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Review

Organic Matter Burial in Deep-Sea Fans: A Depositional Process-Based Perspective

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Abstract: Organic matter burial in the deep-sea fan sediments is an important component of the long-term carbon cycle. Although there is increasing recognition of the importance of organic matter in deep-sea sediments, a major focus has been on mudstones, commonly interpreted as the background sediments, deposited by pelagic or hemipelagic vertical suspension fallout in low-energy fan environments. Emerging evidence suggests that relatively coarse-grained sediment gravity flow deposits (e.g., turbidites and hybrid event beds) can also store a significant quantity of organic carbon, implying that a wide range of depositional processes can result in the concentration and enrichment of organic matter in submarine fans. However, the role of these processes on carbon burial is still not fully understood. This review aims to discuss the impact of three widely documented deep-sea depositional mechanisms/processes, namely vertical suspension settling, grain-by-grain (incremental aggradation), and the en-masse deposition on distribution, burial, and preservation of organic matter in deep-marine deposits. Organic matter accumulated from slowly settling suspension in mud caps (Te or H5 divisions of turbidites and hybrid beds, respectively) is prone to higher oxidation compared to the carbon buried in sandy components of turbidity currents (Ta-Tc units) and hybrid beds (H2/H3 divisions). The burial of organic matter in sandy parts of the deposits has important implications for understanding the fundamental physical processes that control carbon accumulation and preservation in deep-marine rock record.

Keywords: organic carbon; deep-sea fans; carbon burial; turbidity current; suspension settling; hybrid event bed; mudstone; linked debrite

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1. Introduction

Organic matter (hereafter OM) deposition and burial in deep-sea fans is an important component of the long-term carbon cycle [1–13] and represents the second largest global sink (~170 megatonnes of carbon) of atmospheric carbon dioxide after the combined processes of silicate weathering and carbonate precipitation [2]. The amount of carbon buried in these sediments can be stored over geologic timescales, thereby removing atmospheric carbon dioxide and regulating long-term climatic trends [14–18].

Off-shelf transport and ultimate burial of large volumes of terrestrial OM in different parts of the deep-sea fans is commonly attributed to a range of sediment gravity flow and suspension settling processes [1–13]. Traditionally, sediment gravity flows have been subdivided into two end-member flow states, namely debris flows and turbidity currents. Debris flows are characterized by laminar rheology with particle support by a combination of matrix strength, buoyancy and grain-to-grain interaction [19–22], whereas turbidity currents are turbid flows of variable concentration but with significant particle support by turbulence [23–27]. Several earlier flow classifications schemes have been proposed to capture the spectrum extending from cohesive debris flows through to dilute turbidity currents [27–30].

Whilst most of the flow classification schemes envisage discrete flow states, albeit encompassing a spectrum (defined by the degree of turbulence and type of particle support mechanism), the definition of intervening flow types that exhibit mixed behavior (part turbidity current and part debris flow in the same event) has proven less satisfactory. This is despite the fact that mixed flow deposits are widespread in many deep-water basins [6,31–33]. The mixed flow deposits were initially reported from the Aberystwyth Grits on the Welsh coast and were termed 'slurry' beds [34]. Subsequently they were encountered in the Cretaceous Britannia system in the North Sea [35–37]. These deposits with alternating clay-poor and clay-rich sandstones in the Britannia system were attributed to episodic gelation of mud [36] in near-bed layers (i.e., neither laminar nor turbulent but somewhere in between) or cohesion-dominated traction carpets [35]. A recurring facies association in the fringes of several sand-prone, syn-rift Jurassic submarine fans in the North Sea Basins was identified by Haughton et al [31]. These authors documented that sandstone beds displaying full or partial Bouma sequences were surprisingly rare in these systems [31]. Instead, the event beds commonly comprise a basal, dewatered and/or structureless sandstone (H1), capped by a muddy sandstone or sandy mudstone with scattered mudstone clasts and carbonaceous matter, and complex internal fabrics including sheared sand injections (H3 division). These beds were interpreted as 'linked debrites' formed by distal flow transformations [31], prefixed 'linked' to emphasize that the debrites were accumulated as part of the same event that emplaced the sand, as opposed to a separate or standalone debris flow. The widespread recognition of analogous deposits in deep-water fan successions has demonstrated that schemes that place deposits into separate end-member flow states (turbidites and debrites) fail to capture the variability observed in deep-water deposits and a single flow can have zones with very different rheology [31–54]. The flow deposits showing evidence of deposition from turbulent, transitional and laminar flow, all as part of the same event, have been termed "hybrid event beds (HEBs)" [32]. An alternative classification scheme (Figure 1) was thus proposed that distinguishes the deposits of flows that were either cohesive (debris flows, mudflows), non-cohesive (low- and high-density turbidity currents, cohesionless debris flows) or show evidence for mixed behavior at a point (hybrid flows and other types of linked event bed, e.g., debrite–turbidite couplets commonly forming megabeds) [32].

The fine-grained muddy material including OM carried by the sediment gravity currents disperses above and travels beyond the final deposit as a low-density wake and mixes with suspended material in the water column, and slowly accumulates from suspension settling [55]. Periods representing quiescence between the sediment gravity flow events are also characterized by the deposition of background mudstones from suspension settling [56–58]; however, these mudstones are not part of the sediment gravity flow events and hence their role in OM burial and preservation is not discussed here. Traditionally, deep-marine mudstones have been commonly interpreted as the background sediments, deposited by pelagic or hemipelagic vertical suspension fallout in low-energy fan environments [51,56,57], but recent scientific evidence suggest that these deposits may be formed by a range of depositional processes including relatively energetic turbidity currents and transitional flows [57–62]. The observation of the drilled cores in the Laingsburg depocentre, Karoo Basin, South Africa has allowed us to document the variability in depositional processes and stacking patterns between slope and basin-floor mudstones within the same basin margin succession [63]. Basin-floor mudstones exhibited a repeated and predictable alternation of bedsets and massive packages and were interpreted to be deposited by a wide range of low-density turbidity currents (waning, waxing, waxing-to-waning, multi-pulsed), and occasional transitional flows. The slope mudstones were characterized by a higher proportion of low-density turbidites compared to debrites with a less predictable facies stacking pattern, and a higher degree of bioturbation that may affect OM preservation. Hence, understanding facies and related depositional process variability within deep-water mudstone successions is critical to constrain preservation of OM in these rocks.

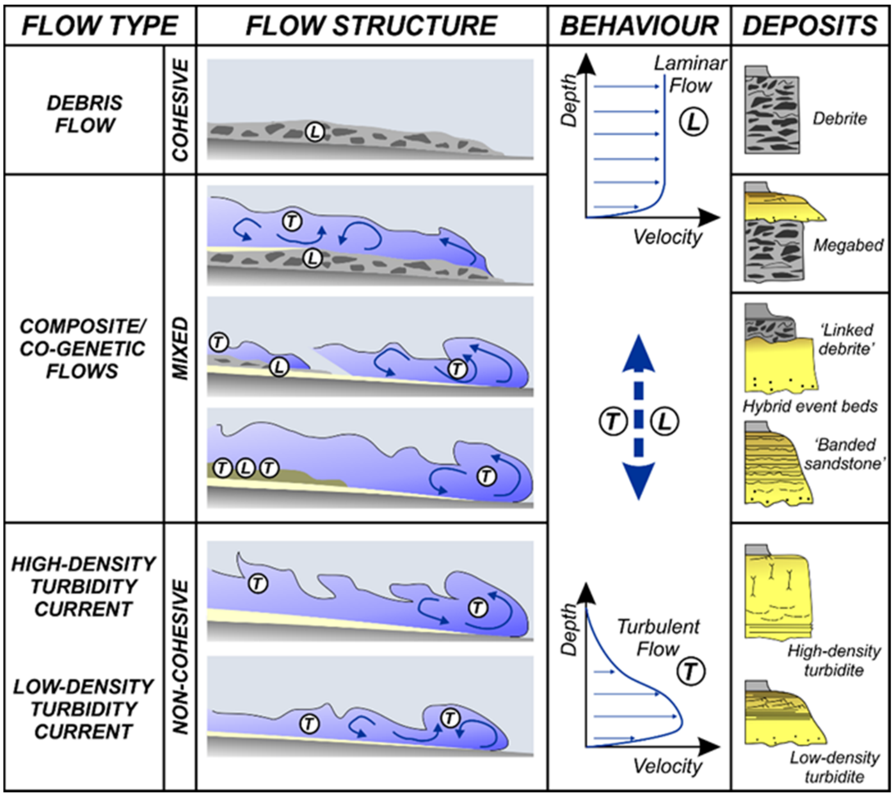

Figure 1. Haughton et al. (2009) classification scheme for event beds emplaced by a wide variety of subaqueous sediment gravity flows emphasizing that many of the deposits are composite or transitional in character, lying between end-member non-cohesive (turbulent) and cohesive (laminar) flow states. Reprinted/adapted with permission from Ref. [32], 2009, Elsevier.

Particulate OM in deep-sea fans comprises heterogeneous mixtures of organic particles from different sources [64–66]. It includes fragments of terrestrial plants such as leaves, wood, spores and pollen grains [1–13,67], remains of marine algae/bacteria referred to as modern carbon [2,68], and a portion of recycled and aged carbon stored in soils and sediments for thousands of years, and referred to as old carbon [2,68]. The presence of these different OM varieties leads to a continuum of age and reactivity of OM in deep-marine sedimentary systems [66]. Although the presence of dissolved organic carbon cannot be ruled out, here we only focus on particulate OM because it represents the fraction that is ultimately buried and has the potential to enter the long-term carbon cycle.

Previous work [1–13,68–70] in deep-marine fan systems has shown that sediment-gravity flows are highly efficient at transporting these different types of OM from the continental shelf into the deep-marine settings, where it becomes preferentially concentrated in specific sub-environments such as channels–levees, lobes and basin floor sheets. During downslope transport, only a small proportion of the carbon survives oxidation (between 50–80% of the organic carbon is remineralized) and ultimately becomes sequestered in deep-sea sediments [71]. Despite increasing recognition of the importance of OM in deep-sea sediments, the focus has been on mudstones (turbidite (Te) and hybrid bed (H5) mud caps and hemipelagites) with very limited emphasis on sand-rich facies (Tb/Tc parts of turbidites) and muddy sandstones (H3 divisions of HEBs). Recent evidence [1,10,11] highlights that sandy divisions in turbidites and muddy H3 divisions of HEBs can also store significant concentrations of land-derived organic carbon to the extent that they could act as conventional source rocks and unconventional reservoirs [1,8]. There is also growing evidence that mud can offer enhanced physical protection to the OM and that the surrounding mineral matrix may regulate long-term global preservation of organic carbon [11,68]. Thus, mechanisms that can sort clay and OM together during transport and deposition are potentially going to lead to enhanced OM burial in the stratigraphic record.

A better mechanistic understanding of OM distribution, the thresholds of its segregation between various deep-water sedimentary facies and of constraining the impact of a range of deep-water depositional mechanisms (suspension settling, incremental aggradation, en-masse deposition) on carbon burial and preservation is important to develop models that aim to forecast the fate and dispersal of organic carbon in deep-sea environments. Furthermore, understanding the nature and occurrence of OM burial in ancient deep-marine deposits is critical to understand the mechanisms and efficiency by which OM has been preserved throughout geologic time, and in turn, better constrain models describing global carbon budgets. The aim of this review is to constrain the impact of different deep-sea depositional mechanisms on the distribution, burial and preservation of OM in the stratigraphic record. This study discusses OM distribution data from the literature on both ancient and modern submarine fans in order to assess patterns of OM distribution and preservation in different deep-water event beds and related mudstones. The key questions discussed include: (i) How is terrestrial OM distributed in different types of sediment gravity flow event deposits (turbidite, hybrid event beds) and mudstones; (ii) what are the controls on OM distribution, burial and preservation in the deep-water rock record; and (iii) what are its implications for the development of improved process-based depositional models for carbon burial. Significantly, the depositional mechanisms discussed here define the common facies associations of OM and thus help illustrate the fundamental physical processes that govern its accumulation and preservation in the rock record. Understanding carbon burial in the context of deep-sea depositional processes also has important implications for understanding the source rock and unconventional reservoir potential of submarine fan deposits.

In the following sections of this study, a comprehensive but non-exhaustive scientific review on OM distribution and burial in different deep-marine event deposits is provided. Where required, the study also combines scientific literature data with some analytical data (acquired by the primary author) to better constrain the distribution of OM in studied deposits. The applicability of the concepts inferred from the literature for terrestrial OM burial elsewhere is touched upon, and wider challenges associated with trying to determine the distribution of OM in different deep-water event beds are considered, with the last part synthesizing the overall conclusions of this study. Furthermore, in this paper, we only focus on terrestrial OM fractionation and burial by three widely documented deep-marine depositional processes, i.e., turbidity currents, hybrid and transitional flows, and suspension settling, without providing exhaustive reviews on different deep-water flow processes and their deposits characteristics. Detailed reviews on different deep-water deposits and related depositional processes including those that are not discussed in the present study (e.g., bottom currents) are provided by [32,33,35,55].

2. Organic Matter Deposition and Burial in Submarine Fans

2.1. Suspension Settling

Suspension settling is an important deep-marine depositional mechanism by which fine-grained materials including clay, silt and OM fall slowly to the seafloor [49,51,56,57]. Muds can be deposited from a low-density suspension and left on top of the sandy component of the turbidites as Te division (Figure 2a) or as H5 division in hybrid event beds (Figure 2b); see [23,32], respectively. Background mudstone deposits are also accumulated from the water column via slow vertical settling and are often vertically stacked with sediment gravity flow deposits in cores and outcrops, but they are not considered as part of flow events (Figure 2c). Muds are commonly interpreted to be deposited in low-energy (distal) fan environments under oxic to anoxic conditions. In proximal energetic fan sectors muds may either be very thin or not expressed at all [11,57]. Organic carbon carried by sediment gravity flows is also often sorted with mud in the mudstones because of their platy particle shape, which facilitates slower settling than denser, relatively rounded, coarser clastic grains (such as quartz and feldspar) with which they are transported [72,73]. Conventional models argued that for preservation of OM bottom water anoxia is prerequisite [71]. However, emerging evidence suggests that low-energy conditions and persistent bottom-water anoxia are not necessary pre-requisites for enhanced OM preservation in these units [8,11,60,74]. The important factor to sequester OM is that at least some OM is rapidly buried in the sediments without being completely oxidized (e.g., [75–78]). This is commonly accomplished if large volumes of OM are supplied to the regions of high primary productivity [79] or when OM is rapidly buried and preserved due to high frequency recurrence of sediment gravity flows events [74] or clay-forced turbulence dampening [11]. It was noted by [74] that during deposition of the Whitby Mudstone Formation, large volumes of organic carbon were delivered episodically to the seafloor and the frequency of depositional events was sufficiently high to minimize oxidation of the OM. However, a limited number of studies have documented the impact of rapid deposition on enhanced preservation of OM in mudstones and transitional flow processes in fine-grained deep-water successions.

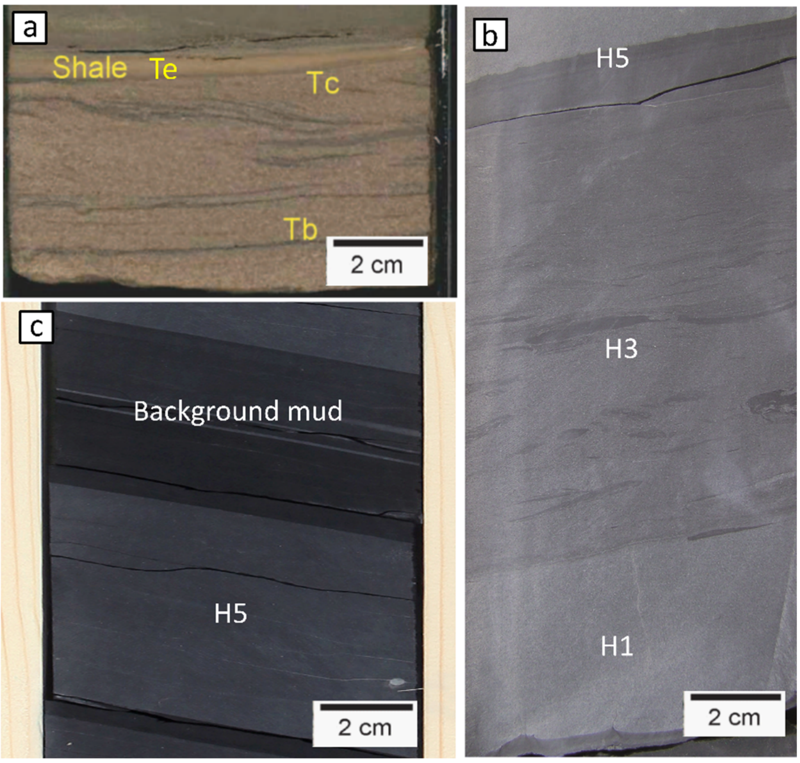

Figure 2. Core photographs showing (**a**) a low-density turbidite with organic-rich (average TOC = 8%) lower sandy divisions (Tb and Tc) and overlain by relatively organic-lean (average TOC = 2%) Te mudstone/shale from a Miocene deep-water succession of Kutei Basin, Indonesia [1]. Reprinted/adapted with permission from Ref. [1], 2006, AAPG; (**b**) Organic-rich H3 division (with 1.24 wt% TOC) of a hybrid event bed overlain by co-genetic H5 mudstone (with 0.6% TOC) from the Ross Sandstone Formation; and (**c**) vertically stacked H5 (0.7 wt% TOC) and background mudstone (0.6 wt% TOC) from the Ross Sandstone Formation, western Ireland.

Deposition of OM via suspension settling could be sufficiently slow and OM is prone to increased bioturbation and oxic degradation [80]. This is evident from the lower TOC content of the deep-marine mudstones compared to their co-genetic or co-eval turbidity current and transitional flow facies in many examples [1,3–5,11]. The average TOC content in sand-rich, parallel laminated Tb sandstones (average TOC = 8%) is significantly higher than co-genetic laminated Te mudstone facies (average TOC up to 2%) in Miocene turbidites from the Kutei Basin, Indonesia (Figure 2a) [1]. Similar TOC trends have been reported in the Ogooué and Congo Fan systems where sandy turbidite facies have significantly higher OM content than their pelagic/hemipelagic muddy counterparts [3–5]. Recently, [11] documented that H5 mudstone division has lower TOC contents (0.6% TOC) than underlying muddy sandstone or H3 division (1.24% TOC) in HEBs from the Pennsylvanian Ross Sandstone Formation, western Ireland (Figure 2b). Higher OM content in deep-water mudstones has been commonly linked to bottom water anoxia ([79,81,82] and references therein). In anoxic conditions, the slowly settling carbon is relatively less prone to oxidation and bacterial degradation. Despite the fact that many deep-marine anoxic mudstones are organic-rich, in some cases these mudstones could be significantly thin and constitute only a minor portion (small percentage) of the entire stratigraphic succession, thereby not sequestrating significant quantities of OM. For example, deep-water mudstones constitute only a small proportion (up to 10%) by thickness compared to HEBs (27%) and turbidites (31%) of the Pennsylvanian Ross Sandstone Formation, western Ireland, an ancient tropical deep-sea fan system [11,51].

2.2. Turbidity Currents

Turbidity currents are turbulent suspensions of sand and mud (with occasional gravel), which are propelled by the downslope component of gravity acting on the excess density. It is one of the most important mechanisms by which OM is transferred from shelf settings to the continental slope and deep-marine fans and basin plain. The deposits of turbidity currents are referred to as 'turbidites' [83]. Refer to Figure 1 for the texture and structure of different turbidity current deposits.

Initial turbidity current models advocated for efficient segregation of the sand and mud in the flows, with the mud deposited as mudstone caps (Figure 3a) [23,25]. Organic carbon carried in largely turbulent flows is often sorted with mud in the mudstone caps (Figure 3a). As discussed in earlier section, OM buried in mudstone caps is prone to oxidation, implying that in many cases the preservation potential of OM in mudstone caps could be relatively low. Prevailing turbidity current models suggest that sandy fractions (Ta-Tc divisions) in turbidites are commonly organically-lean [23,25]. The lower portions of even finer-grained turbidites (Ta divisions) such as those in the Ross Sandstone Formation are organically-lean, although mud-chips and associated OM may preferentially segregate in the lee side of the ripple-laminated divisions sandstones as shown in Figure 3d in [11]. Nevertheless, a limited number of studies have described organic-rich layers in sandy deep-sea turbidites [1,10,84–86], in some cases even within sands of units Ta and Tb (Figure 3b,c), depending on the density and size of organic debris [1,12]. Fine- to very fine-grained Miocene turbidite sandstones in Kutei Basin, Indonesia contain significant quantities of organic carbon (average TOC in Tb division = 8%) in the form of terrestrial leaves and coaly fragments (Figure 3b,c) [1]. The concentration of leaf debris within turbidite sandstones was a function of leaf density, as leaf debris is of slightly higher density and larger size compared to woody fragments, which is why it may have been carried as bedload rather than its common transportation in suspension load by the gravity currents [1]. Woody material has been reported in turbidities from multiple locations such as Gres d'Annot, southeast France and the Marnoso-Arenacea Formation, Italy [12,13], as well as sands in the Bengal Fan in the Indian Ocean [86] and in the Bute Inlet Fjords [10]. Other examples of plant material transported into deep-water marine settings via hyperpycnal flows (direct river discharge) are known from Eocene rocks exposed within the Central Basin of Spitsbergen, Norway [87] and sedimentary basins in Argentina and Trinidad [84]. These studies suggested that one criterion for recognizing hyperpycnal flow turbidites is the presence of continental plant material within the deposits. In many of these examples where organically-rich sandy components have been reported, the sandstones are very fine- to fine-grained with a likelihood of clastic grains being hydrodynamically equivalent to the organic debris, implying that perhaps documenting variation in type, density and shape parameters of the organic material is important to predict OM type zonation in submarine fans [12,13].

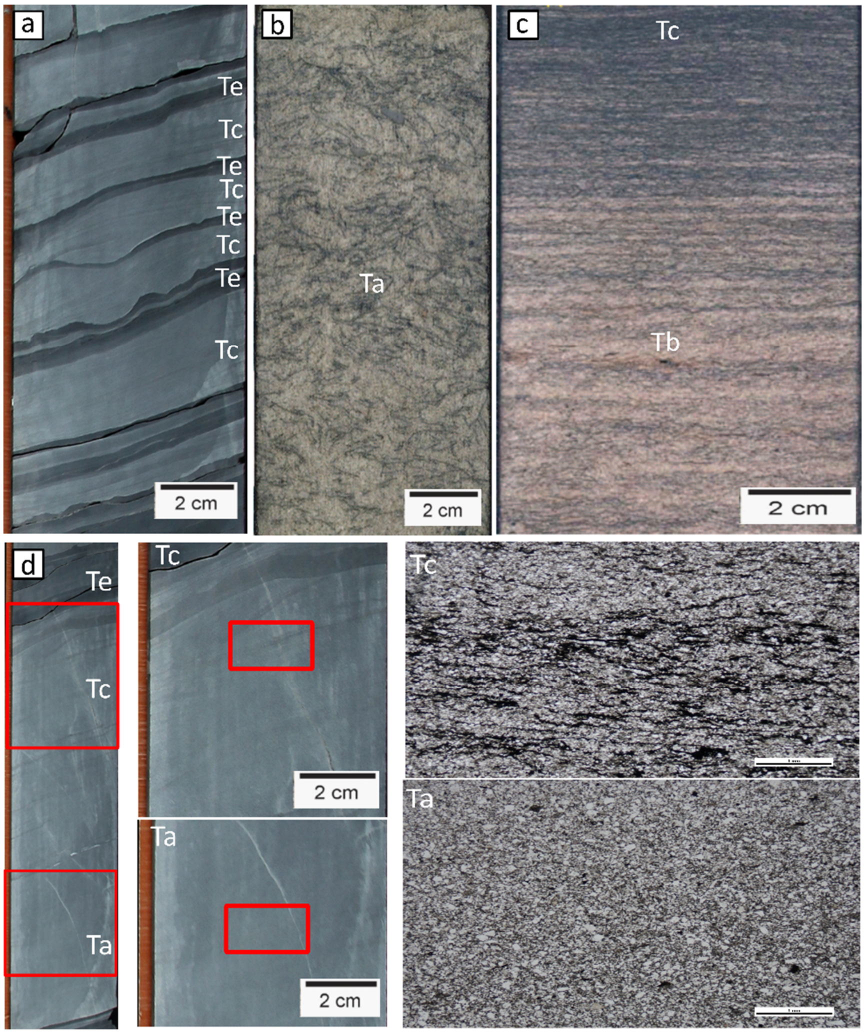

Figure 3. Core photographs showing (**a**) a stack of low-density turbidites with efficient segregation of sand and mud components in the Ross Sandstone Formation, western Ireland; (**b**,**c**) organic-rich Ta (**b**) and Tb-Tc (**c**) divisions in sandy turbidites from the Miocene deep-water succession of Kutei Basin, Indonesia [1]. Reprinted/adapted with permission from Ref. [1], 2006, AAPG; and (**d**) organic-lean sandy Ta and Tc divisions in a turbidite from the Ross Sandstone Formation, western Ireland. In ripple-laminated sandstones, mud chips and minor OM is occasionally fractionated in the lee side of the ripples, as seen in the photomicrograph Tc. Red rectangles on the core photographs show the location of plug samples.

Although a large number of studies [1–6,12,13,62,66,67,88,89] have attempted to characterize and quantify OM contents in both ancient and modern turbidites, they have focused and analyzed the finer grained upper tiers (Td/Te) of the event beds, where OM is commonly thought to be fractionated. These studies may reflect a sampling bias towards more fine-grained lithologies in otherwise sand-rich turbidity current deposits. Furthermore, turbidites commonly dominate in relatively channelized sectors of the fan systems, where these muddy tiers (Td/Te divisions) either constitute a very small part of the turbidity current events, or sometimes are not at all expressed due to fine sediment bypass in the downcurrent direction [90,91]. Where mudstones are present, their accumulation from slow settling suspensions makes them prone to bioturbation and degradation. Moreover, in channelized/proximal settings, the channel edges collapse regularly, supplying turbid flows and redistributing the sediment and OM. This reflects that OM within turbidites may be more prone to oxidation and remineralization due to several cycles of re-suspension [66].

2.3. Hybrid Sediment Gravity Flows

Hybrid and related transitional flows form an enigmatic yet common class of sediment gravity flows and exhibit components of both turbidity currents and debris flows as part of the same event [32]. The resulting deposits typically contain a basal clay-poor turbidite sandstone and an upper matrix-supported linked debrite (Figure 4a–c). High matrix and OM content is one of the key characteristics of HEBs and is commonly linked to sudden changes in original flow behavior. Hybrid flow deposits significantly diverge from classic turbidite models [23–25], and an idealized HEB is comprised of up to five vertically stacked divisions, including a basal, clean, and often graded 'turbidite' sandstone (H1), a banded sandstone (H2) with alternating darker mud-rich and paler mud-poor sandstone bands, a mud-rich sandstone (H3) forming a 'linked debrite' typically with mudstone clasts, mud chips, dispersed mud, and OM. Sometimes H3 divisions can be subdivided into two parts, H3a and H3b, on the basis of differences in textural, mud and OM contents (Figure 4b). For more details on the H3 division sub-structure refer to [53]. A thin well-structured parallel and/or ripple laminated sandstone/siltstone (H4) and a mudstone (H5) couplet caps the event bed. Sometimes the H5 mudstone is capped by a background/hemipelagic mudstone, representing periods of quiescence between the sediment gravity flow events. Hybrid beds are thus complex tiered deposits with different parts of the bed emplaced by distinct depositional mechanisms (incremental aggradation, en-masse deposition, and suspension settling).

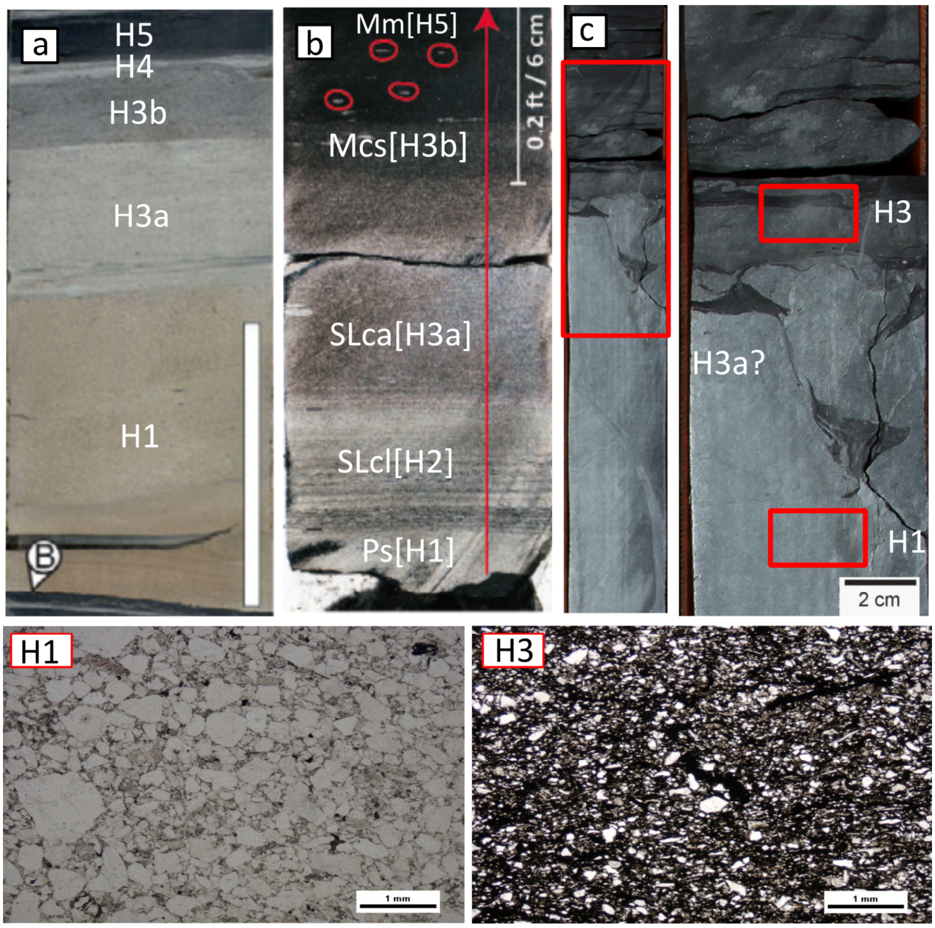

Figure 4. Core photographs showing; (**a**) a type IV hybrid event bed with organic-rich H3b and H5 divisions from the Palaeogene Gulf of Mexico [48]. Reprinted/adapted with permission from Ref. [48], 2012, GSA; (**b**) a mixed siliciclastic–carbonate hybrid event bed with organic-rich muddy

H3b and H5 divisions from the Wolfcamp A Formation in the Permian Basin, USA [8]. Reprinted/adapted with permission from Ref. [9], 2019, AAPG; and (**c**) a hybrid event bed with organically-lean H1 and organic-rich H3 divisions from the Ross Sandstone Formation, western Ireland. Organic matter is preferentially segregated in H3 divisions in hybrid event beds. Red rectangles on the core photographs show the location of plug samples.

Vertical TOC profiles for a range of HEBs show that H1 divisions are generally organically-lean (average TOC << 1%) and most of the OM is hydrodynamically segregated into H3a and H3b sub-divisions (average TOC > 2%) (Figure 4c) [11]. The co-genetic H5 divisions have either equal or lower TOC contents than their H3 counterparts (refer to Figure 2b). The flows preferentially fractionate OM (on the basis of shape and density) into linked debris flows (top and rear of the flows) as revealed by the occurrence of H3 divisions with significant TOC contents (Figure 4c). A positive correlation between OM and mud content exists in HEBs and was interpreted as a function of both hydraulic segregation and enhanced preservation of OM [11]. Clay flocs were also implicated for encapsulation of the significant quantities of the organic particles at the onset of flocculation and during transport, thereby providing a long-term 'physical protection' mechanism [11]. Similar vertical TOC trends have been reported from mixed siliciclastic–carbonate hybrid event beds in the Permian Wolfcamp A succession (Figure 4b) in the Delaware Basin, USA [8], in which the best unconventional reservoir facies are the clay- and organic-rich and carbonate-depleted uppermost parts of HEBs (their SLca and Mcs facies are equivalent to the H3a and H3b parts described by [11] and others). Thus, predicting areas where thick H3 and particularly H3b divisions are developed can be a part of an effective hydrocarbon exploration and development strategy in the deep-water basins [8]. Although OM is dominantly particulate in nature, the chemical sorption of the organic molecules on clay surfaces cannot be completely ruled out due to the presence of abundant clay. Organic carbon protection by clay minerals is a well-known process in sedimentary rocks [68]. Thus, mud-driven flow transformations in sediment gravity currents provide a particularly effective mechanism for the burial of OM in deep-sea fan systems. HEBs are usually dominant in distal lobes [31,32], and thus abundant linked debrites in the distal parts of many deep-water systems are prone to very limited erosion or reworking by subsequent events. In short, high mud and TOC contents and en-masse deposition all favor enhanced OM burial and preservation in HEBs [11].

The widespread occurrence of beds with linked debrites indicates that these are important components of many deep-water successions [31–33,38–40,42], including those basins actively explored for hydrocarbons [31,32,49,92,93]. In some instances entire or parts of the submarine fans (such as distal lobes) are dominated by HEBs. The Pennsylvanian Ross Sandstone Formation, western Ireland, is a case in point where the basal sandy basin-floor sheet system is dominated (>70%) by HEBs with minimal mudstones [11]. This implies that hybrid sediment gravity flows could be important vectors for transferring terrestrial OM to deep-sea floor repositories where it can be efficiently buried in muddy sandstone and/or sandy mudstone divisions over geological time scales.

3. Discussion

Sediment gravity flows have been reported as important vectors for transferring terrestrial OM to deep-sea floor repositories and emerging evidence suggests that deep-marine event beds may incorporate significant TOC [1,6,8]. Inferring the extent of hydraulic fractionation of OM and related components within sediment gravity flows and mapping where this ends up in the deposit is critical for understanding the ultimate fate of OM exported to deep-water sinks and how these components are partitioned across the deep-sea sediment routing system between canyons, channel-levees and lobes [2,3].

Mudstones are accumulated from vertical suspension settling as: (i) organic-rich mud caps (Td/Te units) in turbidites [4,10]; (ii) H5 mudstone caps in hybrid event beds [32,94]; and (iii) background mudstones, albeit not a focus of this study (Figure 5a). In all three cases the deposition of OM could be sufficiently slow and when the sedimentation rates are lower, the diffusion of oxygen from the bottom waters is more efficient and ultimately, even relatively resistant terrestrial OM is prone to significant remineralization [66]. By contrast, OM buried deeper within sand-rich Ta-Tc divisions of turbidites and H3 divisions of HEBs is less prone to oxidation because the sedimentation rate is sufficiently high (Figure 5b,c). However, a majority of the studies on turbidites have documented the mud caps as significant OM sinks [1–6,12,13,62,66,67,88,89] rather than sand-rich divisions. Studies on carbon burial by hybrid gravity flows are still largely under-investigated, but preliminary studies suggest that OM is better preserved in HEBs compared to turbidites and mudstones (Figure 5), due to clay-forced rapid deposition, encapsulation of OM particles in clay flocs at the onset of flocculation and during transport, and subsequent deep-burial beneath the sea floor [11]. In HEBs, the sandstone/mudstone couplets (H4/H5) divisions may further hinder downward diffusion and/or percolation of oxidants into the sediment pore waters [74], thereby further enhancing the OM preservation in H3 divisions. The proportions of different event bed types and mudstones—hybrid event bed versus turbidite versus mudstones—making up most of the deep-water fan successions is thus an important metric to quantify and map OM burial and preservation in deep-sea settings.

Several other factors also dictate OM burial efficiency in submarine fans (e.g., sedimentation rate, sea level, oxygen level, depositional mechanism). The exceptionally high burial efficiency of OM on the Bengal fan, which is close to 100%, is caused by rapid accumulation rates combined with low oxygen concentration in the waters of the Bay of Bengal [2]. Furthermore, relative sea level changes linked to glacial–interglacial cycles greatly affect the sediment transfer and specifically OM sequestration over the geological times scales in the deep-sea fan systems [95,96]. In the Amazon deep-sea fan OM accumulation is controlled by glacio-eustatic sea-level oscillations [96]. Interglacial sea-level high-stand sediments are dominated by marine OM (100%), whereas during glacial sea-level low-stands terrestrial OM (60–90%) is transported beyond the continental shelf through the Amazon canyon and deposited directly onto the Amazon deep-sea fan [95].

This review article also shows that the depositional mechanism/process can also have a profound control on the fate of OM distribution, burial and preservation. It was highlighted by Kvale et al. [8] that the depositional mechanism is an important factor (perhaps more so than water column anoxia) in preserving high TOC contents within the HEB-dominated fan fringe settings in the mixed carbonate–clastic Wolfcamp Fm, in the Delaware Basin. Recently, Baudin et al. [66] showed that it is possible to estimate the efficiency of the different depositional environments and to some extent depositional mechanism in trapping OM fluxes by calculating the percentage of the OM burial in each sector of the fan system. They documented that lobes and levees are significant OM sinks and accumulate about 45% and 52% of the total OM burial in Congo Fan, respectively, whereas the canyon and channel accumulate the remaining 3%. The lobes are more effective than levees because they accumulate about four times more OM compared to levees at the same amount of surface area (inferred from Figure 6 in [66]). Lobes have been referred to as 'mega-sinks' for terrestrial OM by other researchers [9]. Grain-size measurements in the cores indicate that most (up to 80–90%) of the Congo Fan sediment is made of clay and silt [3]. A large proportion of silt and finer clay grains in the distal lobes in the Mississippi Fan has been attributed to diminished turbulence once clay and silt content cross a certain threshold within sediment gravity flows as they expand from confined to unconfined settings downstream of the channel [50]. The role of these muddy components in enhanced physical protection of the OM and regulation of long-term global preservation of organic carbon is very well established [68]. It is highly likely that many of these preservation mechanisms (rapid deposition, bottom water anoxia, lack of bioturbation, etc.) may operate together to facilitate long-term OM preservation in the deep-water rock record.

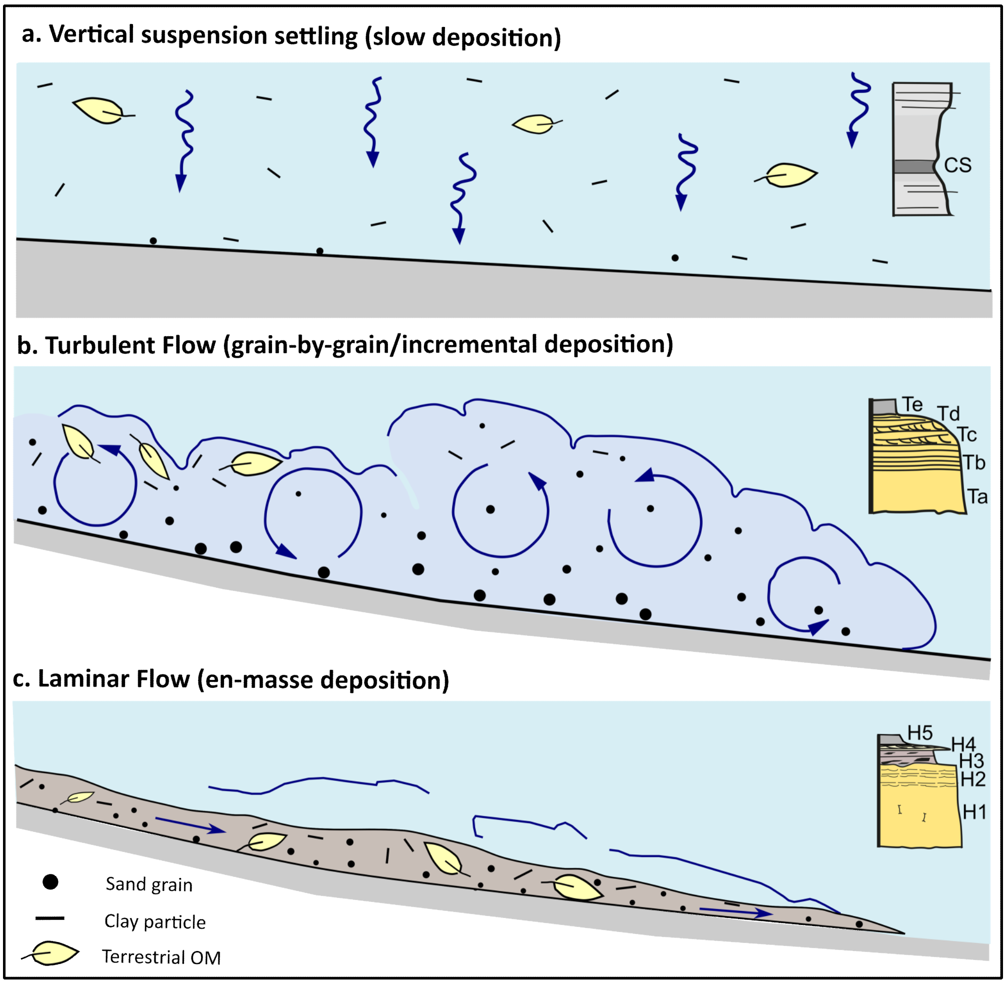

Figure 5. Conceptual models accounting for three dominant mechanisms responsible for OM deposition and segregation in the deep sea. (**a**) In bed capping (Te or H5 divisions) and background mudstones OM is accumulated from slowly settling suspensions and these flows are prone to higher OM oxidation and degradation. CS = condensed section; (**b**) turbidity currents where grain-by-grain deposition takes place, OM is often segregated towards the tops and/or tail regions of the flows (namely Td and Te divisions), although some OM could be deposited as bed load in Ta-Tc parts; and (**c**) hybrid event beds OM is also locked in lower tiers (below H5 divisions, which are equivalent to Te mud caps in turbidites), particularly in H3 divisions emplaced by turbulence-dampened laminar flows, thereby providing higher post-burial protection.

4. Conclusions

Sediment gravity flows are important agents for transferring terrestrial OM to deep-sea fan repositories and emerging evidence shows that relatively sandy deep-marine event beds may also incorporate significant quantities of OM, implying that global carbon burial budgets for the deep-sea fans may have been significantly underestimated. Organic matter accumulated from slowly settling suspension in mud caps (Te or H5 divisions in turbidites and hybrid event beds, respectively) is prone to oxidation and bioturbation compared to the OM buried in sandy components of turbidity currents (Ta-Tc) and HEBs (H2/H3 divisions). Organic matter burial in sandy divisions of turbidites is still not a very widely recognized phenomenon and most of the models still favor OM accumulation in mudstone caps. In hybrid beds, OM is preferentially segregated into mud-rich linked debrite but still sandy H3 divisions. It is also thought that in HEBs clay flocs within laminar flows can also encapsulate significant quantities of the OM during transport, thereby providing a long-term 'physical protection' mechanism. Thus, HEBs can efficiently sequester large quantities of OM because rapid clay-forced deposition and physical protection of OM in cohesive linked debrites (excluding bed tops with intense scavenging) provide a useful mechanism for long-term OM burial in submarine fans. The present study shows that the flow depositional process may exert a strong control on OM distribution, burial and preservation.

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