Porz, L.; Zhang, W.; Hanebuth, T.; Schrum, C.:

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In: Marine Geology. Vol. 432 (2021) 106402.

https://dx.doi.org/10.1016/j.margeo.2020.106402

Physical Processes Controlling Mud Depocenter Development on Continental Shelves – Geological, Oceanographic, and Modeling Concepts

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Abstract

Mud depocenters (MDCs) represent major proximal-marine sinks for fine-grained terrigenous material, carbon, and contaminants on modern continental shelves. Throughout the past decades, several studies have shed light on the physical processes controlling MDC development at various timescales, ranging from controlled flume experiments and in-situ oceanographic monitoring, to stratigraphic analyses of recent and ancient deposits based on seismo-acoustic and sediment-core data. Thereby, key mechanisms related to the formation and maintenance dynamics of MDCs have been discovered: a) cross-shore bottom transport of suspended mud through *gravity flows*, b) interaction of mud with density gradients associated with *oceanic fronts*, c) resuspension and dispersal control of mud by *internal waves*, d) *bedload deposition of mud* forming laminated bedding under energetic flow conditions, and e) mud resuspension resulting from *chronic bottom trawling*.

Among the physical processes identified or proposed, three conceptual paradigms for MDC development can be distinguished: 1. *continuous supply*, associated with a steady sediment supply and hemipelagic settling in relatively calm conditions; 2. *continual resuspension-deposition cycles*, wherein parts of an MDC area are subject to multiple cycles of resuspension, redeposition and reworking before ultimate burial; and 3. *episodic sedimentation and erosion*, in which extreme events such as riverine floods and atmospheric storms dominate the total, long-term sediment flux. Although the predominance of each of these paradigms within a single MDC depends to a large degree on the timescales considered, case studies tend to emphasize processes associated with only one of these three paradigms. As a result, the relative, long-term contribution of individual processes remains largely uncertain for many MDCs.

The ability of numerical models to accurately predict medium to long-term mud accumulation is restricted not only by computational costs, but also by insufficient parametrizations of the muddy sedimentation process. These remain challenging to constrain due to the multiplicity and complexity of factors affecting the cohesive properties of mud, including its state of consolidation, and the amount and type of organic matter present. Bridging the gap between individual events and long-term accumulation is the key to a more complete understanding of sedimentation processes in MDCs.

Keywords: mud, depocenters, shelf processes, sediment transport, numerical models

1. Introduction

Mud depocenters (MDCs) represent major shallow-marine, thus most proximal to the continent, sinks for fine-grained terrigenous material on modern shelves (Hanebuth et al., 2015). Various types of MDC have been categorized, according to their position on the shelf, topographic situation, hydrodynamic conditions, and sediment supply (McCave, 1972; McKee et al., 2004; Walsh and Nittrouer, 2009; Gao and Collins, 2014; Hanebuth et al., 2015). Comprising primarily silt (grain size <63 µm) and often some amount of organic matter (referred to collectively as “fines” hereafter), these sediment depocenters contain geological records important to the study of past climatic, oceanographic, and continental conditions (Potter et al., 2005). Moreover, MDCs serve as habitats and cradle for benthic life (Snelgrove, 1999; Thrush and Dayton, 2002) and as significant sinks, and maybe sources, for anthropogenic contaminants (Mahiques et al., 2015; Hanebuth et al., 2018), making them crucial components in ecosystem functioning. As major carbon storage areas (Blair and Aller, 2011; Bauer et al., 2013), MDCs may be considered an important element in the regional biotic and abiotic carbon cycles (Oberle et al., 2014; Hanebuth et al., subm.), and – on geological timescales – a potential source rock for hydrocarbons (Arthur and Sageman, 1994).

Prompted by their significance regarding ecology and environment, considerable effort has gone into the study of MDCs in the past decades, and various physical mechanisms involved in the formation and reworking of MDC deposits have been identified or proposed (e.g. Swift et al., 1972; Palinkas and Nittrouer, 2007; Wu et al., 2016b). Geological analyses of modern MDCs and their underlying late-Pleistocene to early-Holocene strata have provided insight into long-term formation mechanisms and the conditions under which MDCs initiate and continue developing, including shelf topography, relative sea level variations, and mean oceanic bottom-currents (e.g. Mountain et al., 2007; Syvitski et al., 2007; Hanebuth et al., 2015). Such approaches fundamentally lack, however, the temporal resolution needed to determine various short-term processes that are relevant for the overall shaping and growth of an MDC. To this end, oceanographic studies have progressed in determining the fluid mechanical processes bounding the appearance of MDCs, such as near-bottom gravity flows, internal waves, and oceanic density fronts (e.g. Traykovski et al., 2000; Cheriton et al., 2014; Liu et al., 2018; Williams et al., 2019; Zhang et al., 2019). These advances have encouraged a search for signatures of depositional processes in the microstratigraphy of ancient mudstone analogues (e.g. Leithold, 1989; Macquaker et al., 2010; Lazar et al., 2015; Wilson and Schieber, 2017; Boulesteix et al., 2019). In-situ monitoring and experimental flume studies have shed light on the hemipelagic and near-bed transport and sedimentation mechanisms of fines, including material flocculation dynamics, hindered settling of high-concentration suspensions, and consolidation and erosion processes (e.g. Le Hir et al., 2008; Schieber and Yawar, 2009; Mathew and Winterwerp, 2017; Xiong et al., 2017; Thompson et al., 2019). These results have, in turn, informed process-based numerical methods by constraining parametrizations related to the cohesive nature of mud (e.g. Mehta, 1991; Papanicolaou et al., 2008; Neumeier et al., 2008; Amoudry and Souza, 2011; Sherwood et al., 2018; Winterwerp et al., 2018). Meanwhile, increasing attention to ecosystem functioning has raised new questions regarding the role of benthic and hemipelagic biogeochemistry as well as anthropogenic impacts on the physical properties of mud (e.g. Le Hir et al., 2007; Andersen and Pejrup, 2011; Oberle et al., 2016a). It seems, thus, evident that a combined effort of various stratigraphic analyses, in-situ hydrodynamic monitoring, numerical coastal ocean modeling, and ecosystem research is required in order to advance our understanding of MDC development and functioning.

The goals of this review are to synthesize and structure the existing knowledge on physical mechanisms relating to the formation and shaping of MDCs, including the evaluation of hydrodynamic processes and of the geological record. Referring to existing literature, we discuss unresolved mechanistic problems and underline the necessity of an interdisciplinary approach in order to properly address and fully understand the relevant processes. A focus lies on the representation of physical mechanisms crucial for reproducing the local morphodynamics of MDCs in coastal sediment-transport models. While several of the individual concepts described herein are applicable to sediment dispersal systems in general, this study places emphasis on those mechanisms that are related to the dynamics of MDCs on continental shelves in particular.

The review is structured as follows: Beginning with a chronological assessment of existing literature relevant to the topic, we discuss MDCs from a sedimentological perspective, and present various points of view regarding their formation and maintenance dynamics. The next section describes mud sources and known physical processes involved in locally confined shelf mud accumulation. This compilation includes a discussion on the current state of coastal sediment-transport models required to resolve MDC dynamics. Finally, we summarize recent advances and remaining challenges in this field.

2. Existing concepts

2.1 Past reviews on mud depocenter dynamics

A handful of review articles exists on the topic of shelf mud sedimentation, each with a different focus, and some authors have proposed a classification of muddy shelf sedimentary systems.

McCave (1972) in his seminal work recognized that sites of mud accumulation on continental shelves are controlled by near-bed concentration of fines, particle sinking velocity, and the ratio of bed shear stress and critical shear stress for deposition. Further conceptualizing shelf mud deposition as a balance between near-bed suspended particle concentration and bottom hydrodynamic energy, he suggested five types of depositional mud patterns according to their distances from the coast, from proximal to distal: a) *Coastal* and b) *nearshore* mud deposits form during hydrodynamically calm periods, allowing for the development of sufficient cohesive strength at the seabed to withstand storm conditions. For c) *mid-shelf* deposits, waves and tidal currents limit shoreward accumulation, whereas an acceleration of tidal currents near the shelf edge limits its seaward extent. d) *Outer-shelf* deposits are attributed to settling from river-fed, high-concentration mud flows where storm waves cannot counteract supply. Lastly, e) *mud blankets* draping the entire shelf develop primarily off deltas with high riverine sediment discharge. The study identified advective hydrodynamic processes to be dominant over (non-directed) diffusion. By example of the East Coast of North America, Stanley et al. (1983) presented the concept of a “mudline” to denote the shoreward limitation of mud accumulation. More specifically, the mudline is defined as the boundary beyond which silt and clay content of the sediment increases substantially. The mudline serves as a natural energy level marker that defines the boundary between mobilization and settling of fines, and it may be located anywhere from the inner continental shelf to the middle continental slope depending on the long-term hydrodynamic conditions. Principle factors governing the regional mudline depth are shelf width (often in combination with shelf gradient), volume of sediment supply, and magnitude of bottom current energy. High sediment supply and low bottom-current energy were described as prerequisites for mud to accumulate on a shelf. This relationship was suggested to intensify with narrowing shelf width, that is, a narrower shelf would require higher sediment supply and/or lower bottom-current energy in order to sustain an MDC compared to a broader shelf.

In the ongoing effort to explain the range of the site-specific appearance and geometry of MDCs, a shift of focus over time from the water column to the near-bed environment took place. Most particulate transport occurs, according to Nittrouer and Wright (1994), near the seabed. They identified the mid-shelf as a primary location of MDC development globally and determined wind-driven flows, internal waves, surface waves during storms, infra-gravity waves, buoyant plumes, and surf-zone processes as important mechanisms for cross-shelf transport of sediment. By example of the Northern California shelf, Sommerfield et al. (2007) stressed the importance of an interaction between shelf bathymetry and near-bottom currents, which influences the lateral pattern and rate of mud accumulation on a wide range of temporal and spatial scales. They found that most of the mud transport to the Northern California shelf occurs during river flooding stages, where mud is sequestered through both static and dynamic trapping mechanisms within the bottom boundary layer (BBL: the part of the water column above the stationary seabed that is affected by the drag of ocean currents on the seafloor, typically with a thickness on the order of 10^0-10^1 m, Trowbridge and Lentz, 2018). Static trapping refers to deposition inside local topographic depressions in the receiving submarine basin, while dynamic trapping is characterized by particle flocculation, convergent circulation, and water column stratification leading to rapid sedimentation and sequestration of event deposits. During the past decades, increasing attention has been directed towards local hydrodynamics and biological activity. Gorsline (1984), for example, acknowledged bottom currents causing continual reworking of fines at the seabed, and biological activity leading to pelletization and bioturbation, which may alter the stratigraphic record significantly.

Some authors have focused on processes of mud dispersion related to riverine suspension plumes. McKee et al. (2004) differentiated four basic categories of riverine dispersal-dominated depocenters with respect to their relative position on the shelf and the main hydrodynamic forcing mechanism: a) *deltaic,* b) *subaqueous detached,* c) *shelf escape,* and d) *combined*. This classification is somewhat analogous to that of McCave (1972), though it is specific to river-dominated ocean margins and takes into account shore-parallel and vertical variability in depositional patterns. McKee et al. (2004) emphasized that the region 1-2 m above the sediment/water interface and the mobile upper region of the seabed is an important zone for the transport of fines and for the remineralization of organic matter and nutrients, but they concluded that knowledge of these processes was insufficient at that stage to discern their role in controlling fluxes of fines. Geyer et al. (2004) elucidated dispersal mechanisms of sediment associated with buoyant river plumes, including frontal trapping, particle flocculation and settling, and near-bottom fluxes of suspended fines. Their study emphasized the role of oceanic frontal dynamics in both trapping sediment on the shelf as well as generating high-concentration near-bottom layers that promote cross-shelf transport and deposition.

Walsh and Nittrouer (2009) distinguished five types of riverine-to-marine dispersal systems based on their geographic positions relative to the source, namely a) *estuarine-accumulation-dominated* (EA), b) *proximal-accumulation-dominated* (PAD), c) *marine-dispersal-dominated* (MDD), d) *subaqueous-delta-clinoform* (SDC), and e) *canyon-captured* (CC). Compared to previous classifications by McCave (1972) and McKee et al. (2004), the first two systems (EA and PAD) may be sorted into a nearshore/deltaic type, MDD is analogous to a mid-shelf deposit, SDC may extend from inner to mid-shelf regions, and CC refers to special cases where a submarine canyon is directly connected to the river mouth. A hierarchical decision tree based on fluvial discharge, shelf width, mean significant wave height, and tidal range allowed a prediction of the respective type of system for most of the world's largest riverine dispersal systems. Flocculation of solids dominates in nearshore depositional systems (EA and PD), while suspended sediment gravity flow and current-driven dispersion are the significant mechanisms acting in the dispersal systems where sediment accumulates further offshore (MDD, SDC, and CC). It was found that the distance of an MDC to its sediment source increases with significant wave height and with tidal range. These strong relationships led to the suggestion that in general, dispersal systems may not be sorted into discrete types but rather exist on a continuum as a consequence of the multi-parameter control on their geographic location, shape, size, internal architecture, sediment accumulation rates, and material composition.

Other reviews have focused on the problem of linking short-term transport and sedimentation processes to the overall, long-term geometry and stratigraphy of MDCs. Wright and Nittrouer (1995) differentiated river-supplied sediment dispersal processes on the shelf into four successive stages: 1. *offshore plume dispersal*, 2. *rapid initial deposition*, 3. *resuspension and transport*, and 4. *long-term net accumulation*. The initial Stages 1 and 2 were suggested to be dominant in some shelf systems (e.g. Huanghe and Mississippi), while the subsequent Stages 3 and 4 control other systems (e.g. Amazon and Yangtze). The authors stressed that the timescale of interest is important when considering the dispersal processes; in-situ measurements may not reflect long-term accumulation patterns, because Stage 3 and 4 processes may alter the record lastingly by repeated mobilization or erosion, transport, and redeposition of particles. Gao and Collins (2014) distinguished between wide and narrow shelf topographies under either abundant sediment supply or material starved conditions. MDCs were proposed to develop primarily under a regime of abundant sediment supply. This study inferred that most shelves have incomplete Holocene sedimentary records, and stressed that the duplicity between event-based and average sedimentation can lead to a misinterpretation of the sedimentary record. It was suggested that numerical models may aid in this effort by simulating the formation, post-depositional alteration, and preservation potential of these deposits.

Hanebuth et al. (2015) have recently undertaken an attempt to classify MDCs on continental shelves from a geological perspective, defining eight types with regard to their three-dimensional architecture and long-term depositional pattern. Shelf morphology, sea level, local hydrodynamic regime, and sediment supply were identified as primary factors controlling the depositional geometries. High sediment supply favors the formation of a) extensive *prodeltas* and b) *subaqueous deltas,* attached or in proximity to the river mouth; c) scattered *mud patches* and d) widespread *mud blankets* might occur across the whole shelf and reflect the amount of sediment available. Hydrodynamic forcing produces e) elongated mid-shelf *mudbelts* and f) shallow-water *contourite drifts,* both detached from the fluvial point source. Finally, topography controls the formation of g) local *mud entrapments* and h) *mud wedges,* which deposit inside seabed depressions and behind morphological jumps.

2.2 Paradigms of mud depocenter development

A simple, yet valuable conceptualization of MDC development is based on local mass conservation as described by the Exner equation (Exner, 1925; Paola and Voller, 2005), which can be expressed as

$$\frac{d\eta}{dt} = -A\,\nabla \cdot \boldsymbol{U} \qquad (1)$$

where $\eta(x, y)$ is bed elevation, t is time, $A > 0$ is a coefficient related to bulk density of the deposited grains, and $\boldsymbol{U} = \vec{U}(x, y)$ is a vector field of horizontal sediment flux. In general, sedimentation occurs wherever there is a negative gradient in lateral flux ($\nabla \cdot \boldsymbol{U} < 0$), that is, wherever deposition outweighs erosion. Variations of Eq. (1) are implemented in long-term morphodynamic models (e.g. Zhang et al., 2012) as well as short-term, process-based models (Amoudry and Souza, 2011) alike. Accordingly, the validity and interpretation of Eq. (1) depends upon the temporal and spatial scales considered.

The fact that apparent sedimentation rates scale inversely with the averaged timespan has motivated the concept of *stratigraphic completeness*, i.e. the amount of time and space preserved in a sediment column (Sadler, 1981). As for most modern shelves, MDCs typically exhibit high sedimentation rates (on the order of 1 mm/yr), exceeding those in most other open-ocean environments by an order of magnitude or more. However, stratigraphic completeness may vary widely from one MDC to another. On a 1000 yr scale, completeness may vary from 20–50% on strongly tidal deltaic shelves to 50–90% on calm-water accretionary shelves (Sommerfield, 2006). In systems with high sediment supply, depositional events are often sporadic and followed by phases of reduced input or even erosion. Thus, stratigraphic completeness is usually highest and accumulation rates are most steady in locations where both sediment supply and hydrodynamic energy are low. This (somewhat counterintuitive) insight reflects the episodic nature of sedimentation and erosion. Although completeness tends to be higher in deeper topographic settings, water depth is not a robust predictor of completeness due to the variety of mechanisms influencing sediment accretion on continental margins such as wave and tidal currents, wind-driven flows, sediment supply, and bottom trawling.

In view of the variability of horizontal sediment fluxes and stratigraphic completeness on different timescales, the identified mechanisms related to the formation of MDCs frequently correspond to one of three paradigms: *continuous supply*, *continual resuspension-deposition cycles*, and *episodic erosion and sedimentation events* (Figure 1).

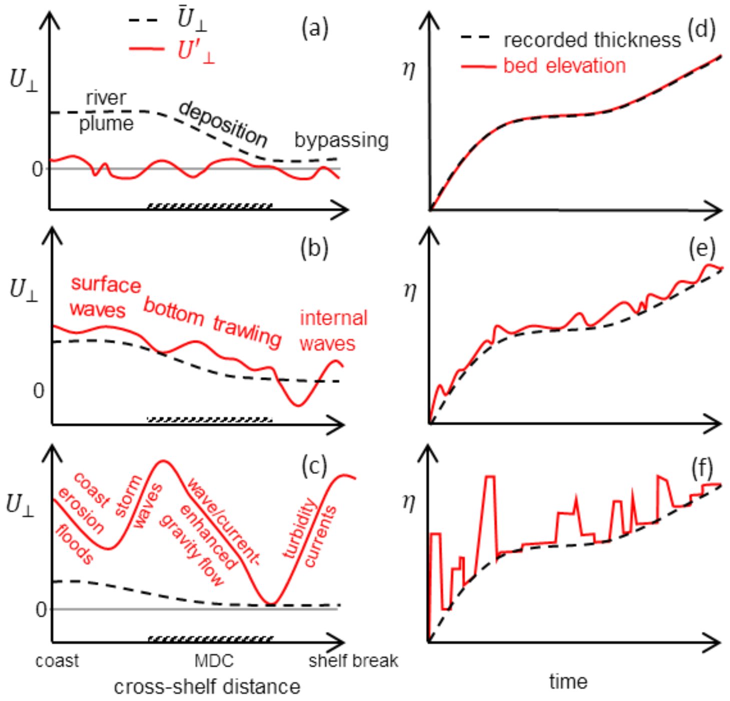

Figure 1. Conceptual illustration of MDC development and likely processes based on (a-c) the cross-shelf component of mud fluxes $U_\perp$ and (d-f) possible time-series of MDC thickness η for (a, d) low-energy settings, (b, e) resuspension-dominated settings and (c, f) event-dominated settings. Here, all scenarios result in the same recorded thickness (d-f, dashed) and MDC position. Deposition occurs where the flux gradient is negative, and negative fluxes are directed onshore. In the cases of (b) and (c), the background flux $\overline{U}_\perp$ (dashed) must not correspond to the position of the MDC on the shelf. In (a, d) low-energy settings, the recorded MDC thickness (dashed) is close to the instantaneous bed elevation (solid), while the recorded thickness deviates from the instantaneous thickness in the cases of (b, e) and (c, f), induced by short-term (hourly to seasonal) deviations $U'_\perp$ (a-c, solid) during high-flux events.

2.2.1 Continuous supply

The first paradigm pertains to the concept of advective and diffusive offshore sediment transport and hemipelagic settling out of nepheloid layers as first described by McCave (1972). The reasoning behind this paradigm is that fines tend to deposit from suspension under calm hydrodynamic conditions. Accordingly, conditions which allow long-term accumulation of fines into an MDC should be exceptionally quiescent. Within the MDC, the presence of such conditions may be expressed in the form of mm-scale mud lamination, as described for many recent and ancient MDCs (e.g. Stanley, 1983; Kuehl et al., 1988; O'Brien, 1996; Potter et al., 2005; Schimmelmann et al., 2016), although this internal layering often becomes lost secondarily due to endobenthic bioturbation. These fine deposits typically display a distinct internal, sub-parallel sediment-acoustic reflection pattern as well (Damuth and Hayes, 1977). This architectural MDC stratification of highest temporal resolution and with an aggradational, sometimes progradational growth history evokes a rather (semi-) continuous picture of sedimentation wherein the MDC is more or less consistently supplied with fresh material. Such a system would be expected to have exceptionally high stratigraphic completeness.

An argument in line with this paradigm was recently made by Williams et al. (2019), who suggested that tidal-current circulation patterns are responsible for retaining fines within patchy MDCs around the British Isles. Regions of cyclonic tidal currents exhibit thinner BBLs than their Coriolis-supported, anti-cyclonic counterparts, because the BBL cannot fully develop within a tidal period in the former situation. A limited BBL thickness promotes enhanced accumulation by a settling of fines from the low-turbulence zone above the BBL and by a limitation of the upward-directed flux of resuspended mud to within the BBL. This study posited that such persisting "background" mechanisms dominate other broad, low-energy shelves as well.

The *continuous supply* paradigm pertains to a state of morphodynamic equilibrium, such that $\nabla \cdot \boldsymbol{U} < 0$ across the MDC. This situation corresponds to steady-state sedimentation, as has been described by regime theory (Swift and Thorne, 1992). When $\boldsymbol{U}$ becomes constant over the entire depositional area, no further net deposition takes place. In such a system, the accommodation space available is completely filled and new deposits are no longer preserved but subject to cross-shelf material export. This type of equilibrium seems to have established in most modern dispersal systems after sea level has stabilized over the later Holocene (Sommerfield et al., 2007; Hanebuth et al., 2015 and references therein).

2.2.2 Continual resuspension-deposition cycles

The second paradigm contends that mud deposition is not a straightforward source-to-sink process, but rather dynamic, and includes multiple cycles of suspension, advection, and vertical mixing before final settling and consolidation. This view is supported by oceanographic monitoring, which shows that short-term peak energy conditions cause frequent resuspension events (Cacchione et al., 1987; Ogston et al., 2000; Cheriton et al., 2014; e.g. Zhang et al., 2019). On timescales from seconds to months, hydrodynamic conditions are highly variable, leading to recurrent phases of resuspension or erosion in geographic areas of net deposition. Such phases are often largely unrelated to variations in river discharge or secondary mud sources in the upper water column (Walsh and Nittrouer, 1999). Intermittent mobilization by internal waves, tidal waves, marine storms, eddies, and secondary bottom-circulation have been found to strongly determine MDC morphology (Zhang et al., 2016; Zhang et al., 2019). As a result, the sedimentary succession (material grain size) in most of the MDCs is either vertically homogenized or graded due to slight material sorting trends, with little visual or stratigraphic evidence of small-scale layering. The result is an acoustically transparent seismo-acoustic signature in-between major, sub-parallel internal reflections (Hanebuth et al., 2015).

Flume experiments have shown that fines can accrete as laminated mud layers even under energetic conditions of sustained bottom flow at a current speed of up to 25 cm/s, (Schieber et al., 2007; Schieber and Yawar, 2009). In these experiments, clay suspensions formed aggregates that transferred to bedload, developing migrating, low-angle ripples, and finally accreted into cm-thick mud beds. Subsequent compaction results in randomly interspersed clay and coarse silt laminae. Increased shear in the boundary layer led to destruction of clay flocs and allowed only silt grains to settle to the bottom and form a silt layer. These laminae are conspicuously similar to those found in many recent muddy depositional environments and ancient geologic mudstone successions, in which a careful examination often reveals signs of energetic deposition or reworking (e.g. Nittrouer and Sternberg, 1981; Macquaker et al., 2010; Ghadeer and Macquaker, 2012; Plint, 2014). Thus, other than solely hemipelagic settling, the mechanism of bedload-transported flocculated mud offered an alternative explanation for the ubiquity of lamination found in MDCs (Yawar and Schieber, 2017).

Within the paradigm of *continual resuspension-deposition cycles*, perturbations of the steady-state become meaningful, and $\boldsymbol{U}$ is to be understood as an instantaneous value. Thus, the horizontal flux may be split into a long-term mean and a fluctuating part which represent deviations from the mean (Sommerfield, 2006): $\boldsymbol{U} = \overline{\boldsymbol{U}} + \boldsymbol{U}'$. In the context of MDCs, $\overline{\boldsymbol{U}}$ may be interpreted as the multi-decadal average background flux related to hemipelagic dispersal and sedimentation and $\boldsymbol{U}'$ are deviations from the average flux occurring on hourly to seasonal time scales due to intermittent disruption, e.g. by storm waves or bottom trawling activities. According to this paradigm, stratigraphic completeness of MDCs should generally be limited compared to a scenario of *continuous supply*, but the resulting stratigraphic gaps might be minimal to negligible, though frequent, depending on event duration and intensity.

2.2.3 Episodic erosion and sedimentation

Contrasting the idea of *continuous supply*, the third paradigm refers to *episodic erosion and sedimentation* processes. In this context, the term “event” is commonly used to describe such environmental fluctuations where $|\boldsymbol{U}'| \geq |\overline{\boldsymbol{U}}|$ with periods from minutes to a few weeks, often triggered by river flood stages or atmospheric storm events. The main justification for this paradigm is rooted in the observation that events of high material flux can sometimes be distinguished from in the geological record, and that they are occasionally observed in the field, leading several studies to term them the main driving mechanisms of mud sedimentation. For example, Ulses et al. (2008) and Dufois et al. (2014) have found that storms and floods play a crucial role on mud dispersal and off-shelf material export in the Gulf of Lions. Marion et al. (2010) described for the Rhone prodelta multi-cm rises in local seabed elevation shortly after a river flood event, and seabed lowering during storms. Similarly, Collins et al. (2017) have described the shelf off northwest Borneo as an alternating storm vs. flood dominated setting, resulting in depositional event beds. Frequent flood events and subsequent near-bottom gravity flows have also been designated as the responsible mechanisms for

MDC development on the Eel shelf off California (USA) and in the Adriatic Sea (Traykovski et al., 2000; 2007).

Though isolated, sandy event beds seem to be conspicuously absent in the record of modern storm-dominated MDCs, the imprints of stormy conditions have been presumed in the record of ancient muddy shelves in the form of tempestite beds (e.g. Pedersen, 1985). Myrow and Southard (1996) identified three endmembers of tempestites according to sedimentary stratification and the presence of sole marks associated with different storm-related processes: wave action (isotropic hummocky cross-stratification), geostrophic current-induced bottom flow (low-angle current ripples), and gravity-driven density flow (shallow-water turbidites).

However, not all events are preserved as a depositional horizon and many of them become disturbed or eliminated after initial deposition. A useful concept in this context is that of the *preservation potential*, i.e. the likelihood that a particular sediment layer will escape total long-term disruption (Wheatcroft, 1990). A muddy bed is more likely to be preserved when its resistance to erosion increases quickly following deposition, or when it is buried by a subsequent sediment layer before it can be destroyed by an event of high bed shear stress (Wheatcroft et al., 2007). Examples of the high preservation potential of flood deposits include the Eel River margin (Sommerfield and Nittrouer, 1999) and the Waipaoa River, New Zealand (Carter et al., 2010). Systems with a low preservation potential are found in the Taiwan Strait (Milliman et al., 2007) and on the Washington shelf off the Elwha River (Eidam et al., 2019).

Figure 2 shows a radiographic image from an MDC in a high-energy environment which contains different features corresponding to all of the three paradigms; laminated background sedimentation (*continuous supply*), flood layers (*episodic sedimentation*), and disturbed layers (*continual resuspension-deposition cycles*).

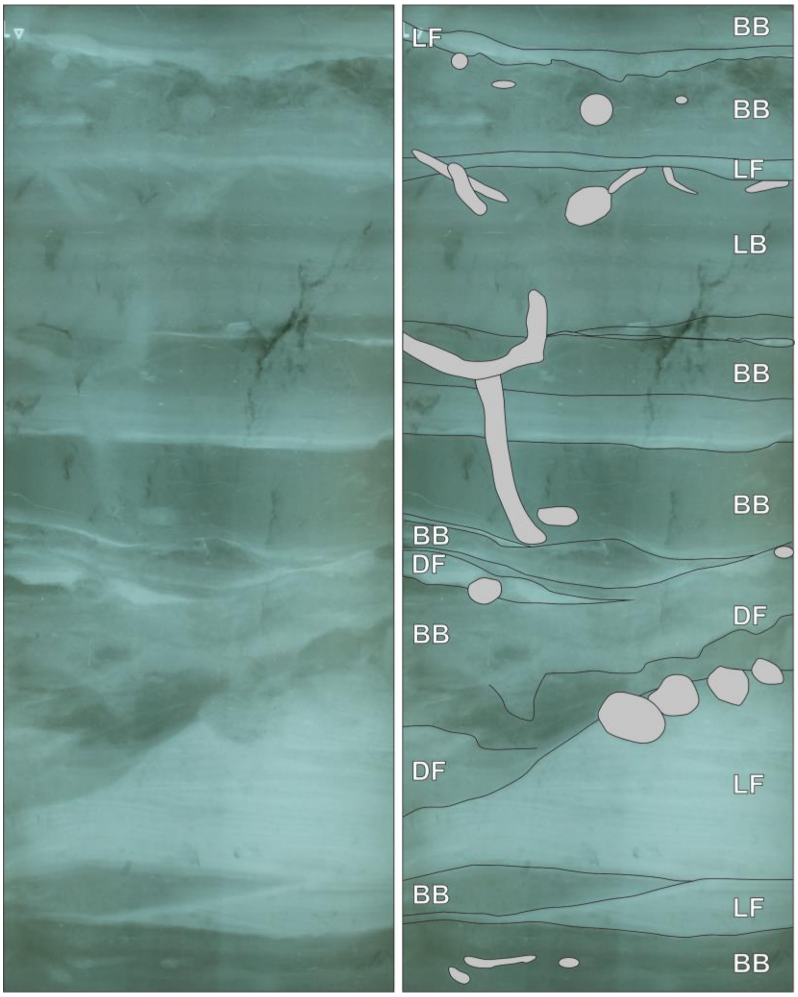

Figure 2. Radiography of a proximal prodeltaic MDC (Guadalquivir River, Gulf of Cadiz, southern Spain). This section illustrates hemipelagic sedimentation (darker) interrupted by recurrent flood event layers (lighter). BB - bioturbated background sedimentation; LB - laminated background sedimentation; LF - laminated flood layer; DF - disturbed flood layer; gray ellipsoids - large burrows; dark, vertical (root-like) features: cracks in slab sample. Core GeoB 19520-2, 20 km off the river mouth, 20 m water depth, 320-345 cm sample depth, 11x25 cm image size, 0.7 cm slab thickness.

3. Controlling factors on mud depocenter formation

Two prerequisites of MDC development are a sufficient supply of fines to the coastal ocean, and a hydrodynamic situation which allows their accumulation on the shelf. This section aims to summarize current knowledge on the sources which deliver mud the coast, the mechanisms which disperse them on the shelf, and the conditions under which mud deposits on the seabed. These mechanisms are linked, wherever possible, to the paradigms introduced in section 2.2.

3.1 Mud sources

While rivers are considered the dominant supplier of fines to the coastal ocean, aeolian and coast-erosional sources do contribute significantly in some settings. These sources often overlap in proximity to the coast and their roles may only become apparent through detailed provenance analyses. As McCave and Hall (2006) put it, “clearly there are some sources that do not produce gravel or coarse sand, but few that supply something fail to provide mud […]”

It is noteworthy that precipitates in the form of biogenic carbonate, silicate, and organic matter do contribute as secondary sources to MDC development (e.g. Nittrouer et al., 1988). Though the amount of carbonate-producing algae is generally limited in siliciclastic systems, some amount of production does occur alongside the terrigenous input (Mount, 1984; Milliman and Droxler, 1996), as may in-situ synthesis of clay minerals in the sediment (Michalopoulos and Aller, 1995; Holland, 2005). The description of these (minor) autochthonous and authigenic sources is, however, beyond the scope of this article.

3.1.1 Fluvial

Most studies of MDCs have focused on river-dominated margins, and this inclination is reflected in the classifications presented by McKee et al. (2004), Walsh and Nittrouer (2009), and Hanebuth et al. (2015). Indeed, most MDCs can be easily traced back to one or more riverine sources, often extending directly from the rivers’ mouths. Though turbid river plumes seem impressive as seen from aerial images, their total load is small compared to near-bottom modes of suspended particle transport and their lateral extent often does not match the geographical location of depocenters (Geyer et al., 2004; Walsh and Nittrouer, 2009; Hanebuth et al., 2015). In a global survey of mudline depths at various river-dominated ocean margins, George and Hill (2008) found no strong correlation between the position of the mudline and the load of nearby rivers. Cross-shelf sediment transport of large river systems seems to be largely uncorrelated with the extent of the freshwater plume, as sediment is quickly lost from the plume and initially deposits near the river's mouth (e.g. Geyer et al., 2004; Nowacki et al., 2012; Pawlowicz et al., 2017).

According to Meade (1996), less than 5 % of the river sediment delivered to the global coastal ocean reach the deep sea; the vast majority becomes trapped in estuaries, floodplains and on the continental shelf. The exact apportionment of the proximally trapped sediment is not known, as most sampling surveys and monitoring stations of rivers are located considerably far upstream of the rivers' mouths. However, some estimates for the amount of solids that escape the coastal zone have been compiled, and it is thought that this portion is dominated by fines (McCave, 2002). Beusen et al. (2005) estimated that 11,000-27,000 Mt/yr of total suspended solids are exported to coastal seas. These estimates are in fair agreement with those of Ludwig and Probst (1998) of 16,000 Mt/yr. Asia is by far the largest contributor (>50 %) with an estimated river export of 12,000 Mt/yr. Dürr et al. (2011) estimated that almost 9000 Mt/yr of the overall global solid discharge are particulate silica (lithic rock and mineral grains), amounting to roughly half of the total suspended solid fraction. Although nearly half of the sediments are delivered by the worlds 25 larges rivers (Milliman and Meade, 1983), Milliman and Syvitski (1992) first established the importance of small mountainous rivers for the delivery of large amounts of sediment to the global ocean. Usually found along active margins with steep topographic gradients, regions dominated by small mountainous rivers, such as the western side of North and South America, southern Europe, and southeastern Asia, exhibit high sediment yields compared to their small drainage basins, and are especially susceptible to events such as floods and mudslides.

Anthropogenic activity impacts riverine sediment discharge in two opposing ways. Increasing erosion due to overuse of land and river bank diking both promote sediment export, while reservoir damming suppresses it significantly by retaining a large amount of material. The amount of fluvial material that is retained by such reservoirs and thus withheld from the coastal ocean has been estimated to 50 % on average (Ouillon, 2018), though values of up to 95 % have been reported regionally (Vörösmarty et al., 2003; Yang et al., 2011). Though the global effects of sediment starving on delta shorelines seems to be limited thus far, the overall trend points toward the ultimate demise of many deltas by the combination of reduced fluvial supply and wave action (Anthony, 2015; Besset et al., 2019). This disequilibrium is perhaps most apparent in subaqueous delta systems, as found off the Yangtze (Yang et al., 2011), Mekong (Unverricht et al., 2013), Danube (Giosan, 2007), and Mississippi Rivers (Maloney et al., 2018). An impressive example was documented at the Minjiang River of southern China, where the subaqueous delta deposits recorded an acceleration followed by a collapse in sedimentation rates in response to increasing soil erosion and progressing dam construction, respectively (Ai-jun et al., 2020).

3.1.2 Aeolian

Airborne particles, including those generated due to wind-driven soil erosion and volcanic eruptions, are known to travel over remarkably large distances before settling (Grousset et al., 2003; Stuut et al., 2009; Van der Does et al., 2018). Yet, the potential role of dust input to the shelf sediment budget is not yet fully explored. Atmospheric dust plumes’ contributions to MDC budgets are associated with great uncertainties regarding total mass due to their strong spatial diffusivity. For example, estimates for Saharan dust production vary widely, ranging from 130 to 460 Mt/yr (Swap et al., 1996), to up to 1400 Mt/yr (Ginoux et al., 2004).

Sand and coarse silt fractions tend to be carried through the atmosphere for relatively short durations (Stuut et al., 2009), though instances of their travel over several thousands of kms have been reported (van der Does et al., 2018). In contrast, fine silt and finer particles may be considered aerosols which, in extreme cases, traverse the entire globe before being washed out by precipitation (Grousset et al., 2003). Some success has been reported in distinguishing fluvial from aeolian inputs in deep sea settings using end-member analyses of grain sizes, where the aeolian fraction occupies the coarser end-member (e.g. Weltje and Prins, 2003; Holz et al., 2007). However, the ambiguities of such methods increase with closer proximity to the coast as the grain size signal becomes more heavily muddled. Aeolian fluxes to the shelf have been studied mainly in the context of paleoclimate to reconstruct past wind directions, distinguish material sources, or identify arid periods. Data from Nizou et al. (2011)

suggest, for instance, that the quantity of material carried as dust plumes from the Sahelian and Saharan regions matches that of the fluvial runoff supplied to the MDCs off the coast of Senegal during arid periods. The authors used a combination of grain size and elemental distribution data to find suitable proxies for fluvial and aeolian material. Here, the fluvial fraction was both finer and contained a larger amounts of aluminum and iron. This contrasted previous studies which had used iron as a proxy for short-lasting dust outbreaks in the Mauritanian mud wedge (Hanebuth and Lantzsch, 2008; Hanebuth and Henrich, 2009). Such ambiguities highlight the difficulty in separating aeolian and fluvial material in an MDC.

Saharan dust was also recognized to contribute to MDCs in the Mediterranean (Martin et al., 1989; Stuut et al., 2009; Wu et al., 2016a) and on the Moroccan shelf (Summerhayes et al., 1976). In fact, Martin et al. (1989) estimated the volume of aeolian input to the same order of magnitude as that of all rivers discharging into the western Mediterranean. Aeolian input also contributes as a secondary source to the MDCs on the inner shelf of the East China Sea compared to the material discharge provided by the Yangtze River (Liu et al., 2014).

3.1.3 Coast-erosional

Another source mechanism that may supply fines to the coast is the physical erosion of consolidated coastal material. According to Young and Carilli (2019), cliffs comprise about 50 % of the world's coasts and they occur, in contrast to rivers, more commonly in mid- and high latitudes than in low-latitudes in both hemispheres. Strong storms and freeze-thaw-cycles are known to have strong impacts on mid- and high-latitude coasts, respectively (Davies and Clayton, 1980). As cliff erosion takes place primarily during storms, this mode of supply is often episodic and subject to strong temporal variability. The frequencies and intensities of storms are modulated by the regional climate, but erosion rates are also expected to increase with sea level rise (Dickson et al., 2007). For example, cliff retreat rates on parts of the Polish coast have almost tripled, from 0.55 to 1.49 m/yr on average, over the past decades compared to the previous century (Uścinowicz et al., 2004). At the same time, coastal protection measures combating cliffy shoreline retreat act to reduce erosion, but also hinder the supply of cliff-derived material towards offshore depocenters, by as much as 75 % in the case of the Norfolk Cliffs in the UK, for instance (Clayton, 1989).

Prémaillon et al. (2018) compiled a database of coastal cliff erosion rates from 1530 cliffs worldwide. Their statistical analysis concluded that lithology, specifically rock resistance, is the dominant predictor of erosion rate. Marine forcing such as wave height, leading to cliff undercutting and material out-washing, and climatic variables show a much smaller correlation with the rate of erosion. Somewhat surprisingly, the number of frost days is the only climatic variable that shows a significant positive correlation with erosion rates, while marine climate (such as wave forcing) exhibits a weaker influence.

Syvitski et al. (2003) estimated that about 400 Mt/yr of material erode from coastal cliffs globally, though this number is deemed particularly uncertain compared to their fluvial and aeolian counterparts. Although many studies have focused on the role of eroding cliffs in delivering sand to beaches and its alongshore transport, little is known about the transport and fate of the fine fractions supplied in this way. There has long been consensus that fines tend to be moved beyond the shoreface by subsequent winnowing of waves, such that horizontal gradients of hydrodynamic bottom energy are reflected the grain size gradients on the seabed (e.g. McCave, 1978; Swift and Thorne, 1992; Anthony and Aagaard, 2020). It seems, thus, indubitable that this material may become available for further transport and potential deposition in MDCs. Yet, potential connections of cliff erosion to MDC development have remained tentative.

For the southern Baltic Sea, about 90 % of the material stored in MDCs of the central basins was estimated to derive from erosion of soft cliffs in Germany and Poland (Gingele and Leipe, 2001). The overall regional riverine sediment discharge plays, in contrast, only a minor role. Similarly, sediment supply to the East Anglian coast is dominated by erosion of the chalk cliffs of Norfolk, Suffolk and Holderness in the UK (McCave, 1987), some of which may deposit in the mud patches in the North Sea (McCave, 1973; Dronkers et al., 1990).

Along the California coast, the situation is reversed, with rivers accounting for the bulk (90 %) of fines, while cliff erosion makes up about 10 % (Farnsworth and Warrick, 2007). Cliff erosion, nonetheless, might become locally significant: The contribution of cliff-supplied material is expected to close the budget of the mudbelt on the shelf off Santa Cruz and Davenport (Xu et al., 2002). A large amount of the silty offshore deposits comprises cliff-sourced material near Santa Monica (Limber et al., 2008). Because this material does not remain on the beach for long after initial erosion, it is reasonable to assume that it is transported cross-shore and contributes to the MDCs on the shelf. An extensive survey of the grain size composition of coastal cliffs of Southern California was carried out by Young et al. (2010), where fines comprise 23% of the cliff material on average. However, even the sand fraction does not necessarily remain on beaches entirely, as part of the fine sand bypasses the coastal zone and deposits offshore. In this context, a useful concept is that of the littoral cutoff diameter (Limber et al., 2008; Carlin et al., 2019), i.e. the minimum grain size that is retained on the beach, while grains smaller that this diameter travel farther offshore. This cutoff may be significantly larger than 63 µm (~125 µm at the Californian coast; Limber et al., 2008), which has important implications for the potential of cliff erosion to contribute to MDCs, as neglecting the grain size window between 63 µm and the littoral cutoff diameter underestimates the amount of sediment supplied to the offshore (by up to 124% in the case of Californian cliffs; Limber et al., 2008). In a sediment core from the Monterey Bay, Carlin et al. (2019) attributed higher amounts of sand in this grain size window to periods of enhanced cliff erosion by storms while sections lacking sand in this grain size window suggested periods of fewer storms. Notably, these trends were found to be independent of the total sand fraction within the muddy deposit. Thus, the amount of littoral sand found within an MDC seems to be a useful proxy for cliff material.

3.2 Mud dispersal on continental shelves

Following the delivery to the shallow coastal ocean, various hydrodynamic processes are responsible for the transport of fines across a continental shelf, and three particular types of processes have received much attention recently: gravity-driven flows, internal waves, and dynamics of hydrographic fronts. During the last century, material transport within the BBL in the form of dilute bottom nepheloid layers and their advection by bottom currents was identified as a highly effective dispersal mechanism of fines on continental shelves (Hill and McCave, 2001). Here, a *dilute* suspension is one of relatively low concentration (<1 g/l) in a bottom flow in which turbulence is fully developed. In natural conditions, turbulent mixing dominates at these concentration levels, and interactions of the suspension with flow dynamics (through self-stratification) and with itself (through particle-interactions) are usually not observed. Several occurrences of bottom nepheloid layers on the shelf associated with resuspension by atmospheric storms were reported during this time (e.g. Sternberg, 1986; Cacchione et al., 1990; Sherwood et al., 1994), showing the pervasiveness of recurring resuspension and transport events in shelf settings. On the mid-shelf mudbelt off of the Russian River in Northern California, storm-induced bottom currents are responsible for up to half of the total sediment flux (Drake and Cacchione, 1985). Sahl et al. (1987) attributed mud deposition on the Texas shelf to river-derived bottom nepheloid layers, which are maintained by riverine input, waves and currents in the nearshore, and by the action of internal waves on the outer shelf. Vitorino et al. (2002) observed bottom nepheloid layers several meters in thickness during storm conditions on the Portuguese shelf.

Although the concept of dilute near-bottom suspension is appealing as an analogy to the Rouse-like equilibrium suspension profiles common in open-channel flows, such as they occur in most rivers and estuaries, the focus of research has shifted towards modes of high-concentration near-bottom flows. Based on data from different coastal settings, Friedrichs et al. (2000) found that resuspension within the BBL may lead to a negative feedback loop, by which the density stratification induced by the suspension dampens turbulence, thus hindering additional resuspension. The resulting concentration remains nearly constant within the boundary layer, deviating markedly from the Rouse-like profiles expected under open-channel flow conditions.

3.2.1 Gravity-driven flow

Gravity-driven flows of sediment suspension are short lasting, thus episodic, events of high lateral flux. They form when the density of the near-bottom suspension is high enough with respect to the surrounding fluid that it moves down-gradient in the form of a fluid layer separated from the overlying water column as a result of gravitational acceleration. This phenomenon is well known from the continental slope and from submarine canyons, where steep bathymetric gradients (>0.7°) lead to auto-suspending flows and, ultimately, to the formation of turbidites (Bouma et al., 1985). These turbidity currents represent the primary conduit for the escaping of sediment from the shelf to the deep ocean, and considerable effort has been carried out recently to analyze the flow structures of such events and their corresponding deposits (e.g. Payo-Payo et al., 2017; Maier et al., 2019; Simmons et al., 2020). Although the continental shelf is generally not steep enough to allow for this form of auto-suspension, gravity-driven bottom flows have been shown to form on the shelf under the influence of wave- or current-enhanced near-bottom energy (Wright and Friedrichs, 2006), or in vicinity of a river mouth and along the submarine part of river deltas with high sediment loading, leading to hyperpycnal (negatively buoyant) conditions.

Three preconditions for gravity-driven flows to develop seem to be a high sediment concentration at the bottom, weak (ambient) onshore-directed currents, and a sufficiently steep slope (≳0.03°, Wright and Friedrichs, 2006). However, the precise combination of parameters required to trigger gravity-driven flows are not yet understood, because their episodic nature makes them difficult to observe directly, and the environments in which they have been observed often differ strongly from one another. The general trend of both in-situ and geological studies seems to point toward gravity-driven flows as a very common, if not ubiquitous phenomenon on continental shelves globally (e.g. Macquaker et al., 2010; Plint, 2014; Zhang et al., 2016; Denommee et al., 2016; Peng et al., 2020).

The occurrence of gravity-driven flows derived from river discharge was, for a long time, considered rare because the net buoyancy of the initially outflowing freshwater plume with respect to the receiving ocean waters is usually positive. Thus, extremely high sediments concentrations are required for hyperpycnal plumes to evolve at river mouth areas (>36 g/l, according to Mulder et al., 2003). Recent studies from the Elwha River dam-removal experiment in Washington State suggest that gravity flows are unlikely to form in tidally energetic systems and that the major mechanisms for transport are tidal current-induced bedload transport and river-plume advection (Eidam et al., 2016; 2019). Those results highlight the limitations for forming hyperpycnal river plumes within tidally energetic systems, even in case of an extremely turbid river. In these systems, the traces of major sediment delivery events may, instead, be erased from the sedimentary record within weeks after material settling. Increasing evidence shows, however, that in environments with steep bathymetric gradients, gravity-driven flows do occur at considerably lower concentrations than previously thought (e.g. Parsons et al., 2001). In the Squamish Delta, Canada, Hage et al. (2019) observed a gravity flow at only 0.07 g/l which was triggered during a period of high water discharge which forced the turbidity maximum towards the steeper part of the delta. Similar conditions shortly after did not result in comparable gravity flow, the likely reason being that no more erodible mud was available to maintain the self-sustaining flow.

In shelf settings that are less steep, instead of forming directly from river efflux, gravity-driven flows may occur at a later stage, when settled material is being resuspended or kept in suspension temporarily by tidal currents or waves. Conceptually predicted by Moore (1969) and confirmed by observations on the Amazon (Sternberg et al., 1996), Eel (Traykovski et al., 2000), and the Waipaoa (Walsh et al., 2014; Hale and Ogston, 2015) and Waiapu continental shelves in New Zealand (Ma et al., 2008), among others, wave- and current-enhanced sediment gravity flows have solved a contradiction that challenged traditional views of plume settling; Measurements on the Eel shelf indicated that rapid deposition of flood sediment occurs beneath the river plume in near-coastal waters, but long-term accumulation is centered on the mid-outer shelf (Sommerfield and Nittrouer, 1999; Wheatcroft and Borgeld, 2000). Here, wave-induced mobilization of the initial, muddy flood deposits and subsequent seaward density flow has been identified as the key mechanisms leading to cross-shelf transport. The majority of cross-shelf sediment flux is associated with a few major flood and storm events which occur over short time windows of just one to two weeks every few years. A comparable process has since been observed for the low-energy Adriatic shelf (Traykovski et al., 2007) and in several other geographic areas, as summarized by Wright and Friedrichs (2006).

To what extent gravity-driven flows play a role with regard to the net material budget of a late Holocene MDC is still unclear. For example, while Friedrichs and Scully (2007) have attributed the majority of the large flood deposit from the Po River to wave-enhanced gravity flows, Traykovski et al. (2007) have posited along-shore advection by mean currents to be the main transport mechanism.

In the rock record, ‘‘wave-modified turbidites’’ associated with wave-supported sediment gravity flows have been identified (Myrow et al., 2002; Lamb et al., 2008). Here, normal grading associated with decelerating flows are overprinted by hummocky cross-stratification due to waves. Reverse-to-normal grading occurs in some distal parts and point towards deposition under waxing-to-waning conditions which are common in sediment gravity flows. Lamb and Mohrig (2009) have shown in a model study that bedforms and sediment grading patterns in gravity flow deposits can record multiple episodes of flow waxing-waning pulses even during a simple single-peaked flooding event. Mulder et al. (2003) defined the “hyperpycnite” sequence as a “compound of a basal coarsening-up unit, deposited during the waxing period of discharge, and a top fining-up unit deposited during the waning period of discharge”. Muddy hyperpycnites typically show distinct lamination with sharp, erosional contacts and little bioturbation, reflecting near-instantaneous sedimentation, in contrast to the gradual, hemipelagic settling of mud from suspension (Bhattacharya and MacEachern, 2009).

3.2.2 Internal waves and intermediate nepheloid layers

Internal waves play a crucial role within the paradigm of continual resuspension-deposition cycles. They are ubiquitous in stratified waters and they occur in a wide range of amplitudes and wavelengths (5-50 m and 0.5-15 km, respectively; Shanmugam, 2013). Interaction of internal waves with the seafloor can lead to resuspension of seabed sediment which may feed one or more intermediate nepheloid layers (INLs, e.g. McPhee-Shaw and Kunze, 2002). These layers of elevated sediment concentration are detached from the seafloor and spread seaward along isopycnals. Much attention has been directed toward resuspension by internal waves at the shelf break (as reviewed by McPhee-Shaw, 2006), where INLs often occur due to reflection and breaking of incoming open-ocean internal waves, which transport shelf sediment offshelf. Sediment resuspension by internal waves that form due to the hydraulic jump where a shelf current runs over the shelf edge has also been observed (Bogucki et al., 1997; Klymak and Moum, 2003; Bogucki et al., 2005; Quaresma et al., 2007). The mechanisms of resuspension and transport by internal waves were recently summarized by Boegman and Stastna (2019), but the full range of effects on MDC development is not yet fully understood.

The potential role of internal waves in MDC development is twofold: Firstly, winnowing of fines by incoming and shoaling internal waves provides a mechanism which constrains the seaward limit of an MDC, as found on the narrow, high-energy Iberian shelf (Zhang et al., 2019). Secondly, transport within INLs that are generated by an interaction of internal waves with the seabed may disperse mud laterally (McPhee-Shaw et al., 2004). When internal waves break due to a shallowing seabed topography, a short pulse of shoreward sediment transport (run-up) is followed by a prolonged phase of seaward transport (back-wash). While the net shoreward transport is mostly restricted to coarse-grained bedload material, fines are usually injected into the water column and transported offshelf within the INL (Sahl et al., 1987; Bourgault et al., 2014). Cheriton et al. (2014) have shown, however, that INLs caused by internal wave resuspension may also transport fines shoreward and, thus, add to MDC material accumulation.

Pomar et al. (2012) have suggested that internal waves are responsible for hummocky cross-stratification on the mid- and outer shelf below the maximum storm base. A conceptual facies model has been developed on the basis of an ancient carbonate ramp in order to distinguish the characteristics of such “internalites” from those of turbidites at the continental slope and tempestites in shallower areas (Bádenas et al., 2012). Though all three deposit types show a basal erosion surface and a subsequent depositional phase, internalites do not show the coarsening and thickening upward trend induced by differential settling in storm deposits. Furthermore, internalites thin out gradually to disappear in both up- and downdip directions.

3.2.3 Hydrographic front dynamics

The dynamics of oceanic fronts may encompass all of the aforementioned mechanisms, and both episodic and long-term stable fronts have been associated with MDC development. In a general sense, the term “front” describes a sharp lateral density contrasts between water masses, often marking a boundary to lateral fluxes. A front needs not be stationary, but can vary spatially with winds, tides, seasons, or over geological time intervals (e.g. Geyer et al., 2004; Bender et al., 2013).

Stable fronts, linked to the paradigm of continuous supply, have been characterized as traps for suspended matter on shelves (Geyer et al., 2004). The water column is often well-mixed on the shallow inner shelf due to highly turbulent conditions associated with river outflow, waves, and tides. This well-mixed zone transitions to a stratified marine environment in the frontal zone. As a mechanism analogous to estuarine sediment trapping, the phenomenon of frontal trapping due to flow convergence in the near-bottom layer leads to a high concentration of suspended mud in the frontal zone, which may deposit rapidly due to particle aggregation and water column self-stratification. For example, Castaing et al. (1999) have shown that the locations of thermohaline fronts coincide with the sites of patchy MDCs on the Gironde shelf during winter. The study documented a sharp decrease in bottom water turbidity beyond this front and postulated that the front acts as a permanent barrier to the seaward escape of fines. Interpreting the decrease of turbidity across the front as a decrease in $\boldsymbol{U}$ according to Eq. (1) explains the presence of these MDCs. Another example for a modern MDC under frontal control is the 1000 km long mudbelt extending from the mouth of the Yangtze River southward along the Chinese coast and into the Taiwan Strait. Liu et al. (2018) have identified a laterally dynamic, stratification-induced vertical oceanographic barrier as a key mechanism during winter season, which prevents suspended mud to escape seaward. The hydrodynamics of the front result from an interplay of river plume and coastal currents, leading to isopycnals that prevent cross-shelf flow, confining the mud within the mud belt. Wang et al. (2019) have described a similar mechanism in the Yellow Sea: A seasonally shifting, vertical thermal front determines the lateral boundary of the MDC east of the Chinese Shandong Peninsula. Bi et al. (2010) explained the dispersion patterns of fines from the Yellow River by tidal shear forces that prevent transport of suspended fines beyond the shear front, mitigating transport to the submarine delta.

On the high-energy northwest Iberian shelf, a different type of frontal mechanism occurs, which is more episodic in nature. Here, storm-driven, downwelling-promoted thermohaline fronts limit the shoreward accumulation of the MDC (Zhang et al., 2016; Villacieros-Robineau et al., 2019). This phenomenon has been explained conceptually by Kämpf (2019), who showed that during episodes of coastal downwelling due to sustained strong winds, extreme bed shear stress at the shoreward side of an oceanic density front may erode the seabed as far as 20 km offshore. In a 2D numerical model experiment, downwelling-favorable winds induced a cross-shore circulation that mixed the nearshore waters, in turn shutting down the cross-shore circulation. This shutdown was accompanied by a strong along-shelf jet at the frontal zone between mixed and stratified waters, which extended downward to the seabed. The jet moved offshore with the front, essentially “plowing” the seabed. At the Dutch coast, Horner-Devine et al. (2017) described the mechanism of “frontal pumping” which transports fines resuspended by waves in the nearshore to the inner shelf. In this case, fronts occur in the form of fresh water lenses that emanate from the Rhine River and then propagate onshore and alongshore. During the passage of these fronts, a two-layer, counter-rotating velocity field associated with tidal straining develops, where the velocity is directed offshore in the bottom layer.

3.3 Settling and post-depositional alteration

Aside from the hydrodynamic mechanisms described above, the properties of mud itself and its modification by biological and human activity, both in suspension and at the seabed, have proven crucial when explaining MDC appearance. In contrast to sandy and coarser sediment, the cohesive nature of fines complicates the description of both vertical mud flux and post-settling processes (e.g. van Rijn, 1993; Winterwerp, 2011). These processes are of particular importance during the *rapid initial deposition* and *resuspension and transport* phases (stages 2 and 3 of the sedimentation process described by Wright and Nittrouer, 1995). It is this timeframe which, to a large extent, determines the long-term preservation potential of newly formed mud layers. An excellent summary of mud settling and resuspension mechanisms was given by Winterwerp (2011), and the effects of biota on sediment transport processes were reviewed by Andersen and Pejrup (2011).

3.3.1 Cohesive properties

A distinction has been made between silt particles smaller and larger than 10 µm (McCave et al., 1995; Chang et al., 2006). Around this size, a transition is thought to occur between cohesive and non-cohesive behavior. The finer sized particles (<10 µm) settle and erode as aggregates, while the coarser silt size (10-63 µm) has been termed “sortable silt”, allowing its applicability as a paleo-current proxy in deep-sea deposits (McCave et al., 1995). This approach has not been established for MDCs, where primary productivity and, thus, the effect of aggregation is potentially larger than in the deep sea. For example, erosion experiments by Law et al. (2008) using sediment samples from the Gulf of Lions pointed to a size cutoff for non-cohesive behavior, i.e. “sortability”, at 16 µm. Most of our knowledge of the cohesive and rheological properties of natural muds stem from studies in mud flats, estuaries, and embayments, but the cohesive properties of those nearshore sediments may differ strongly from those of mid- and outer shelf MDCs. Fettweis and Lee (2017), for example found a strong increase in aggregate sizes and porosities from the nearshore to the offshore in the North Sea. Overall, little consensus seems to have been achieved regarding the general description of cohesive mud properties.

Fines tend to collide into aggregates which can be many times larger than the individual particles. The maximum diameter of aggregates is thought to be limited to the local microscale of turbulence, which usually does not exceed 1 mm in coastal and shelf seas (e.g. Fettweis et al., 2006; van der Lee et al., 2009). Aggregation occurs both in the form of coagulation (also termed “salt flocculation”; Eisma, 1986; Wolanski and Gibbs, 1995) due to attractive forces inherent to clay mineral grains in a saline environment, and in the form of flocculation, resulting from the binding of sediment components by sticky extracellular polymeric substances (EPS), which are excreted by fungi, bacteria, and plankton (Grabowski et al., 2011; Tourney and Ngwenya, 2014). Both flocculation and coagulation may take place simultaneously and are therefore difficult to discern even in a laboratory setting. However, studies of estuarine sediments have suggested that, whenever a substantial amount of organic matter is present, biogenic flocculation is the dominant process over coagulation (Andersen and Pejrup, 2011), and a robust correlation seems to exist between maximal floc size and the ratio of algae concentration and to sediment concentration (Fettweis and Lee, 2017; Deng et al., 2019).

The main effect of aggregation of particles on sediment transport is accelerated sinking of the aggregates compared to that of individual grains. The difference in effective sinking velocity may span orders of magnitude, for instance, few mm/s for an aggregate versus 0.01 mm/s for a single clay particle under quiescent conditions. It is, thus, not surprising that aggregation is considered a major and indispensable controlling factor in the development of MDCs (Hill et al., 2007). Enhanced deposition due to aggregation has been evoked to explain the appearance of different kinds of river-fed MDCs around the world. Examples include the wide, supply-rich, high-energy Amazon shelf (Cacchione et al., 1995), the narrow, low-supply, event-dominated Eel shelf (Hill et al., 2000), and the epicontinental, sediment-starved, low-energy Po-shelf (Fox et al., 2004; Milligan et al., 2007). Accelerated sinking of aggregates does not, however, necessarily lead to equally enhanced deposition. This discrepancy is due to the secondary breakup of aggregates at increasing shear stress near the seabed (Dyer, 1989; Manning and Dyer, 2002). Thus, while aggregation can encourage mud deposition by rapid deposition directly off a river mouth, it may also enhance the development of a highly concentrated bottom layer, which may will convey the material further offshore.

The collision and interaction of particles with each other within a high-density fluid transport medium generally leads to a decrease in particle sinking speed. This phenomenon is referred to as *hindered settling*, and its effect enhances with increasing suspended particle concentration. In the case of cohesive particles, aggregation and hindered settling take place simultaneously. At low particle concentrations, aggregation is the dominant effect over hindered settling, resulting in a net downward acceleration in particle sinking. At concentrations of a few g/l, hindered settling overpowers the aggregation effect, leading to a net deceleration in sinking (Figure 3; Winterwerp, 2002). A conceptual model of Kämpf and Myrow (2014) revealed that for a given shear stress, mud suspensions of both low and high concentrations remain in suspension more easily than those of intermediate concentrations as a direct result of the hindered settling effect. This represents a possible mechanism for the development of high-concentration suspensions that travel downslope as a gravity-driven flows (section 3.2.1). Conversely, self-stratification of the suspension hinders turbulent mixing, creating a positive feedback that may lead to a collapse of the suspension. In the absence of significant turbulent mixing, the result is a highly concentrated bottom layer that allows for rapid settling. A one-dimensional model by Winterwerp (2001) predicted that above a certain saturation concentration of the suspension, the concentration profile will quickly collapse into a thin fluid mud bottom layer. This behavior is remarkably similar to the dampened turbulence induced by self-stratification observed in coastal zones by Friedrichs et al. (2000; see Section 3.2). In both cases, a stability criterion involving density stratification and vertical turbulence is evoked, the ratio of which (i.e. Richardson number) determines whether a stably stratified near-bed layer may develop.

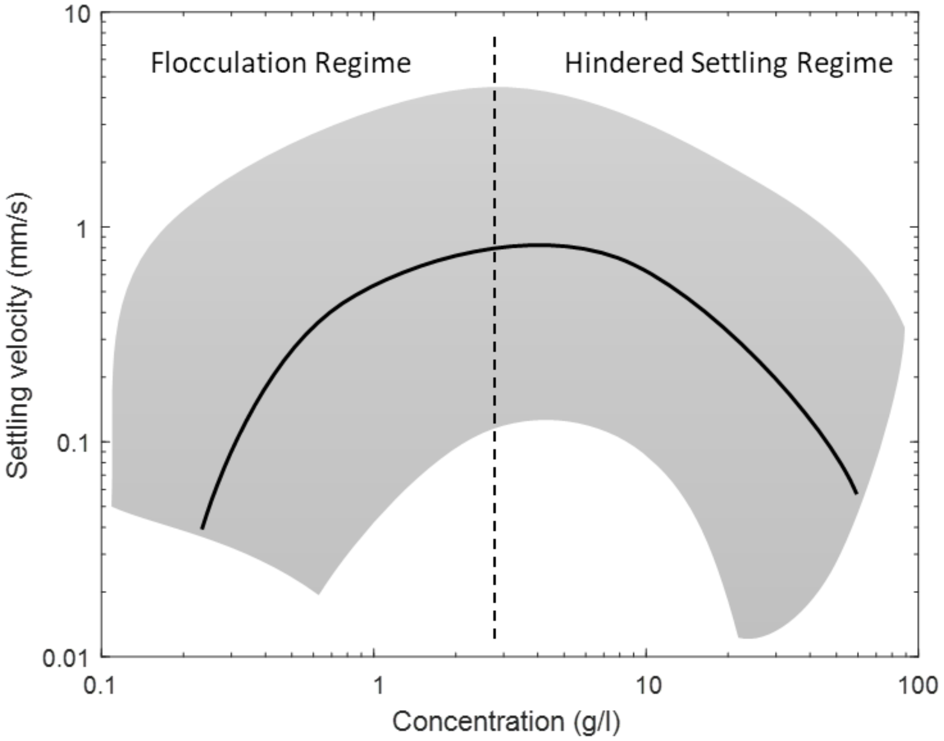

Figure 3. Conceptual diagram of the relationship between suspended sediment concentration and settling velocity (solid black line). For concentrations below 2-3 g/l, settling velocity increases with

higher concentration due to flocculation. Above that concentration, particle interactions with each other decrease the settling velocity. The shaded area encloses data sets of estuarine mud flocs compiled by Winterwerp (2002).

Along with aggregation, consolidation, i.e. the compaction and strengthening of a deposit with time by expulsion of pore water, is a key characteristic of mud that limit its offshelf transport. In fact, modeling studies by Harris and Wiberg (2002) have suggested that, without these two mechanisms, all mud would eventually be removed from the shelf. The general effect of consolidation is both lowering the height of the seabed and increasing substrate resistance to erosion with time. The latter is especially significant in those high-energy settings in which short-term events dominate the sediment supply. In those settings, the time between deposition and development of sufficient shear strength determines whether a deposit will remain in place or whether it will be remobilized during the next episode of high bottom shear stress. The stabilizing effect of cohesion on the sediment architecture in an energetic setting was demonstrated by experiments of Straub et al. (2015): Compared to the non-cohesive case, the cohesive experiment exhibited significantly higher variability in overall relief. The most apparent natural display of this effect is found in deltas, which develop deep, avulsing channels. The reason for the high lateral variability is that cohesion increases the maximum steepness that can be sustained across a landscape. Wherever bottom currents influence an MDC's surface, one can therefore expect higher lateral variability in thickness compared to a sandy deposit in an equivalent settings.

Aside from strengthening through self-weight consolidation alone, the role of biota in altering the resistance of mud to erosion has received increasing attention over recent decades (e.g. Le Hir et al., 2007; Andersen and Pejrup, 2011). Remarkably low contents of clay and EPS are found to dramatically alter the deposit response to particle mobilization. Field studies by Lichtman et al. (2018) found that an increase in EPS content up to 0.05 % drastically lowers the material transport rate compared to clean sand substrate. Besides microalgae, it has been recognized that secondary production of EPS by heterotrophic bacteria assemblages, which are ubiquitous in muds, contribute to biostabilization

(Gerbersdorf and Wieprecht, 2015). Valentine et al. (2014) and Valentine and Mariotti (2020) studied the effect of biofilms on deposit erodibility and found that the presence of a biofilm always reduces erodibility at low shear strengths (~0.1 Pa), while only a "mature" biofilm (>3 weeks old) reduces erodibility at moderate shear strength (~0.4 Pa). Notably, this effect seems to overpower that of material consolidation by pore water expulsion on timescales of a few weeks.

As opposed to the stabilizing effect of microbenthos, macrobenthos generally has a destabilizing effect: Its physical presence enhances seabed roughness, sometimes by an order of magnitude compared to a smooth muddy seabed (Pope et al., 2006), leading to enhanced near-bottom turbulence. Bioturbation through burrowing further increases erodibility, which reduces bottom shear strength, or through direct bioresuspension (Le Hir et al., 2007). It has also been proposed that enhanced permeability created by burrows and tubes directly promotes sediment dewatering and, thus, can accelerate consolidation (Richardson et al., 2002).

Typical values for the critical shear stress of soft beds lie in the range of 0.1-5 Pa (Winterwerp et al., 2012), depending on its state of consolidation, though much smaller and much larger values are possible for freshly deposited and well-consolidated muds, respectively. Thompson et al. (2019), for example, measured critical shear stresses as low as 0.02 Pa at muddy sites in the Celtic Sea. Based on extensive in-situ erosion measurements, they parametrized critical shear stress with a range of sediment characteristics (organic carbon and bulk density, sorting, kurtosis, porosity, percentage fines and chlorophyll a concentration). Though the resulting model fits the data well (R^2=0.99), the authors concluded that generalized predictions of critical erosion thresholds from sediment properties are not yet possible and that instead, localized parametrizations are still necessary. One reason for this is that the stress history, i.e. the history of resuspension, swelling, and consolidation phases is not captured by these parametrizations. In this light, a period of "high preservation" seems just as important for mud accumulation as a period of high sediment flux, as pointed out by Paola et al. (2018).

3.3.2 Bottom trawling

As a common, often chronic anthropogenic contribution, resuspension by the fishing practice of bottom trawling is a dominant erosion mechanism on many MDCs (Oberle et al., 2018). The deployment of heavy gear pulled over the seafloor disturbs the upper few cm to dm of the seabed, frequently resuspending a large amount of fines.

According to Amoroso et al. (2018), 14 % of the continental shelf and slope regions worldwide are affected by bottom trawling, reaching >50 % in some European seas. Oberle et al. (2016a) estimated a total of 21,870 Mt/yr of sediment is resuspended globally in this way, which is at the same order of magnitude as the global riverine supply. Mengual et al. (2016) linked a 30 % decrease in mud content in the seabed deposits of the Bay of Biscay since 1967 to intense bottom trawling. Similarly, Palanques et al. (2014) found an artificial coarsening-upward trend within the uppermost 20 cm of the muddy Ebro prodelta. Puig et al. (2015) described redeposition of mud from the flanks of a canyon in the NW Mediterranean, forming a new depocenter along the canyon’s deeper axis. Some attempts have been made to quantify the net effect of off-shelf export of fines caused by chronic bottom trawling. On the NW Iberian shelf, Oberle et al. (2016a) calculated a six-fold increase in off-shelf sediment transport due to bottom trawling compared to natural (storm-driven) conditions, assuming all recurrently resuspended fines are eventually advected into the deep ocean. Churchill (1989) estimated that bottom trawling is responsible for about 10 % of the resuspended mud in the New England Mud Patch. Applying a simple model that assumes constant off-shelf directed current velocity, he concluded that bottom trawling does not seem to cause significant net erosion. Similarly, Ferré et al. (2008) posed that trawling-induced resuspension contributed a few percent to the total export of fines on the Gulf of Lions shelf.

From these examples, it seems that fate of fines resuspended by bottom trawling depends largely on the strength and direction of bottom currents prevailing during and after resuspension in the trawled area. In any case, bottom trawling imparts a significant signal onto the sub-recent record of MDCs, which may manifest as material contortion, homogenization, winnowing, and re-sorting of the preexisting near-surface stratigraphy, including organism disturbance, substrate ventilation, and nutrient recirculation (Oberle et al., 2016b).

3.4 Numerical modeling of mud sedimentation processes

During the past decades, numerous numerical models have been developed to describe sedimentation processes of mud in estuarine and coastal shelf environments (e.g. Scully et al., 2003; Harris et al., 2005; Neumeier et a., 2008; Hsu et al., 2009; Bourgault et al., 2014; Zhang et al., 2016, 2019). They have proven indispensable tools in comprehending the influences of short-term hydrodynamic processes on MDC development. A survey of such models was conducted by Amoudry and Souza (2011), who summarized that the predictive ability of regional sediment transport models was limited by inadequate parametrizations of several important processes, including erosion, flocculation, consolidation, and biological effects. We find many of the general shortcomings laid out by those authors to still be valid today.

Process-based models of mud transport and dynamics fall into two categories: 1) high-resolution (10^{-2}-10^{0} m scale) one-dimensional or two-dimensional vertical models (1DV or 2DV), and 2) coarse-resolution (10^{1}-10^{3} m scale) three-dimensional (3D) models. Models of the first category directly resolve two- (or multi-) layer flow where an inviscid water layer overlays a mud layer with specific rheological properties (e.g. Longo, 2005; Hsu et al., 2009; Amoudry and Liu, 2010; Espath et al., 2014). The limitation to one- or two-dimensional vertical planes allows resolving a detailed interaction between turbulence and mud by the use of Direct Numerical Simulation (DNS) or Large-Eddy Simulation (LES) approaches (e.g. Hu et al., 2012; Deng et al., 2017). The theoretical soundness and satisfactory performance of these models in capturing small-scale physical interactions between fluid and mud has been demonstrated for various flow conditions in laboratory in settling tank and open channel experiments (e.g. Chauchat et al., 2013). However, the expensive computational cost of such models often impedes their use for studying large-scale coastal MDC dynamics.

Models of the second category are often called “coastal ocean sediment transport models”, which are meant to capture the transitional nature of sediment dynamics between coastal shelf environments and deep ocean (Kirby, 2017; Fringer et al., 2019). Coastal ocean models must be able to simulate both highly frictional, ageostrophic motions governing sediment dynamics in estuaries and coastal shelf seas and the dispersal of fine particles across shelf towards the open ocean. These models are normally discretized at a scale (10^1-10^3 meter in space and 10^0-10^2 s in time, Warner et al., 2008; Syvitski et al., 2010; Zhang et al., 2018; Fringer et al., 2019) that is much larger than the one on which turbulence, sediment particle-particle interactions and particle-fluid interactions occur (10^{-2}-10^0 meter in space and 10^{-2}-10^0 s in time). Therefore, the small-scale processes have to be either solved by sub-grid modeling or simplified by empirical formulae (Zhang, 2016). Coastal ocean sediment transport models treat sediment as a continuum rather than individual particles and assume that suspended sediment particles effectively follow the water flow and their concentration is small enough (normally less than 1 g/l) to ignore particle-particle interactions. The presence of sediment in a spatial unit is in this case represented by a concentration value. By integrating a mass balance equation of sediment into the Reynolds-Averaged Navier-Stokes equations of water flow, coastal ocean models have the capability to resolve sediment transport and deposition on continental shelves to the first order of approximation (Amoudry and Souza, 2011).

Most coastal-ocean sediment-transport models divide sediment into two or multiple grain size classes to consider contrasting transport modes regarding a specific particle size distribution (e.g. Warner et al., 2008; Erikson et al., 2013; van Maren and Cronin, 2016; Kirby, 2017). In almost all existing models, the modeling of sand and mud classes is still separated assuming that these different classes do not influence or interact with each other in the water column (Warner et al., 2008; van Maren and Cronin, 2016; Kirby, 2017; Sherwood et al., 2018; Delft3D-Flow, 2019). Their interactions are considered only for a thin layer (normally within a few cm) near the seabed in the case of high sediment concentration (>10 g/l) that may significantly affect settling (e.g. hindered settling) and resuspension (Styles and Glenn, 2000; Zhang et al., 2016).

Parameterization of the settling velocity of mud is particularly important in coastal shelf seas where mud is transported mainly in the form of aggregates (Winterwerp, 2011; Soulsby et al., 2013). Aggregation and break-up of mud poses a great challenge in modeling using the multiple grain size division approach because the variation of floc size changes with environmental factors such as turbulence shear and stratification (Zhang et al., 2020). By now, no coastal ocean model explicitly couples a biological model with a sediment transport model to account for mud flocculation and de-flocculation. Instead, a common method is to ignore flocculation parameterizations and assume static floc sizes with behavior that is essentially tuned to match observations (Soulsby et al., 2013; Fringer et al., 2019). The difficulty of achieving a flocculation model which matches observations is illustrated by the model of Soulsby et al. (2013): Their formulas for sinking velocities of macro- and microflocs include a total of eleven tunable parameters, the calibration of which requires an extensive experimental dataset. Spearman and Roberts (2002) concluded from an inter-comparison of different flocculation models with field data that adding complexity to flocculation models does not necessarily improve their performance, and that a simple power law model, or even a fixed (mean) settling velocity, often produce the most accurate results.

Diaz et al. (2020) recently demonstrated the high sensitivity of simulated mud fluxes on settling and erosion parameterizations. Using a numerical model of the Gironde estuary an adjacent shelf which was extensively calibrated against near-surface sediment concentrations in the estuary, they showed that vastly different sediment parametrizations could reproduce the measured near-surface sediment concentrations with similar skill. Meanwhile, uncertainties of residual mud fluxes among the model runs using different parameter sets reached up to 93 %. This shows the importance of near-bottom measurements of suspended sediment for validating numerical models in order to mitigate uncertainties associated with equifinal parameter sets.

The realistic modeling of the consolidation process of soft mud is critical for a quantitative modeling of MDC development. While some approaches deal exclusively with reduction of porosity and the associated subsiding of the bed (e.g. Toorman, 1999; Merckelbach and Kranenburg, 2004), others focus on the increase of critical shear stress for erosion with time and with depth below the seabed surface (e.g. Sanford, 2008). An approach where both effects are treated simultaneously was implemented by Le Hir et al. (2011), who related shear strength to relative mud mass concentration through a simple power law. It may be argued that within MDC modeling, the evolution of critical shear stress is of far greater concern than the evolution of bed height, as even a pluricentimetric subsidence of a bed due to consolidation will not substantially alter the hydrodynamics in water depths of several meters or more. In fact, both a coastal ocean model's vertical grid spacing and uncertainties in the model bathymetry are usually far greater than the consolidation effect on the timescales covered by such models.

Some of the most important processes for mud transport and deposition occur near the seabed, as described above. However, the bottom-closest layer in coastal ocean models is normally too thick to resolve these processes, in particular wave-supported sediment gravity flow, which is confined to the wave boundary layer that is limited to not more than 20 cm above seafloor (Zhang et al., 2016). To bridge the gap in a model between the seafloor and the bottom-most grid point (which is normally higher than a few tens of centimeter above the seafloor), parameterizations of the BBL are used in coastal ocean models. The classic theory describing the BBL under the combined effects of currents and surface gravity waves by Grant and Madsen (1979) was later extended to include the effect of sediment-induced stratification in the near-bottom water column (e.g. Glenn and Grant, 1987; Styles and Glenn, 2000). Application of BBL parameterization taking into account the effect of sediment-induced stratification of the wave boundary layer proved helpful in modeling the development of coastal shelf mud deposits (e.g. Wang, 2002; Zhang et al., 2016). To account for the transport of gravity-driven sediment flows (e.g. fluid muds or wave-supported sediment gravity flows) on the seafloor in coastal ocean models, either two-layer approaches resolving the Reynolds-averaged fluid mud transport in the BBL (e.g. Hsu et al., 2009) or simplified formulations by the use of gradient Richardson number and buoyancy anomaly across the lutocline to approximate the transport velocity of gravity-driven sediment flows (Scully et al., 2003; Harris et al., 2005; Wright and Friedrichs, 2006;

Zhang et al., 2016; Zang et al., 2020) have been applied. Though these models are not able to represent the internal structure of the flow, they were able to predict the positions of gravity-flow deposits with good accuracy.

Most coastal ocean sediment transport models are based on the hydrostatic primitive equations under the Boussinesq approximation – a valid approximation for mesoscale and submesoscale (≥1 km) water motions which have a horizontal scale much larger than its vertical scale (Marshall et al., 1997). However, non-hydrostatic pressure becomes important when water motions that are much smaller than the local water depth have significant impact on sediment transport (Quaresma et al., 2007; Masunaga et al., 2017; Shi et al., 2017; Zhang et al., 2019). These motions include internal solitary waves, oceanic fronts, tidal bores, convective overturning, and water flow over short-wavelength bedforms such as dunes and ripples. Resolving such processes in coastal shelf seas is computationally expensive because it requires very high resolution in both time (second-scale) and space (meter-scale), which often impedes the use of 3D coastal ocean sediment transport models for studying mud dispersal associated with these fine-scale processes (Fringer et al., 2019). Nevertheless, 2D versions of non-hydrostatic coastal ocean models using a cross-shelf vertical plane and neglecting along-shelf variations proved useful in understanding mud dispersal by single processes such as internal solitary waves (Masunaga et al., 2017).

Although process-based coastal ocean models are robust in capturing sediment transport and deposition/erosion patterns on short time scales such as days and months, direct application of these models to longer-term (decadal-to-millennial scale) is severely restricted and they can hardly perform better than behavior-oriented models built on assumptions of morphological equilibrium or quasi-equilibrium in response to certain driving forces (Zhang et al., 2012; French et al., 2016). Exclusion of the impacts of stochastic extreme climatic events (storms and floods), system self-organization and biophysical factors in process-based models often leads to results that systematically deviate from observations (e.g. Zhang et al., 2010). Hybrid models, which combine the advantages of process-based modeling (for mechanisms that can be both mathematically and physically well described) and behavior-oriented formulations (for less-known intrinsic self-organization, morphological equilibrium and biological impacts), seem to be the best choice for modeling long-term development of complex coastal sedimentary systems including MDCs (Roelvink, 2006; Brown and Davies, 2009; Zhang et al., 2014; French et al., 2016). Nevertheless, the development of such models is in a very early stage and there is still lack of consensus on tackling the difficulty in upscaling, coupling, localization, thresholds, scale invariance and interwoven biology and geochemistry (Syvitski et al., 2010).

4. Discussion and conclusions

Many of the tasks facing MDC research relate to the ubiquitous scale problem in sedimentary geology: Modern subaqueous deposits lack signatures induced by low-order effects such as climatic variations and tectonics, which usually dominate ancient strata, while in-situ and laboratory studies tend to be biased towards individual, high-flux events. Therefore, any comparison of ancient geological records, modern soft-sediment deposits, and in-situ/laboratory monitoring and experiments faces a fundamental difficulty. This disparity has been summarized by Woodroffe and Murray-Wallace (2012): "*Coastal scientists presently have a relatively good understanding of coastal behavior at millennial timescales, and process operation at contemporary timescale. However, there is less certainty about how coasts [and continental shelves] change on decadal to century timescales*". Particularly the relationship of individual events occurring in periods of minutes to weeks with multi-decadal patterns remains an open challenge. This issue was raised some time ago by Dott (1983, 1996) and expanded on recently by Miall (2015) and Paola et al. (2018), who surmised that the rare events that lead to long-term preservation of a deposit are not catastrophic transport events but short-lived intervals of rapid deposition that trap the background sedimentation.

The three paradigms of MDC development – *continuous supply, continual resuspension-deposition cycles*, and e*pisodic erosion and sedimentation events* (section 2.2) – offer alternative explanations for the development dynamics of MDCs, and specifically for the occurrence and thickness of individual strata within MDCs. The disparity of timescales of oceanographic versus geological approaches makes it challenging to reach a conclusion about the validity of each of the paradigms regarding a specific MDC. In general, high-flux processes that influence an MDC's morphology, such as gravity flows, occur locally, while stable hydrographic fronts influence regional scales. On timescales longer than those on which episodic events and bedform-scale perturbations take place, depositional processes are implicitly time-averaged, and $\boldsymbol{U}$ in Eq. (1) represents the steady-state, or residual flux. In contrast, an equilibrium is seldom observed on time-scales on which the lateral flux of fines is dominated by individual events, where $|\boldsymbol{U}'| \gtrsim |\overline{\boldsymbol{U}}|$ (Zhou et al., 2017). Thus, the extent to which perturbations effect the morphology depends upon frequency and amplitude of $\boldsymbol{U}'$, which are correlated with the environmental statistics (e.g. frequency and intensity of storms and floods, or biological activity). In relatively calm settings with low supply of fines, $|\boldsymbol{U}'| \ll |\overline{\boldsymbol{U}}|$ and the overall extent and geometry of an MDC may be reasonably represented by the conceptualization of dynamic equilibrium driven by hemipelagic settling and mean current patterns. In high-supply and high-energy settings, events and perturbations become important for explaining the overall geometry and extent of a MDC. In both cases, fluctuations of $\boldsymbol{U}'$ influence small-scale shape variations as well and individual laminae within the record. This treatment is in line with that of Nittrouer and Sternberg (1981), who tackled the problem of strata development by considering the ratio of vertical mixing rate to accumulation rate. As this ratio increases, structures become less distinct and strata become more homogeneous. The variability of strata preserved through time is controlled by the relationship between the residence time of particles within the surface mixed layer and the natural cyclic period of sedimentation, the time after which extreme flood or storm depositional products are averaged out (in the range of 10^0-10^2 yrs, Curray et al., 1964). An important consequence of the former two paradigms (*continuous supply* and *continual resuspension-deposition cycles)* is that an MDC will tend to deteriorate when sediment supply decreases (Hanebuth et al., 2015). The reason is that, assuming other environmental factors remain unchanged, a decrease in $\overline{\boldsymbol{U}}$ from the landward side of an MDC will lead to a decrease in $\nabla \cdot \boldsymbol{U}$ on the seaward side. This connection is not necessarily true for the third paradigm (*episodic* *erosion and sedimentation*); for example, flood deposits may accrete even when the mean sediment supply decreases.

Three general conclusions may be drawn regarding MDC development:

1. Episodic, high-flux events are highly likely to influence MDC development in a range of oceanographic settings.
2. The three paradigms of MDC development – continuous supply, continual resuspension-deposition cycles, and episodic erosion and sedimentation - may be partially reconciled by consideration of various spatial and temporal scales on which the sedimentary processes take place.
3. The relative contributions of episodic events to long-term MDC development is not known for many systems.

Since the introduction of the *mudline* as the shoreward limit of muddy deposition on the continental margin, considerable progress has elucidated those processes responsible for moving fines from the sediment source along- and cross-shore. For fines, the shear stress threshold for initiation of motion is close to that of resuspension. For this reason, fines have commonly been treated as either suspended or settled, and bedload transport by rolling/saltation such as observed in sand is typically not associated with fines. However, researchers have become increasingly aware that in many settings, energetic modes of near-bottom transport are the dominant dispersal mechanism for fines. Among the recent developments in explaining the appearance of MDCs, five discoveries stand out:

The mechanism of *wave- or current-enhanced sediment gravity flow* explained why some MDCs are located considerably further offshore than would result from plume advection alone. Similarly, episodic, *storm-generated density fronts* associated with strong bottom shear stress have been shown to keep the inner shelf free of mud. By contrast, the seaward limit of mud deposition has remained more elusive. To this end, resuspension by *internal waves* and shielding of deposits by lateral density gradients associated with *stable density fronts* have been identified as processes which increase and decrease, respectively, the seaward extension of MDCs. The observation that mud can accrete through *bedload-deposition of fines* showed that MDCs may develop in environments which are more energetic than commonly assumed and offered some explanation of mm-scale laminae found within many recent and ancient deposits. Finally, the impact of *chronic bottom trawling* on many MDCs has been shown to significantly enhance off-shelf transport and rework the top few dm of the seabed. Relevant processes discussed in this review are summarized in Figure 4.

Though numerical modeling was proven to be an indispensable tool for the study of MDC dynamics, the implementations of morphodynamic processes into 3D coastal circulation models continue to lag behind their hydrodynamic counterparts (Fringer et al., 2019). Discrepancies between predictions and measurements of one order of magnitude remain common for near-bed sediment concentration and suspended-load transport, making further improvement on parametrizations of muddy transport processes necessary. In addition, many of the parametrizations developed for the processes of erosion, settling, and consolidation were realized using mud samples taken from to estuaries, bays, or mudflats. The applicability of those coastal parametrizations to those offshore settings, where most MDCs are found, is yet to be demonstrated. This effort would likely contribute to the solution of the aforementioned timescale problem; for example, a more sophisticated parametrization of material consolidation at the seabed should be able to predict whether a deposited sediment layer will lastingly remain in place or be destroyed during one of the following erosive events. Applying high-resolution, process-based models to long-term morphological changes also represents a challenge due to limits in computational resources. A compromise between model accuracy and computational cost may be achieved by reducing processes to their main driving terms on the scale of interest while omitting or averaging small-scale processes. The obvious drawback of this approach is that it requires a priori knowledge of the significant mechanisms, determining the contribution of which is usually the objective of a modeling study. Another common method is the use of a morphological acceleration factor to speed up the adjustment of landscapes to hydrodynamic forcing. For large acceleration factors or strong forcing, this approach may lead to issues with stability and accuracy of predicted bed levels, when nonlinearities in the hydrodynamic response occur (Jones et al., 2007).

Bridging the gap between short-term processes and long-term accumulation patterns through the identification of morphological equilibrium–disequilibrium cycles is the key towards a more complete understanding of sedimentation at and around MDCs.

Acknowledgements

This study is a contribution by the Helmholtz Society through the PACES II program. W. Zhang acknowledges the support from the I^2B project "Unravelling the linkages between benthic biological functioning, biogeochemistry and coastal morphodynamics – from big data to mechanistic modeling" funded by Helmholtz-Zentrum Geesthacht. We thank two anonymous reviewers for their detailed comments which helped to improve this manuscript.

Data statement

No data was used in the preparation of this article.

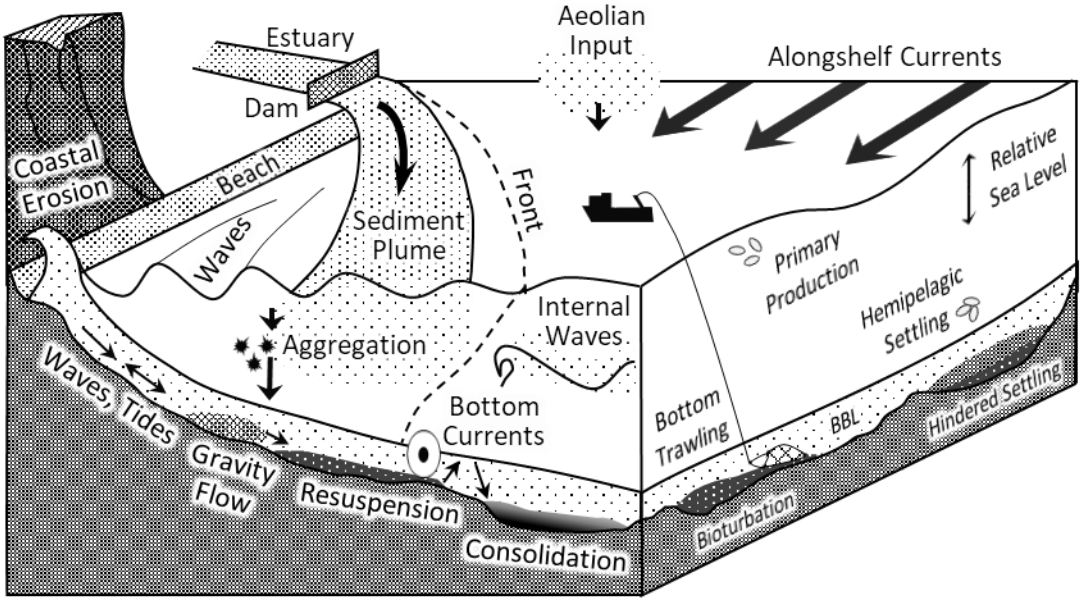

Figure 4. Conceptual diagram illustrating the major source-to-sink processes influencing MDC development. Modified after Nittrouer and Wright (1994).

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