottom-waters are well oxygenated. It is important to note that the Fraser is a deep-water delta, prograding into water over 200 m deep approximately 5 kilometers from the delta front, and several characteristics of the mud deposits in that setting are best regarded as a counterpoint to muds deposited in relatively shallow epicontinental basins.

In addition to the sediment transported in hypopycnal plumes, sediment-laden density currents can be generated at river mouths in 3 ways (Zavala et al., 2021). First, rapid deposition at a river mouth can lead to oversteepening and submarine failures that initiate density currents. These density currents can transport both sand and mud downslope and basinward (e.g., Coleman et al., 1993; Hart et al., 1992; Keller et al., 2017).

Second, hyperpycnal flows can be generated if suspended sediment concentrations cause the water to be denser than the ambient marine water (Mulder & Syvitski,

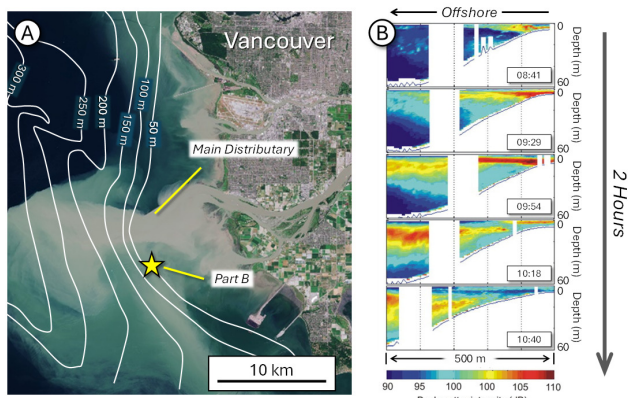


Figure 2. Suspended sediment deposition from a hypopycnal plume on the Fraser Delta, Canada. A) European Space Agency satellite image showing simplified bathymetry, the location of main distributary channel, and the location of the suspended sediment profiles shown in Part B. The hypopycnal plume extends >10 kilometers offshore. Image collected at high tide during a period of relatively low fluvial discharge. Wind was pushing the plume to the southeast on this day. Latitude/longitude of center of image approximately: 49.09°/-123.37°. **B)** Consecutive acoustic doppler current profiles (in backscatter intensity) collected at location of star in Part A but during a period of high fluvial discharge. Modified and reproduced with permission from Hill et al. (2008). Backscatter intensity is a proxy for suspended sediment concentrations, primarily fine sand in this case. Over a 2-hour period of ebbing tide, a hypopycnal plume transported sediment (red-yellow colors) several hundred meters from the river mouth before it began to settle. Finer grained mud is transported greater distances seaward, especially where it emanates from the main fluvial distributary, as seen in Part A.

1995). In this case, a dense, sediment-laden river flow issuing from the river mouth plunges as a jet toward the sea floor and travels basinward under the influence of gravity. These types of flows generate the hyperpycnites of Bhattacharya and MacEachern (2009) who suggested those deposits form a significant component of Cretaceous muddy shelf deposits in the North American Western Interior Seaway. Mulder et al. (2003) predicted that at least 84% of all rivers can generate at least 1 hyperpycnal flow per 100 years but that only 4 in 10 modern rivers generate hyperpycnal flows annually. Hyperpycnal flows are clearly not ubiquitous, annual features of most river mouths, and it is therefore not actualistic to infer that all or even most mud in epicontinental seaways was transported basinward by such currents.

Finally, hyperpycnal flows can be generated at river mouths if a turbidity maximum, a zone of high suspended sediment caused by flocculation within a river or estuary, is pushed out of the river mouth at high fluvial discharges

and/or spring tides (Hage et al., 2019). This process has not been widely documented for modern rivers.

Once deposited on a shelf, via any means, mud can be re-suspended by storm waves, wind-generated currents, tidal currents, and breaking of internal waves within the water column. When waves resuspend fine-grained sediment, and the sea-floor slope is adequate, resuspended mud can move downslope as fluid mud in wave-enhanced sediment gravity flows (WESGFs; Traykovski et al., 2000; Macquaker et al., 2010). Figure 3 illustrates a portion of the Pacific continental shelf seaward and north of the Eel River in northern California. This area was studied by the STRATAFORM project (see summary in Sommerfield et al., 2007) that combined oceanographic and geologic analyses to evaluate sediment transport on modern continental shelves. During high fluvial discharges, the hypopycnal plume transports and deposits mud on the inner shelf many tens of kilometers north of the river mouth, in accordance with the previous discussion of how oceanic fronts and Coriolis force affect movement of such plumes. However, most mud does not stay on the inner shelf in this area. Instead, it is subsequently transported downslope (offshore) under the com-

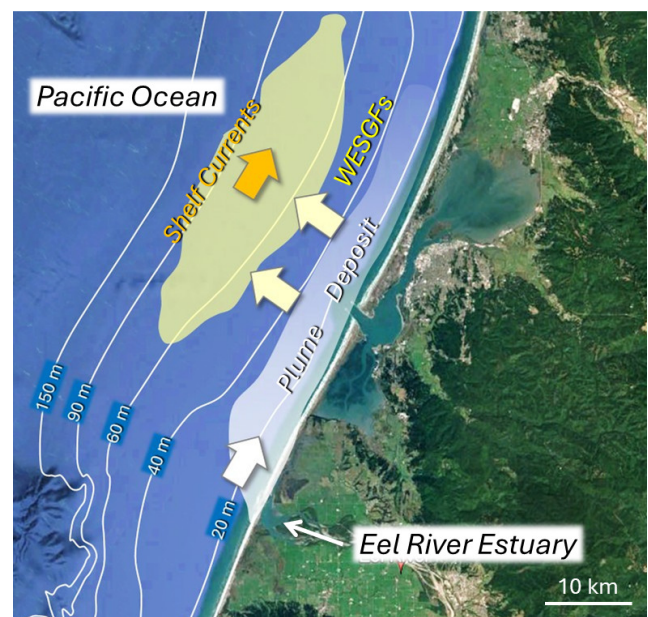


Figure 3. Google Earth image of a portion of northern California, showing the coastline near the mouth of the Eel River estuary. At high fluvial discharges, hypopycnal plumes deposit mud on the inner shelf north (to the right) of the river mouth (white shading). Most mud from this deposit is subsequently transported basinward by wave-enhanced sediment gravity flows (WESGFs; yellow arrows) and resedimented as part of a mid-shelf mud belt (yellow shading). Once on the outer shelf, muds are reworked along depositional strike by waves interacting with shelf currents (orange arrows). Simplified continental shelf bathymetry and locations of mud deposits modified from Traykovski et al. (2000). Latitude/longitude of center of image approximately: 40.78°/-124.35°.

bined influence of waves and gravity to form a mid-shelf mud belt. Coring by Crockett and Nittrouer (2004) suggested that only about 10% of plume-derived mud is preserved on the inner shelf where it is interbedded with sand. This mud was deposited during large fluvial discharges and was not completely winnowed before being buried by the next layer of sand. Whereas these observations and the results of Traykovski et al. (1999) highlighted the purely downslope movement of density-driven currents, data of Puig et al. (2003) showed that most of the mid-shelf mud, originally deposited by WESGFs, was subsequently transported along the bathymetry in response to resuspension of bottom sediments by waves with advection by wind- and tide-generated currents.

Few recent descriptions of ancient muddy shelves discuss the existence of suspended sediment transport in nepheloid layers although they are known to be important agents of sediment transport on modern shelves (Díaz et al., 1996; Lorenzoni et al., 2009; Nittrouer & Wright, 1994; Oliveira et al., 2023; Pak & Zaneveld, 1977). Nepheloid layers are water masses that have higher suspended sediment concentrations than overlying and/or underlying water and they can be several tens of meters thick (McCave, 1986). Nepheloid layers can be generated by resuspension of bottom currents or fluvial discharges and can travel both along and across shelves because their movement is driven by oceanic currents (wind generated, geostrophic, etc.) rather than simply by gravity.

Halper and McGrail (1988) measured suspended particulate matter, current velocity, and water temperature on the outer continental shelf (~100 m water depth) near the Texas – Louisiana border. They defined a bottom nepheloid layer (BNL) up to 10 m thick and composed of sediment (mostly clay and silt) that had been resuspended in shallower water and transported offshore in that layer by shelf currents. The BNL in that area was not generated by local resuspension of bottom sediments by waves, even during the passage of major storms, because the study area was below storm wave base.

Díaz et al. (1996) studied the transport of mud, mostly clay aggregates, in nepheloid layers basinward of the Ebro Delta (Fig. 4). Their study was not associated with the passage of major storms or during major fluvial discharge and so is probably a good analog for fairweather processes on shelves. Their data show a BNL locally over 10 m thick that extended offshore ~30 kilometers towards the shelf margin out to a water depth of >80 m. The dominant transport direction for the BNL was alongshore (southwest) mostly in response to ambient currents on the shelf. The BNL and intermediate nepheloid layers (within the water column) form as sediment is resuspended in shallow waters during storms. Clay and fine silt remain suspended in these layers, even as aggregates, after passage of storms because of the fine-grained sediment's low settling velocities.

Several factors affect the utility of modern shallow-marine environments as analogs for mud deposition in ancient deposits. Because of Holocene transgression, most shelf areas do not receive significant amounts of river-borne mud, and estuaries (like that of the Eel River; Fig. 3) trap sedi-

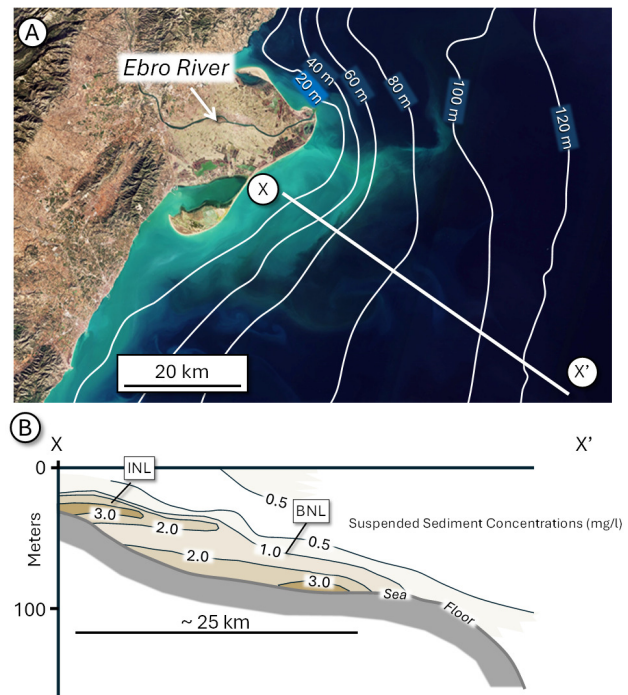


Figure 4. A) Satellite image of the Ebro Delta showing simplified shelf bathymetry and location of profile X-X' of Part B. Note light color of hypopycnal plume that is deflected to the right and restricted to a few 10s of kilometers offshore. Latitude/longitude of center of image approximately: 40.58°/ 0.97°. B) Profile of suspended sediment concentrations define nepheloid layers (suspended sediment concentrations > 0.5 mg/l) along the profile X-X'. Bathymetry and profile location redrawn from Díaz et al. (1996). The bottom nepheloid layer (BNL) extends several tens of meters above the sea floor and several tens of kilometres offshore. An intermediate nepheloid layer (INL) is also in the profile. Suspended sediment measured in October 1984, typically a time associated with low fluvial discharge, satellite image from December 2024, generally a time of low to moderate fluvial discharge.

ment. Damming of rivers has also reduced sediment fluxes in many cases. As such, processes and fluxes defined by studying those systems are unlikely to be representative of ancient prograding shorelines. Mid-shelf mud belts like those of northern California (STRATAFORM study area) and elsewhere develop on relatively sediment-starved modern continental shelves (e.g., Hanebuth et al., 2015) and are not ideal analogs for thick, laterally extensive shales of ancient epicontinental basins. In these latter basins, river-borne mud must have accumulated everywhere on the shelf, leading to progradation, i.e. sediment was deposited faster than it could be removed.

A different type of challenge is associated simply with studying sediment transport on modern shelves. Studies like those of Díaz et al.'s (1996) study of the Ebro continental shelf, the STRATAFORM study of the California continental shelf (e.g., Sommerfield et al., 2007), and the AQUIMAR study of the Portuguese continental shelf

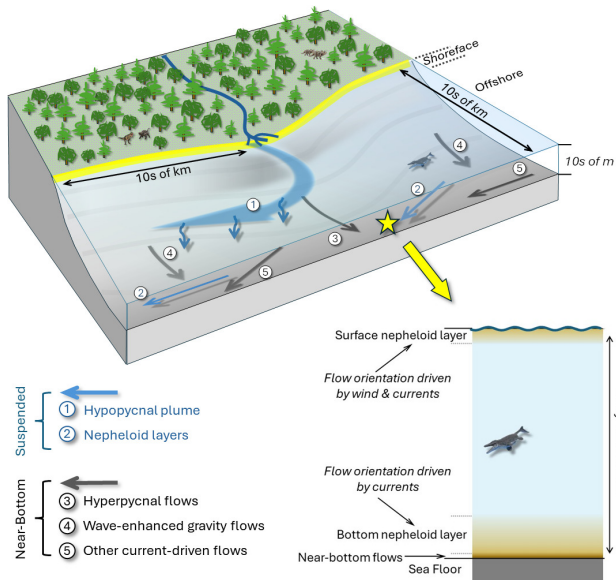


Figure 5. Diagrammatic illustration of processes that transport mud offshore and alongshore as near-bottom flows (grey arrows) and in suspension (blue arrows). Inset at lower right shows water-column structure 10s of kilometers from the shoreline in water many 10s of m deep. See text for discussion.

(Oliveira et al., 2023) involve equipment (current meters, sediment traps, suspended sediment profilers, etc.) that is expensive and logistically challenging to deploy. It is typically not possible to characterize sediment fluxes at the sea floor and in the water column at multiple locations on the shelf simultaneously. For example, measurements of sediment fluxes on the northern California shelf during the STRATAFORM project were constrained to the bottom <1 m of the water column and sediment fluxes in nepheloid layers above that level in the water column could not be defined with the equipment available. For these and other reasons (e.g., difficulties associated with measuring currents and sediment fluxes on the shelf during intense storms) it is not feasible to quantify and compare the relative proportions of mud transported in hypopycnal plumes, nepheloid layers, hyperpycnal flows, WESGFs, or other types of flow on modern continental shelves.

A DEPOSITIONAL MODEL

A viable depositional model for mud deposition in ancient epicontinental basins must include the mechanisms, transportation in suspension and in bottom currents, observed to disperse mud from river mouths to continental shelves. That depositional model must also explain the pervasive occurrence of sedimentary structures in shales that indicate the precursor muds were deposited by bottom currents. The model needs to explain how mud can be transported tens to hundreds of kilometers both downslope and along slope to form laterally extensive mud blankets. I contend all these conditions can be satisfied by recognizing the transport path from river mouth to final site of deposition is likely to be a multi-stage process that can include sep-

arate stages of sediment transport in suspension and via bottom currents. I summarize these processes in Figure 5 which portrays the proximal area of the depositional model presented by Hart (2016) and Hart et al. (2024). The data needed to make quantitative generalizations about the relative contributions of various mud dispersal processes are simply lacking. For that reason, I purposely choose to be qualitative in the following discussion.

I suggest that much, or most silt and clay supplied to the sea by river mouths is deposited from buoyant plumes and settles on the shelf within several tens of kilometers of river mouths. In general, these muds will be bioturbated, obliterating any laminations or thin beds that may have been generated by fluctuations in sediment discharge. This model agrees with published data about the preponderance of mud transport in rivers as wash load (Cohen et al., 2022), experimental evidence that flocculation-enhanced settling begins only after the plume is a few kilometers from the river mouth (Strom & Keyvani, 2016), STRATAFORM measurements of plume deposits on the inner shelf along strike from the Eel River (Fig. 3), and satellite imagery that shows the occurrence and locations of hypopycnal plumes (e.g., Fig. 1).

I argue the flux of mud to the shelf via hypopycnal plumes is, on average, greater than the flux from hyperpycnal flows. Although the amount of sediment transported basinward by hyperpycnal flows can be substantial, the available data indicate these flows are not generated annually at most river mouths (Mulder et al., 2003; van Loon et al., 2019). It is also important to stress that hyperpycnal flows, when generated at river mouths, only transport sediment downslope. Their deposits are restricted to areas directly seaward of river mouths and so, by themselves, these flows will not generate laterally extensive shales of ancient epicontinental basins.

However mud is first deposited on the shelf, the sedimentary record clearly shows reworking by waves and bottom currents appears to effectively transport and modify most of those deposits, and that type of multi-stage sediment transport is implied by Figure 5. The STRATAFORM project and similar studies show that net along-shore sediment transport on a shelf occurs in two end-member ways. The first path begins with plume-derived mud deposited on the inner shelf along strike from a river mouth. This mud can be transported offshore by bottom currents during storms (e.g., Fig. 3). Bottom currents generated by coastal set-up during storms could transport inner-shelf mud obliquely offshore due to the combined influence of gravity and the Coriolis force. In outer shelf settings, remobilization and along-strike (and offshore) transportation of mud by bottom currents occurs through various combinations of waves and currents, the latter being generated by winds, thermohaline circulation, tides, or other forcing mechanisms (e.g., Díaz et al., 1996; Slingerland & Keen, 1999; Poag et al., 2003; Hanebuth et al., 2015; Schieber, 2016). Multiple episodes of deposition and remobilization could be possible in the relatively shallow shelf settings believed to characterize epicontinental basins, and the flows that erode and transport mud on the shelf generate erosion sur-

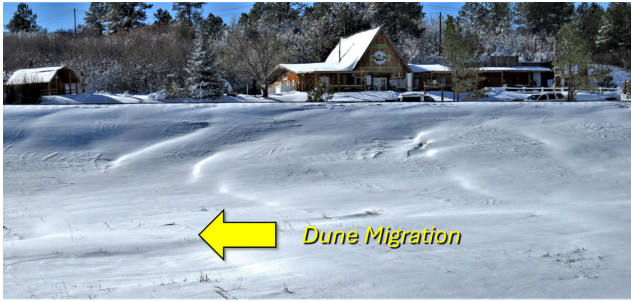


Figure 6. Snow forming wind-blown dunes, indicating transportation as bedload. The snow was originally a suspension deposit. A useful analog for conceptualizing how bottom currents can generate bedforms by reworking of mud first deposited from suspension.

faces, graded beds, laminations, and ripples that are commonly described in ancient shelf shales (e.g., Bhattacharya & MacEachern, 2009; Plint, 2014; Schieber, 2016; Wilson & Schieber, 2015). To summarize, most suspension deposits are reworked by bottom currents on the shelf.

Certain accumulations of snow are useful for understanding how sedimentary evidence of transportation by bottom currents in muds can be so abundant in sediment first deposited from hypopycnal plumes (Fig. 6). Snow settles from clouds that are moved by wind, i.e. the snow is a suspension deposit. Under the appropriate conditions, snow on the ground can be reworked by bottom currents (wind) to form dunes, ripples, and erosion surfaces. Sedimentary structures preserved in the snow indicate it was transported as bedload. Other than its composition, there is no sedimentary evidence that the snow originated as a suspension deposit.

Note that resuspension of mud generates nepheloid layers that transport mud in suspension in directions that are defined by the ambient currents. The currents need not be strong to transport dispersed clays or clay aggregates long distances. In North America's Cretaceous Western Interior Seaway (KWIS), those currents could include those associated with the same counterclockwise gyre that transported Tethyan waters northward along the eastern margin of the seaway and Boreal waters to the south along its western margin (Slingerland et al., 1996). There are no data to constrain how volumetrically important this type of transport might have been, but modern analogs suggest the amount of sediment dispersed this way would not be zero.

I propose there are three cases where suspension deposits are likely to be preserved (Fig. 7): in very proximal settings near river mouths where high sedimentation rates deposit mud and sand faster than it can be reworked, in shelf settings where “fair-weather shales” are interbedded with sandy “event beds” (e.g., storm deposits, hyperpycnal flows), and in distal areas dominated by pelagic deposits.

An example of rapidly deposited mud in a shallow, proximal area is shown in Figure 8. This outcrop exposes an Upper Cretaceous sharp-based shoreface sandstone overlying a thick package of shale, deposited along the western

shore of the KWIS. Between the two deposits is a sandstone unit with large load structures indicating the sands were deposited quickly onto poorly consolidated, perhaps thixotropic, mud. The stratigraphic position of the muds suggests they could have been deposited from suspension

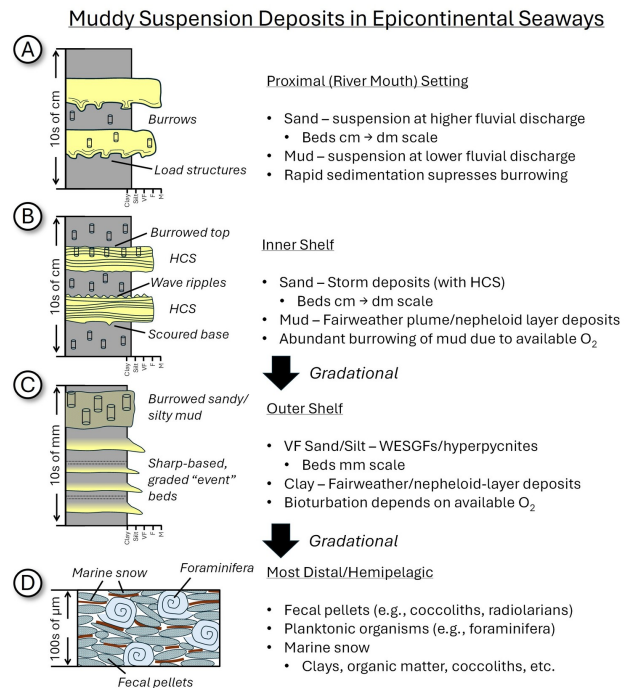


Figure 7. Simplified illustrations of muddy suspension deposits that have not subsequently been reworked by currents. Note differences in scale between images. A) Muds deposited at lower fluvial discharges interbedded with sands deposited at higher fluvial discharges. Rapid sand deposition results in soft-sediment deformation structures. B) On the inner shelf, hummocky cross-stratified sandstones (HCS) represent storm deposits and interbedded muds represent muds deposited from suspension between storms (“fair-weather shales”). C) In outer shelf settings, thin sharp-based sandstone/siltstone “event beds” can be produced by either wave-enhanced sediment gravity flows (WESGF) or hyperpycnal flows emanating from a river mouth. Thin claystone beds are nepheloid layer deposits deposited between events. In well-oxygenated settings, bioturbation can homogenize the sediment. Note implied gradation in thickness, texture and sedimentary structures between inner-shelf (Part B) and outer-shelf (Part C) settings. D) In some basins, distal areas can receive little siliciclastic input. Organomineralic aggregates (“marine snow”), including clays and very fine silt carried in suspension, settle to the sea floor along with fecal pellets and remains of larger pelagic organisms. Pelagic components can be calcareous (e.g., coccoliths) or siliceous (e.g., radiolaria). Note implied gradation in composition between claystones deposited by nepheloid layers (Part C) and calcareous/siliceous shales dominated by remains of pelagic organisms.



Figure 8. Load structures (arrow) at the base of a sharp-based shoreface, Upper Cretaceous Atarque Member of the Tres Hermanos Formation, near Moreno Hill, western New Mexico (approximate latitude/longitude: 34.59° / -108.77°). Seated person circled at lower left for scale. Inset at lower right shows detail of the structures to the right of the arrow (hat for scale). The sands were deposited on soft muds that were possibly hypopycnal plume deposits as shown in [Fig. 7A](#).

(hypopycnal plume) in a rapidly prograding, very proximal area ([Fig. 7A](#)).

A second scenario for preservation of muddy plume deposits is as “fair-weather shales” interbedded with sandy tempestites (e.g., hummocky cross-stratified sandstones, wave-enhanced sediment gravity flows) in shelf deposits (e.g., Dott and Bourgeois, 1982; Jelby et al., 2020; [Figs. 7B,C, 9](#)). I suggest these shales are plume deposits, representing mud sedimentation in the relatively calm (“fair-weather”) periods between the storms that generated the sandy tempestites. Where the shales appear to gradationally overlie sandy tempestites, the interpretive challenges of distinguishing mud deposition from waning flow versus hemipelagic deposition between storms are analogous to those associated with interpretation of d and e divisions of Bouma sequences, as noted many years ago by Dott and Bourgeois (1982). The case for a break in sedimentation at the top of tempestites, i.e. storm versus non-storm deposits, is easiest to make when sharp contacts are present between the sandy storm deposits and overlying shales ([Fig. 9A](#)). Further offshore, wave-enhanced sediment gravity flows were described by Macquaker et al. (2010) as having an uppermost clay-rich drape that can be burrow mottled. I argue some of that clay-rich material could represent slow sedimentation from surface plumes or nepheloid layers.

A third possible path for preservation of muddy suspension deposits is via deposition from nepheloid layers. Sediment in modern nepheloid layers consists primarily of clay-size particles with minor fine-grained silt. Sedimentation rates are likely to be slow. In very distal areas, sili-

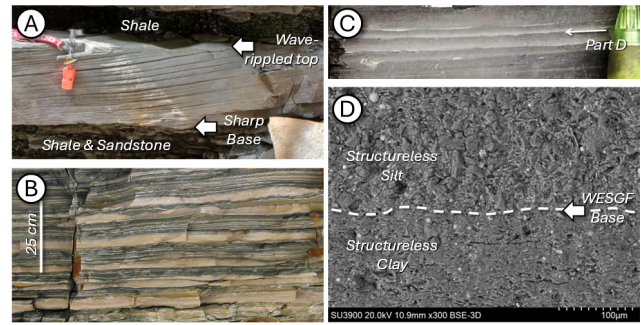


Figure 9. Mud and tempestites (c.f. [Figs. 7B,C](#)). **A)** Recessive bed of shale abruptly overlying hummocky cross-stratified sandstone bed in the Lower Cretaceous Cadotte Formation, British Columbia. Note wave ripples at top of the sandstone. The sedimentology suggests the overlying shale bed is not genetically related to the sandstone. **B)** Millimeter- to centimeter-scale very fine-grained sandstones (with ripple cross lamination and flute marks) interbedded thin shales (dark grey) in the Upper Cretaceous Mancos Shale, Book Cliffs, Utah. The sand was transported offshore by storms, suggesting the shale could represent fair-weather deposition of mud from suspension. **C)** Millimeter-scale wave-enhanced sediment gravity flow (WESGF) deposits in the Upper Cretaceous Belle Fourche Formation of Alberta (location of core, 6-4-17-13W4, shown in [Fig. 9D](#)). Pen at right for scale. **D)** SEM image of the erosional contact between a claystone and the overlying WESGF deposit (approximate location shown by arrow in Part C). The textural characteristics of the claystone are those expected for deposits of nepheloid layers.

ciclastic mud might be mixed with planktonic debris (e.g., foraminifera, coccoliths) to varying degrees. The thin, sub-millimeter scale, clay-rich intervals shown capping wave-enhanced sediment gravity flow deposits in [Figure 9C,D](#) have the expected textural characteristics and could conceivably be deposits of nepheloid layers generated by the same storms that generated the underlying graded beds. [Figure 10A](#) shows clay-mineral aggregates mixed with coccoliths and marine organic matter (defined via Rock-Eval analyses) in an early Turonian marlstone of the Second White Specks. The clay aggregates are likely to be marine snow, coalesced clay platelets transported in nepheloid layers, that settled to the sea floor along with the coccoliths (e.g., Hart, 2016; Macquaker, Keller, et al., 2010; [Fig. 7D](#)). [Figure 10B](#) shows a claystone from the mid-Turonian Carlile Shale. The clay-dominated texture, with scattered pieces of marine organic matter and planktonic foraminifera (not shown), is that expected for deposits of a nepheloid layer in which remains of planktonic organisms form a minor component. Note that both the Second White Specks and Carlile Shale samples shown in [Figures 10A,B](#) were deposited over 500 km from the contemporaneous shoreline ([Fig. 10C](#)).

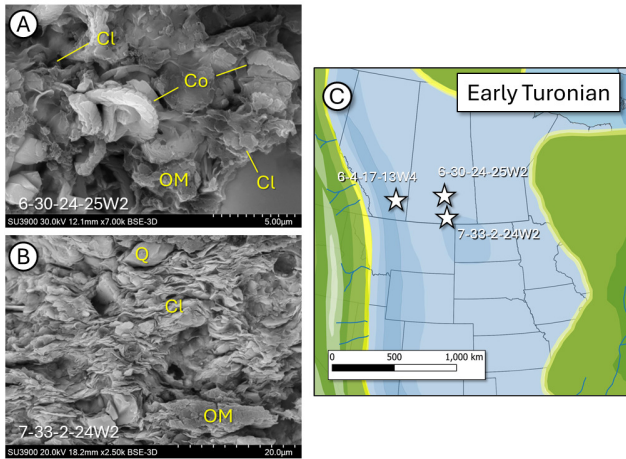


Figure 10. A) Clays (Cl), originally marine snow, with coccolith elements (Co) and marine organic matter (OM) in the lower Turonian Second White Specks Formation in the 6-30-24-25W2 core. B) Claystone with marine organic matter and fine-grained quartz silt (Q) from the mid-Turonian Carlile Shale in the 7-33-2-24W2 core. C) Location map showing approximate Early Turonian paleogeography and the locations of cores illustrated in Parts A and B and in Fig. 8C,D. An offshore-directed gradation in sediment between siliciclastic suspension deposits with minor pelagic biogenic components (Part B, Fig. 7C) and pelagic muds with minor siliciclastic mud (Part A, Fig. 7D) represents the distal portion of the facies model presented by Hart (2016; Hart et al., 2024).

Aside from the examples just presented, suspension deposits that have not subsequently been reworked can be predicted to have certain physical characteristics: they should be laminated (unless bioturbation destroys primary sedimentary structures), they should drape underlying topography, their grain size should decrease gradually away from the sediment source, and sedimentation rates (and hence sediment thickness) should decrease away from the sediment source. For example, variations in the relative contribution of plume-derived sediment (from coastal rivers) and primary productivity have generated laminated mud in anoxic basins below 250 in the Cariaco Basin (Lorenzoni et al., 2009). In contrast, plume deposits forming prodelta deposits of the Fraser Delta are pervasively bioturbated at those depths because the sea floor is well-oxygenated (Hart et al., 1998). Muddy suspension deposits drape underlying topography in prodelta areas of the Fraser

Delta (Hart et al., 1995, 1998) as they do in deep-water continental slope settings (e.g., Prather et al., 1998). Typically, these and other characteristics of plume deposits are only found at significant water depths (e.g., below 100 – 200 m depth) where sediments are not subsequently reworked by wave- or wind-generated currents. They may not be preserved in the relatively shallow waters of continental shelves or epeiric seaways.

PARTING THOUGHTS

Observations of modern prodelta and shelf settings clearly demonstrate that mud can be dispersed from river mouths in suspension and via bottom currents. The available evidence suggests that deposits of hypopycnal plumes should form a significant, if not dominant, component of sea-floor mud deposited within several tens of kilometers of river mouths. The best available analyses of modern hypopycnal flows suggest they are not commonly generated at most river mouths. These observations appear to conflict with interpretations of ancient shelf shales being predominantly, if not exclusively, bottom-current deposits.

Sedimentologists studying shales in ancient shallow-marine and shelf environments are therefore faced with a dilemma. There are three possible ways to reconcile the discrepancy between observations of modern mud dispersal processes and interpretations of shales in epicontinental basins: a) modern systems are not good analogs for ancient systems (if all mud in ancient systems was dispersed from river mouths by bottom currents), b) suspension deposits are under-recognized in ancient systems, or c) most muddy suspension deposits are eroded and transported by bottom currents. I suggest the latter two scenarios are likely to be true. Where did all the suspended sediment go? Most of it was reworked.

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